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Development of a high resolution permafrost distribution model in the Aksu catchment, Central Tian Shan

Dissertation zur Erlangung des akademischen Grades

Doktor der Naturwissenschaften (Dr. rer. nat.)

vorgelegt von

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Abbreviations

ASTER	Advanced Spaceborne Thermal Emission and reflection Radiometer
a.s.l.	above sea level
BMBF	Bundesministerium für Bildung und Forschung ("Federal Ministry of Education and Research")
BTS	Basal Temperature of the Snow cover
CAIAG	Central Asian Institute for Applied Geosciences
CAREERI	Cold and Arid Regions Environmental and Engineering Research Institute
CAS	Chinese Academy of Sciences
DEM	Digital Elevation Model
DFG	Deutsche ForschungsGemeinschaft ("German Research Foundation")
ETM+	Enhanced Thematic Mapper Plus
GIS	Geographic Information System
GPS	Global Positioning System
GST	Ground Surface Temperature
LIA	Little Ice Age
LIGG	Lanzhou Institute of Glaciology and Geocryology
MAAT	Mean Annual Air Temperature
MAGST	Mean Annual Ground Surface Temperature
MODIS	MOderate-resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NDVI	Normalized Differenced Vegetation Index
NIR	Near-InfraRed wavelength
PISR	Potential Incoming Solar Radiation
SPOT	Satellite Pour l'Observation de la Terre ("satellite for observation of earth")
SRTM	Shuttle Radar Topography Mission
SuMaRiO	Sustainable Management of River Oases along the Tarim River
USGS	United States Geological Survey
VC	Vegetation Cover
VIS	VISible red wavelength

Acknowledgments

First of all I want to thank my supervisor Prof. Dr. Lorenz King. He introduced me to the fascinating and challenging research in an international and interdisciplinary community. He opened the doors for me to international conferences, summer schools, field work and my research visits to Zermatt, Nanjing and the University Centre in Svalbard, which provide me with valuable input for my dissertation. With his dedication and his extensive network of international colleagues and friends, he ensured that my field campaigns and data gathering were a great success even under these difficult circumstances. I am also very grateful to my second supervisor Prof. Dr. Peter Felix-Henningsen for his support especially during the final stage of my dissertation. Meeting him the first time as a student at the University of Tübingen back in 2009, I was very happy to have him as my supervisor in Giessen.

Writing a dissertation based on original data and field work in such a remote and far away area as the Central Tian Shan, I was very dependent on my project partners and friends in China and Kyrgyzstan. Without Sun Zhandong, Gao Qianzhao and Li Zhongqin organizing fieldwork and gathering the data in China would have not been possible under these difficult circumstances. Conducting the fieldwork, Johannes was of great help defying the difficult weather and hard work at 4.000 m a.s.l. For the excellent support in Kyrgyzstan I want to thank Bolot Moltobekov, Ryskul Usubaliev and Murataly Duishonakunov for the administrative support and for their help in the field. Murataly besides being a great colleague and researcher to discuss complex scientific topics is also a good friend to share the occasional beer with. It was also very generous of Arjen Stroeven and Jon Harbor to let me join their field campaign and give me valuable insight into their research in different areas of the Aksu catchment.

The numerous project meetings with all partners of the Aksu-Tarim project were very helpful for the evaluation of the results and planning of the future tasks. The nice atmosphere at these meetings ensured a good cooperation and best possible outcome of the project despite the difficulties in conducting fieldwork, which all sub-projects had to face. At the working group of Prof. Dr. King in Giessen I was very fortune to have such nice colleagues especially in Christoph, Ina, Nadine, Usha and Murataly. It was a pleasure to discuss my results with them as well as enjoying the time after work in our weekly “colloquium”. Last but not least I want to thank my family and Anne for their constant support. I hope I can make up for the occasional “Sorry, don’t have time” in the future. Without them, I wouldn’t have finished this dissertation. Thank you!

Stephan Imbery, Juni 2014, Giessen

Summary

Climate change is of great concern for the arid regions in Central Asia and significantly affects the hydrological cycle. Agricultural, social and economic development depends heavily on the water discharge from the rivers originating in the high mountains of the Central Tian Shan. While surface runoff in general is expected to increase in the short to mid term due to the melting of glaciers, little is known about the long term variations of permafrost and corresponding ground ice. Therefore, the overall aims of this thesis are (1) to identify key factors influencing the ground thermal regime, (2) to develop a local permafrost distribution model and (3) find implications for ground ice contents.

The study focuses on the Aksu river, which contributes more than 70% to the overall discharge of the Tarim basin in Western China. As a first step, a dense ground temperature monitoring network is installed in an exemplary subcatchment. The temperatures are recorded hourly over two consecutive years (August 16th 2010 to August 15th 2012). Besides topographic features (altitude, slope and aspect) snow cover is identified as a key factor for both spatial and inter-annual variations of the ground thermal regime. As a second step, the monitored temperature data are used to develop an empirical-statistical permafrost distribution model. The model incorporates data derived from satellites and a Digital Elevation Model (DEM), such as Potential Incoming Solar Radiation (PISR) and altitude. The model output consists of the Mean Annual Ground Surface Temperature (MAGST) simulated with a 30 m horizontal resolution. The simulated MAGST was then classified into four likelihood groups for permafrost occurrence to create a high resolution permafrost distribution map for the whole research area.

Due to the close interaction between the glacial and permafrost environment, large water resources exist in the form of rock glaciers and ice cored moraines. Furthermore, the existence of massive ground ice was verified by direct assessments at locations with low slopes and fine grained sediments. In general, the ground ice content in the Central Tian Shan is very high, which is also confirmed by analysis of zero curtain periods at different depth of the active layer. Therefore, the results in this study clearly stress the importance of the permafrost environment for the water balance in the entire region. The reaction time of permafrost to climate change is much slower than that of glaciers and large amounts of ground ice can be preserved over long time periods.

Zusammenfassung

Die wirtschaftliche Entwicklung in den Trockengebieten Zentralasiens ist eng mit dem Wasserabfluss aus den angrenzenden Gebirgen verknüpft. Daher sind die Auswirkungen des Klimawandels auf diese Region von großer Bedeutung. Allgemein ist von einer Erhöhung des Wasserabflusses durch das Abschmelzend der Gletscher im Zentralen Tian Shan auszugehen. Die Verbreitung von Permafrost und der Einfluss von Bodeneis sind hingegen weitgehend unbekannt. Die Ziele der vorliegenden Arbeit bestehen somit darin (1) Faktoren zu identifizieren, welche sich auf die Untergrundtemperatur auswirken, (2) die Entwicklung eines statistisch-empirischen Modells zur Permafrostverbreitung und (3) Indikatoren für das Vorkommen von Bodeneis zu finden.

Das Untersuchungsgebiet befindet sich im Einzugsgebiet des Aksu. Dieser Fluss entspringt im Zentralen Tian Shan und trägt über 70 % zum Gesamtabfluss im Tarimbecken in West China bei. Insgesamt wurden an 69 Standorten Logger und Temperatursensoren installiert, welche die Untergrundtemperatur in stündlichem Intervall über zwei Jahre hinweg messen (16. August 2010 – 15. August 2012). Durch statistische Datenauswertung konnten die topographischen Faktoren (Höhe über Meer und Hangneigung) sowie die Schneebedeckung als wichtigste Parameter für räumliche Variationen der Untergrundtemperatur identifiziert werden. Darauf aufbauend wurde mit diesen Parametern ein empirisch-statistisches Model zur Permafrostverbreitung entwickelt. Die benötigten Daten wurden mithilfe von Satellitendaten abgeleitet (Digitales Höhenmodel, Potenzielle Sonneneinstrahlung etc.). Das Resultat des Modells ist die flächenhaft simulierte durchschnittliche jährliche Oberflächentemperatur für das Untersuchungsgebiet. Diese ist ein idealer Indikator für Permafrostvorkommen und wurde in eine Karte zur Permafrostverbreitung mit 30 m horizontaler Auflösung umgewandelt.

Das Untersuchungsgebiet zeichnet sich durch eine hohe Verbreitung von Blockgletschern und Moränen mit massiven Eiskernen aus. Weiterhin wurden durch direkte Untersuchungen vor Ort große Mengen an Bodeneis auf Höhen über 3.800 m nachgewiesen. Durch die detaillierte Analyse der tieferen Untergrundtemperaturen konnte zudem große Bodeneisvorkommen für den gesummten Zentralen Tian Shan abgeleitet werden. Die Ergebnisse dieser Arbeit sind daher von großer Bedeutung für weitere Studien in dieser Region und heben den Einfluss von Permafrost auf den Wasserhaushalt hervor. Insbesondere vor dem Hintergrund des Klimawandels können durch die langsamere Reaktionszeit von Permafrost auf Temperaturerhöhungen im Vergleich zu Gletschern große Mengen an Bodeneis auch über lange Zeiträume erhalten werden.

1 Introduction

1.1 Research background

High mountains fulfil an important function as "water towers" in the water cycle of semiarid and arid regions (e.g. Sorg et al. 2012, Bolch & Marchenko 2006, Viviroli et al. 2007). Runoff generated in high mountains frequently contributes more than 90 % to the total discharge of large river basins (Viviroli et al. 2003). High mountains are therefore a key resource for the overall economic and social development. They provide freshwater for irrigation, industries, hydropower, extraction of natural resources, domestic use as well as natural vegetation and wildlife. This dependency is particularly severe in the arid environment of Central Asia. Rivers originating in the high ranges of the Central Tian Shan make the much needed water resources accessible for the agricultural intensely used plains from the Aral Sea in the east to the Chinese province of Xinjiang in the west (see Figure 1, Publication 1 and Figure 2). In the arid Tarim basin in Xinjiang, traditional cultivation of cotton and fruit would be impossible without this water discharge from these rivers. The Tarims largest tributary - the Aksu - delivers freshwater from the highest parts of the Central Tian Shan for extensive irrigation and land reclamation measures downstream.

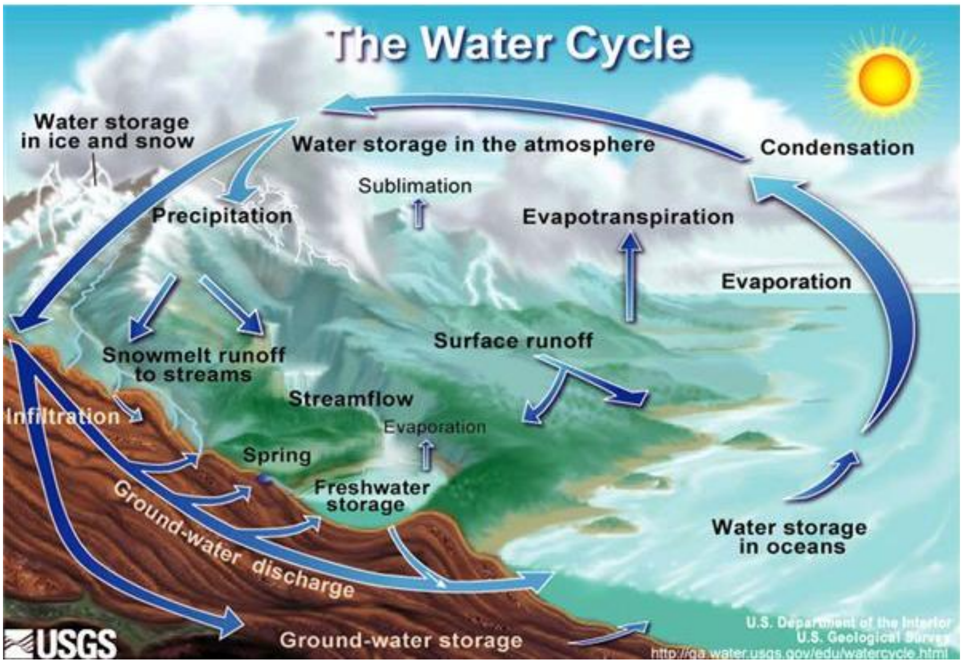

Figure 1: The water cycle: high precipitation in mountain ranges and water storage in the form of ice and snow in glaciers and the permafrost environment (USGS, 18-Mar-2014, http://water.usgs.gov/edu/watercycle.html).

While rates of potential evapotranspiration regularly exceed precipitation by far in the lowlands, higher precipitation rates and lower potential evapotranspiration lead to runoff formation in the adjacent mountains. Considerable fractions of the annual precipitation fall as snow in the glacial and periglacial belts of the Central Tian Shan. Consequently, varying amounts of water are stored in the cryosphere (glaciers, ground ice, perennial firn and snow fields) and temporary as winter snow cover (see Figure 1). Climate change actually leads to an accelerated ablation and retreat of high mountain glaciers in most parts of the world, and to a runoff increase of the related rivers in the short to middle term. Whereas this is a well-known fact, the contribution from the permafrost environment is almost unknown (e.g. Sorg et al. 2012, Bolch & Marchenko 2006).

Permafrost is defined as ground, where temperatures remain at or below 0 °C for at least two consecutive years (Washburn 1979). Permafrost environments are as diverse as the research questions, ranging from “cold” to “temperate”, “continental” to “marine” and “lowland” to “altitudinal/alpine” permafrost. Therefore methods and approaches need to be adjusted not only to the question at hand, but also to the local climatic and topographic conditions. Frozen ground in form of winter-frost or permafrost constitutes a key ecological factor. It forms a temporary or perennial aquitard that strongly modifies hydrological, geomorphological and biological cycles. Frequency and depth of soil freezing and thawing determine the ratio between surface runoff and infiltration of precipitation water. This ratio affects soil erodability as well as the availability of soil water for plant growth. Knowledge of distribution patterns, depths and dynamics of frozen ground is therefore essential for all geo-scientific questions in periglacial landscapes.

Ground thermal regime and frozen ground are the result of energy and moisture exchange between atmosphere and the ground surface. The key variable resulting from these exchange processes is the ground surface temperature, which is transmitted into subsurface temperatures through topography, surface characteristics and ground thermal properties. The presence of frozen ground, both seasonally and perennially, in turn influences the ecological site conditions depending on its local characteristics. The amount of soil water is of special interest in this context, as a frozen layer constitutes an aquitard near the ground surface, which inhibits the percolation of precipitation and melt-water to the groundwater table. Under the same climate conditions the state of frozen ground may be distinct due to differences of rock features and the amount of soil. Phase change processes associated with freezing and thawing of soil water therefore are the main control factors of geomorphological activity in periglacial landscapes. At the same time the hysteresis of transferred temperature waves in soil layer and the phase of change of soil water can be comprehended (see Figure 12 and chapter 4: “Discussion and outlook”). This especially concerns the depth change of permafrost, where temperature change is decelerated for very long periods (Chen 1997).

The variation of frozen soil depth is generally closely related to varying air temperature and solar radiation. At present, these relationships are quite well understood in polar lowlands (e.g. Washburn 1979, Williams & Smith 1989, French 1996), while still little is known about the function of corresponding processes under the more pronounced topography and characteristic forms of high mountain environments like the European Alps (King 1984, 2000, Tenthorey 1992, Keller 1994, Hoelzle et al. 1999, Hoelzle et al. 2001, Mittaz 2002) or the mountain ranges of Central Asia, like the Tian Shan (e.g. Aizen et al. 2002, Gorbunov 2004, Hagg et al. 2007). In high mountain environments, ground temperatures can vary significantly according to local conditions such as slope, exposure, subsurface materials or vegetation even within short distances (Publication 1, Gubler et al. 2011, Roedder & Kneisel 2012). Snow is another highly significant factor for the thermal state of underlying frozen soils (e.g. Smith 1975, Goodrich 1982, Zhang et al. 1996, Ishikawa 2003, Zhang 2005). The existence of a considerable snow cover does not only insulate the heat loss of the ground, but also delay the effects of external conditions on the thermal state of frozen soils. Over northwestern China the long-term variability of snow cover is marked by a stochastic oscillation superimposed on a small increasing trend during 1951-1997 (Qin et al. 2006).

Research on the role of ground ice in the water balance of high mountain catchments has so far consisted of local studies predominantly in temperate latitudes like the Alps (e.g. Tenthorey 1992, Keller 1994, Krainer & Mostler 2002, Rist & Phillips 2005) or the Rocky Mountains (e.g. Clow et al. 2003). A few studies from semiarid and arid mountain regions are available in addition to the above cited work of Schrott (e.g. Croce & Milana 2002, Brenning 2005, Bolch & Marchenko 2006). The amount of ground ice largely depends on the predominant grain size and pore space. While in fine grained sediments, the formation of ice lenses is favoured due to oversaturation of the pore space, common ice contents in coarse substrates range from 30 to 50 % of the total volume (Haeberli et al. 1993).

The emission of greenhouse gases and the expected rise of global-mean temperature presents a serious threat to stability and spatial extend of permafrost worldwide (IPCC 2007). As permafrost warms up and the active layer is thickening, seasonally frozen ground has already decreased by 7% in the northern hemisphere since 1900, and the annual average of snow cover in the period of 1988-2004 shows a reduction by 5% compared with the period of 1967-1987 (Lemke et al. 2007). Impacts of degrading permafrost range from natural hazards (e.g. rockfall and debris flows), destruction of infrastructures (e.g. pipelines and roads) and emission of greenhouse gases (e.g. CO_2 and CH_4) to severe changes in the water balance especially in temperate and arid environments (e.g. Haeberli 2013, Gruber & Haeberli 2007, Callaghan et al. 2010, Bolch & Marchenko 2006, Woo et al. 1994). Even a special report on "Policy Implications of Warming Permafrost" by the United Nations Environment Programme (UNEP 2012) confirms that the importance of permafrost under climate change conditions cannot be underestimated. Huge economic expenses are expected, e.g. with maintenance costs for infrastructures solely in Alaska believed to increase by US $3.6–$6.1 billion up to 2030, as a result of degrading permafrost (Larsen et al. 2008). The long term cost of Arctic methane release could be as high as $60 trillion and thus approaching the $70 trillion value of the global economy in 2012 (Whiteman et al. 2013). Taking into account natural hazards and especially water shortage, economical losses as well as environmental and social long term consequences due to permafrost thawing are difficult to predict. Therefore, the importance of original field data on the thermal regime of permafrost and the development of new permafrost distribution models exceed their regional relevance. They also present a major contribution to the overall research and understanding of the permafrost environment within the scientific community and its effect on the global system under climate change conditions.

1.2 Research area

Climate

The Tian Shan, situated in Central Asia, extends some 2,500 km from east to west. It is one of the highest mountain ranges in the world and can be divided into a Western, Inner, Northern, Central and Eastern Tian Shan. Maximum altitudes range from more than 7,000 m a.s.l. in the Central Tian Shan to about 6,000 m a.s.l. in the Inner and 5,000 m a.s.l. in the other parts of the Tian Shan, respectively. The climate in the Aksu-Tarim research area is highly continental. However, there are harsh contrasts, ranging from the source of the Aksu river in the Central Tian Shan to the Taklamakhan desert in the Tarim basin. Average annual precipitation in the Tian Shan is decreasing from northwest to southeast (Figure 2). The climate station closest to the headwaters of the Aksu river is known as “Tian Shan” climate station (3,600 m a.s.l). The annual average temperature is -7.6 °C, with particular cold winters (-21.5 °C January average) due to its high valley location. With an annual average of only 311 mm, precipitation in the Central Tian Shan is relatively low even at high altitudes.

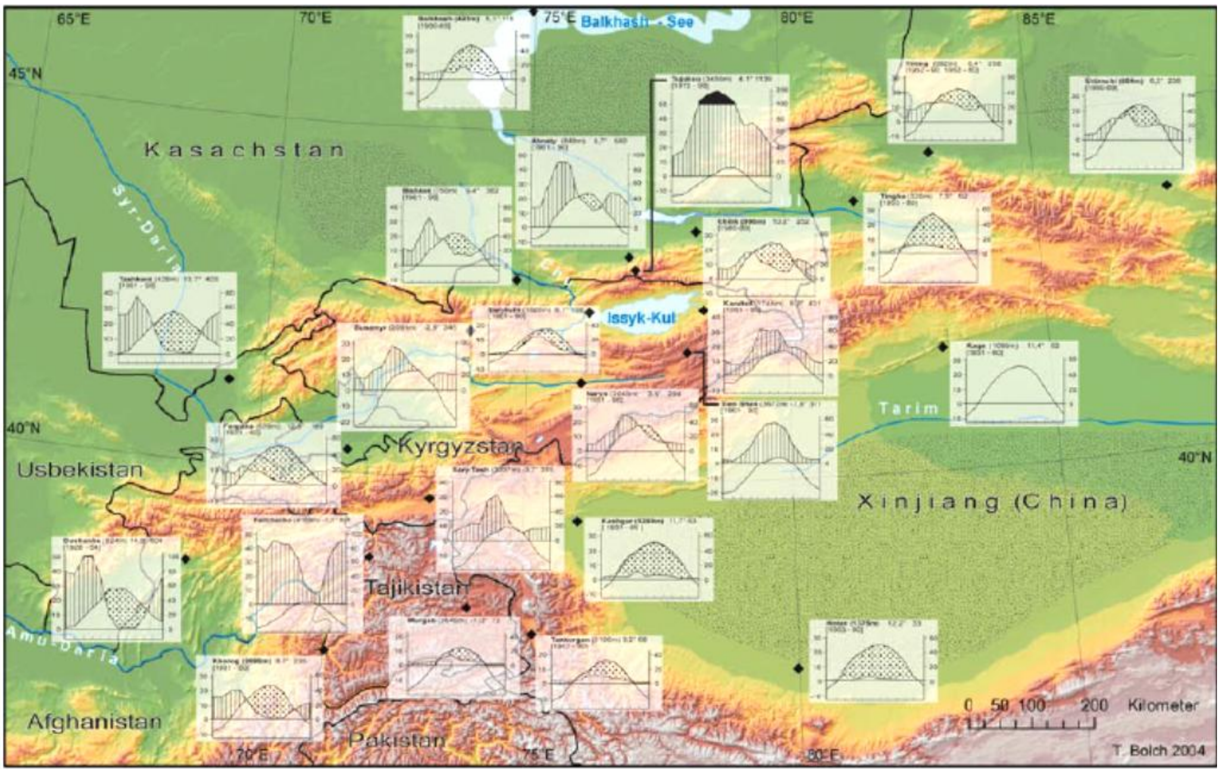

Figure 2: Location of climate stations in the Tian Shan and spatial variation of annual precipitation (Bolch 2006).

The Tarim basin covers an area of about 480,000 km² and can be described as a middle latitude desert. Average temperatures range from -27 °C in winter to 39 °C in summer. Potential evaporation rates exceed by far the annual average precipitation of 48 mm, dropping to 25 mm in the basin center (Tang & Chen 1992). As a result, natural vegetation, agriculture, settlements and industries depend on the river runoff from the surrounding mountain ranges as their major water source.

Hydrology and irrigation

Runoff generated in the Central Tian Shan is of great importance for the entire central Asian region. With its headwater in Kyrgyzstan, the Naryn drains to the west and provides freshwater to the people and cotton fields on its long way to the Aral Sea. The Aksu, also originating in Kyrgyzstan, drains to the south of the Central Tian Shan. It is one of four major tributaries to the Tarim. With a total length of 1,321 km, the Tarim is China's longest inland river and also the main water resource in the region. Settlements and industries extract freshwater from the river as well as from the groundwater, which is recharged by the rivers of the Tarim Basin (Hou et al. 2007).

Extensive land reclamation over the last 50 years required large amounts of water to be diverted to irrigation in the Tarim Basin. This resulted in a continuous reduction of runoff in the tributaries and the main-stream of Tarim River. Figure 3 gives an overview on the scale of irrigation fields and the location of gauging stations along the main stream. Economic development in the Aksu-Tarim catchment strongly depends on natural freshwater reserves, with agriculture – mainly water intensive cash crops like cotton and fruits – being traditionally the main source of income. In the last decades however, an additional large scale consumer of water emerged: the extraction and mining industries (Thevs 2011). Because of the population growth, development of large oil and gas fields and the general "go west" policy, competition for the limited water resources has been intensified in recent years.

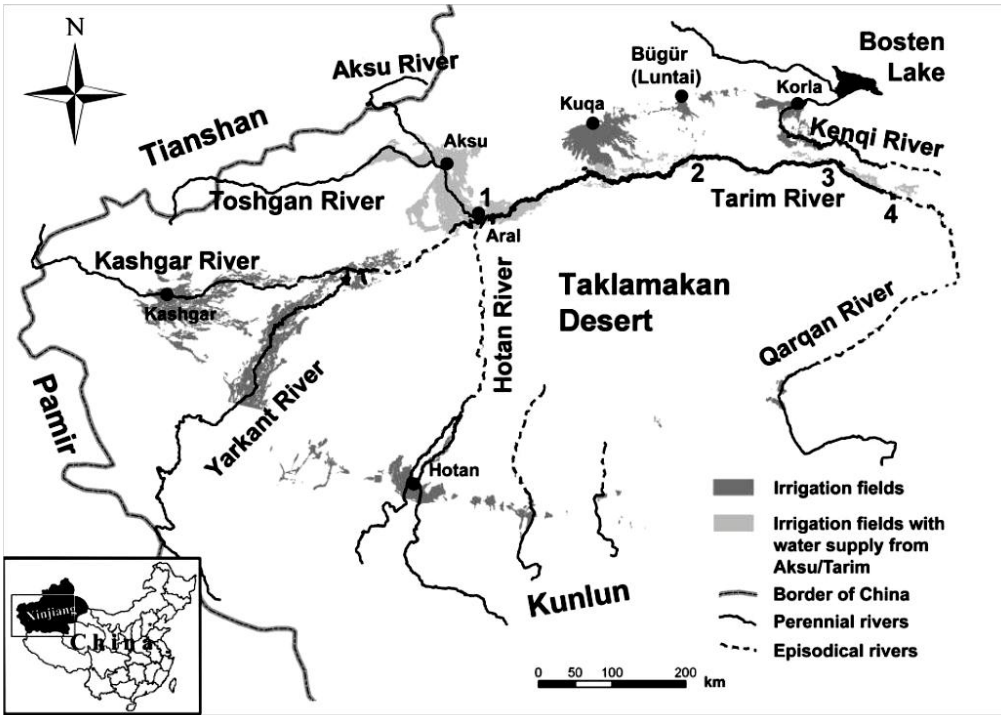

Figure 3: Location of irrigation fields and gauging stations in the Tarim basin; 1: Aral, 2: Yingbaza, 3: Qala Reservoir, 4: Daxihaizi Reservoir (Thevs 2011).

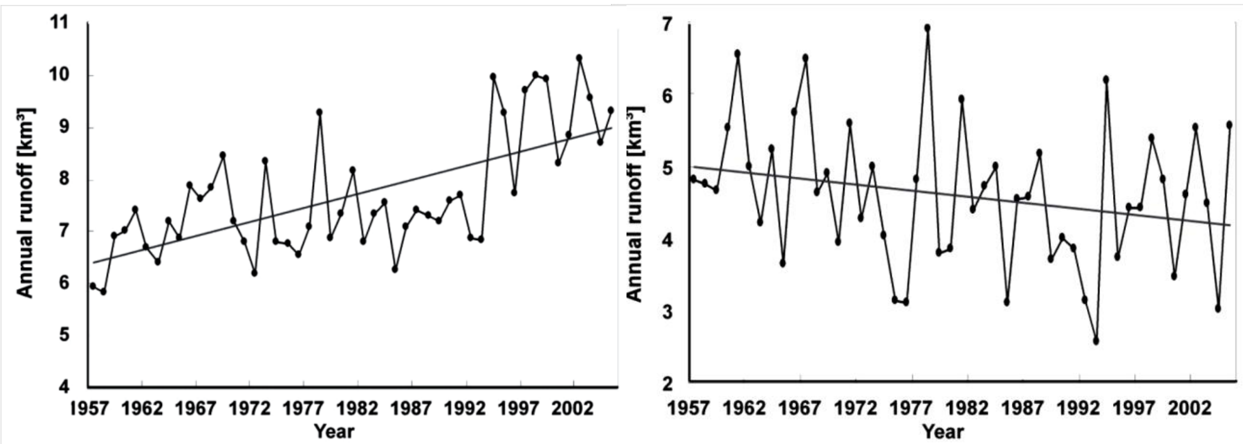

Figure 4: (A) Annual runoff of the Aksu river (20 km north of Aksu city) and (B) annual runoff at Aral gauging station (Tang & Deng 2010).

Looking at annual runoff at gauging stations along the Aksu river (about 20 km north of Aksu City) and at Aral gauging station (see Figure 3 for exact location), results of the extensive irrigation and land reclamation policy become obvious (Figure 4). Over the last 50 years, water discharge in the headwaters of the Aksu river is clearly increasing. However, at Aral gauging station the annual runoff is decreasing at the same time. Further down at the lower reaches of the Tarim this trend is even more evident. Although runoff in the Aksu catchment is increasing, water actually reaching the lower part of the Tarim is decreasing due to the rising water demand for irrigation.

Nonetheless, the Aksu is still indisputable the most important tributary to the Tarim (Table 1). It contributes more than 74 % to the total inflow of the Tarim, with increasing tendencies (Lei et al. 2001, Tang & Chen 1992). Due to the catchments location in the highest part of the Central Tian Shan, meltwater from the cryosphere (snow, glaciers, permafrost) ensure continuous runoff even during the hot summer months, while Hotan, Yarkant and Kenqi may dry out during long periods of the year.

Table 1: Composition of water resources of the Tarim river between 1981 and 1993 (Lei et al. 2001).

Item	Inflow of Tarim River	Composition			
		Aksu River	Yarkant River	Hotan River	Konqi River
Water quantity/$10^8 m^3$	45.11	33.58	0.23	9.18	2.12
Proportion (%)	100	74.44	0.51	20.35	4.70

Cryoshpere

The highly continental climate of the Central Tian Shan makes it an ideal place to study the close interactions of the glacial and permafrost environment. With increasing continentality – and associated lower winter temperatures and decrease in annual precipitation - the altitudinal lower limit of permafrost is generally decreasing, while the lower limit of glaciation is increasing (King 1984, 1986). While this relationship was developed by King (1984, 1986) for central Scandinavia (see Figure 5) the general principle also applies for Central Asia. The presence of large amounts of debris on top and surrounding major glaciers - a typical phenomenon in the region (Wang et al. 2011) – furthermore enhances this interaction. Temperatures in coarse debris are typically 2.5 - 4 °C colder than surrounding mean annual air temperature (MAAT) (Gorbunov et al., 2004). Debris covered glaciers, ice cored moraines and rock glaciers are therefore very common in the upper part of the Aksu catchment.

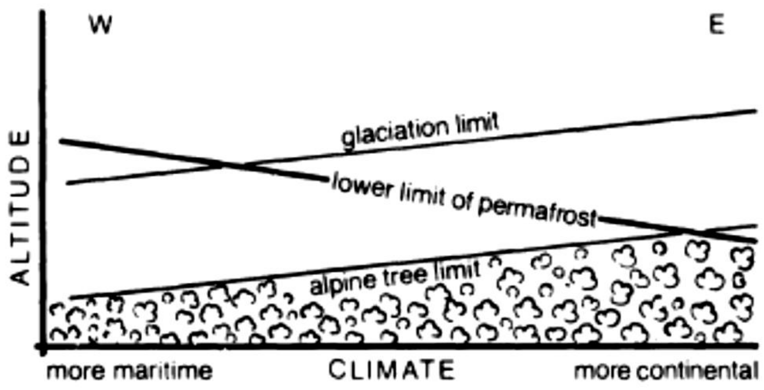

Figure 5: Relationship between climate, lower limit of permafrost, tree limit and glaciation limit in central Scandinavia (King 1986).

Stretching across the China-Kyrgyzstan border, the Aksu catchment is located in the heart of the Central Tian Shan between 41°10’N-42°50’N and 78°30’E-80°30’E. The largest glaciers mainly originate from the vicinity of Tomur Peak. With 7,435 m a.s.l. it is also the highest mountain of the Tian Shan. 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 comprehensive analysis and discussion of permafrost and glacier surveys and maps in China is given by Ran et al. (2012). A major issue is the lack of resolution and/or primary data in existing maps. Mountain permafrost generally has a very high special variability (e.g. Gubler et al. 2011). Therefore, these maps and surveys cannot inform in detail about the thermal state and distribution patterns of permafrost in the region. The development of more reliable and higher resolution permafrost distribution models and maps is hence a priority for further applications.

A brief overview of permafrost research in the Central Tian Shan, as well as a description of permafrost features in the Gukur catchment, where detailed field investigations were carried out, is given in Publication 3. The assessment of permafrost indicators in various locations of the Aksu catchment and implications on ground ice contents of permafrost and the active layer is described in chapter 4 “Implications for the water balance and outlook”.

1.3 Research integration and objectives

In the future, climate is expected to be warmer than today due to anthropogenic emissions of greenhouse gases, mainly CO_2 (IPCC 2007). As a result, the global-mean temperature may rise between about 1.5° and 6° C by the end of this century and significant changes in the hydrological cycle are expected. Considerable locally varying precipitation responses may be induced by changes in atmospheric wind flow patterns, exceeding the average predicted regional climate change. To assess these changes and their effects on the regional hydrological cycle in western China, particularly the Aksu-Tarim basin, an interdisciplinary and international approach is necessary. Therefore, the DFG (Deutsche Forschungsgemeinschaft) funded AKSU-TARIM research bundle "Climate Change and Water Resources in Western China" was launched in March 2010. The main goal of this research group is the integrative assessment of the local to regional hydrological cycle including the atmospheric components, the processes related to glaciers, snow cover and permafrost as well as the river runoff at the southern slopes of the Tian Shan. In an interdisciplinary effort, scientists from the reputable Chinese research institute CAREERI (Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou), various Chinese universities (e.g. Nanjing University) and the Central-Asian Institute of Applied Geosciences (CAIAG, Bishkek) join researchers from several German universities (see below) to tackle these challenges in five interlinked subprojects:

AKSU-TARIM-CLIM

The atmospheric component of the hydrological cycle and the issue of anthropogenic climate change is addressed by a chain of global, regional and local climate models and validated with post-processed observational data in the AKSU TARIM-CLIM project.

Julius-Maximilians-University Würzburg
University of Hamburg

AKSU-TARIM-MELT

Field and modelling studies at the scale of individual glaciers are dealt with in the AKSU TARIM-MELT project. The aim is to improve our knowledge of ablation as a function of surface structures on glaciers with and without debris cover by an extended ablation model. In addition, the resulting runoff as a crucial contribution to total freshwater availability in the Aksu Tarim basin is assessed by a hydrological model.

Ludwig-Maximilians-University München
Commission for Glaciology of the Bavarian Academy of Sciences and Humanities, München

AKSU-TARIM-RS

While AKSU TARIM-MELT and AKSU TARIM-CRYO are focused on the local scale of individual glaciers and valleys, the regional perspective of the cryosphere is addressed in the AKSU TARIM-RS project. Based on remote sensing data the variability and changes of the glacier extent and permafrost distribution in the entire Aksu Tarim catchment are studied.

Technical-University Dresden

AKSU-TARIM-CRYO

The thermal regime and distribution of permafrost in exemplary parts of the Tian Shan are examined at the Justus-Liebig-University Giessen to study the contribution of permafrost to the hydrological cycle in the catchment. This includes detailed field studies as well as the development of a high resolution permafrost distribution model. Majority of the research for this dissertation was conducted within this subproject. Hence, challenges, research goals and objectives are given in more detail:

Water discharge is regularly dominated by the summer ablation of the glaciers, which may contribute up to two third to the total annual discharge in selected catchments of Central Asia (Aizen et al. 1995). On the other hand, proportions of up to 30 % permafrost meltwater to the local catchment runoff were proven by a case study in the High Andes of Argentina (Schrott 1998). For the Northern Tian Shan, Gorbunov & Severskyi (1998) estimated the total volume of ground ice in the Bolshaya Almatinka river basin to be about 87% of the total surface ice volume in the basin. However, it is evident that the periglacial fraction will increase in the long term due to the clearly shorter response time of glaciers to climate warming compared to the permafrost environment. Furthermore, permafrost thawing has a huge impact on the temporal discharge of water and the fractions of surface and subsurface runoff in the Tian

Shan (e.g. Woo et al. 1994). With a deepening active layer, total storage capacity of infiltrating meltwater is increased and runoff delayed.

The assessment of water resources stored in the periglacial belt is of great importance for the development and sustainability of the entire region. Therefore, examining spatial and temporal variability of ground surface temperatures under climate change conditions is a valuable contribution to the overall goals of the AKSU-TARIM research bundle. Only by assessing the relevant factors influencing the temperature regime and distribution patterns of permafrost, predictions can be made on the stability and amounts of ground ice, stored in the periglacial belt of the Central Tian Shan.

Furthermore, the AKSU-TARIM-CRYO subproject is based on and integrated into a long tradition of permafrost research at the Justus-Liebig University of Giessen. Through numerous successful projects, a reputable scientific background and a strong integration within the scientific community developed over the past decades. Starting with early pioneering research on the permafrost environment in Europe (e.g. King 1984, 1986, King et al. 1992, King & Åkerman 1993, Harris et al. 2001) the research group extended its expertise to technical aspects on building in permafrost environments (e.g. Ulrich & King 1993, King & Kalisch 1998, King & Herz 2001, Hof et al. 2003), the assessment of local permafrost variations (e.g. Herz et al. 2003, Philippi et al. 2003, Herz & King 2003, Gruber et al. 2004) and long term effects of climate change on the thermal regime of permafrost (e.g. Hof et al. 2003, King et al. 2003, Harris et al. 2003). Furthermore, the AKSU-TARIM-CRYO project and research for this dissertation also benefited from a strong scientific discourse on methods and regional permafrost characteristics in recent research projects at the Justus-Liebig University in Giessen e.g. in pioneering permafrost studies in Georgia (e.g. Gavardashvili et al. 2007, Schaefer et al. 2009, Keggenhof et al. 2011) and Kyrgyzstan (e.g. Duishonakunov et al. 2013, Duishonakunov et al. 2014) as well as conducting joined field work in the Central Tian Shan (e.g. Imbery et al. 2012, Sun et al. 2014) and the long term research area of Zermatt in the Swiss Alps (e.g. King et al 2012, King et al. 2014).

The main research goals for this dissertation can therefore be summarized as follows:

- Development and installation of a ground surface temperature monitoring network.
- Understanding the distribution patterns and characteristics of permafrost.
- Identification of factors affecting the spatial and temporal variability of ground surface temperatures.
- Developing an empirical-statistical approach for modelling mountain permafrost distribution in the Central Tian Shan.
- Creation of a high resolution permafrost distribution map (30 m resolution) of the Gukur catchment and adjacent areas based on the monitored temperature data.
- Providing background knowledge and essential input to assess the role of permafrost in the overall hydrological cycle under climate change conditions.

2 Methodology

In the Northern Tian Shan, permafrost research started already in the mid-1950s (Gorbunov 1967, 1970) and has been extensively studied since then. However, very little is known about permafrost distribution and characteristics in the Central Tian Shan and the Chinese part of the Aksu catchment in particular. Without any detailed information on permafrost distribution, the subsurface thermal regime or even basic input data (e.g. mean annual air temperature), the installation of high resolution temperature sensors and loggers is a first step to gain continuous empirical data in a remote and insufficiently documented region like the Chinese part of the Central Tian Shan. Only with representative information on mean annual ground surface temperatures (MAGST), site specific parameters can be identified that influence the spatial and temporal variability of permafrost (see Publication 1). Furthermore, the monitored temperatures (MAGST) are used as input data to develop an empirical-statistical model for permafrost distribution (see Publication 2). Detailed descriptions on data and methodology are given in attached publications (Appendices A – C). This chapter only completes that information by presenting additional background information on field work and permafrost distribution modelling.

Field work

Field work was carried out on different scales in the Central Tian Shan. Analysis of selected permafrost features providing valuable information on permafrost distribution and ground ice content was performed at various locations in the whole Aksu catchment. However, the installation of the high resolution temperature monitoring network and the detailed mapping of permafrost features were limited to the Gukur catchment research area.

The Gukur catchment, sited in the vicinity of Tomur Peak, is a direct tributary to the Aksu river and was chosen for detailed fieldwork and the analysis of spatial and temporal variability of shallow ground temperatures (Figure 6). 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) and are surrounded by an extensive periglacial area (see Figure 1 in Publication 3 for the location of the Gukur catchment and Figure 2 in Publication 3 for a more detailed view of the research area).

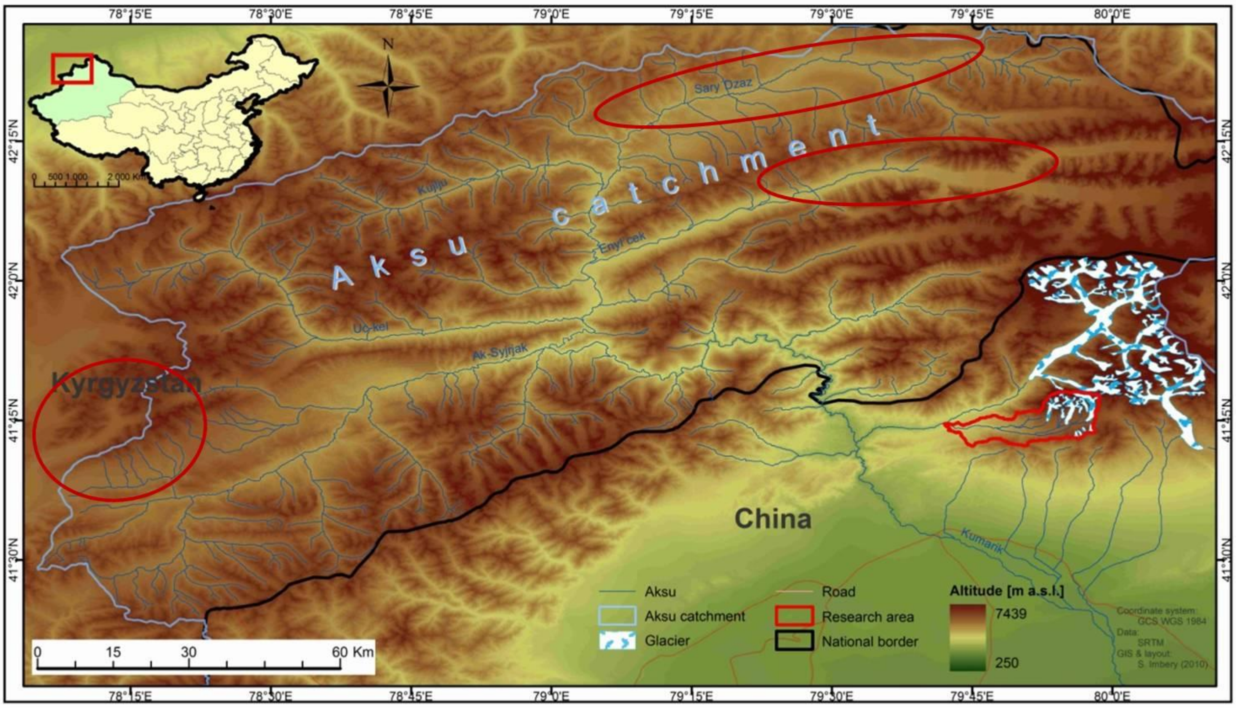

Figure 6: Main tributaries to the Aksu river and location of the research areas.

In August 2010, high resolution thermistor strings and M-Log5W wireless mini-data-loggers (http://www.geoprecision.com) were installed in the central part of the ca. 130 km² Gukur catchment. Exact position (GPS-data) of the mini-data-loggers as well as local parameters (altitude, aspect, slope, vegetation and ground cover) is shown in Table 2. Additionally, the main permafrost features, like rock glaciers and ice cored moraines were mapped (for experiment design and detailed information on instruments and data quality see Publication 1).

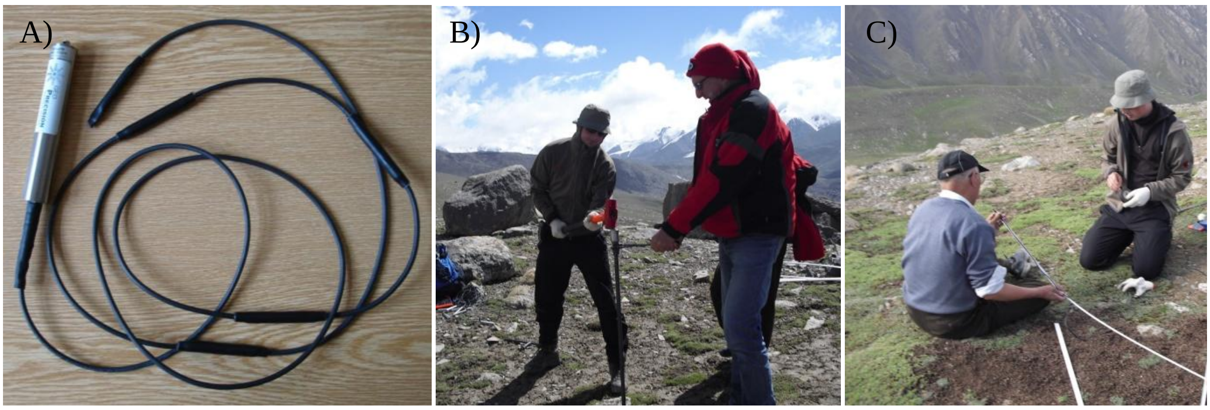

Figure 7: A) M-Log5W wireless min data logger attached to the developed thermistor string; B) preparation of borehole C) attachment of thermistor string to plastic rod to secure sensor spacing before inserting it into the borehole.

Table 2: Location and parameters of all installed temperature loggers in the Gukur catchment; depth: position of the lowest sensor in cm below surface (upper most sensors always at 2 cm b.s.); substratum: S1 = fine (d < 2 mm), S2 = medium (d between 2 mm and 63 mm), S3 = coarse (d > 63 mm); vegetation cover: VC1 = dense grass cover, VC2 = sparse grass cover, VC3 = total absence of grass cover; (table continuing on next page).

Logger ID	Latitude [north]	Longitude [east]	Altitude [m a.s.l.]	Depth [cm b.s.]	Slope [°]	Aspect	Wind exposure	Substrate	Vegetation cover
A50222	41.7403839	79.7533285	2476	2	7	north	sheltered	S1	VC1
A5021D	41.7392918	79.8011256	2826	2	5	west	exposed	S1	VC1
A50208	41.7339706	79.8397861	3213	2	11	west	exposed	S2	VC2
A10212	41.7305302	79.859623	3406	102	9	north	exposed	S2	VC2
A10229	41.7326213	79.8596391	3416	102	5	east	exposed	S1	VC1
A1022A	41.7300826	79.8673579	3439	102	7	south	sheltered	S3	VC3
A1022B	41.7332068	79.8625590	3442	102	10	north	sheltered	S1	VC1
A5021F	41.7338666	79.8651681	3477	2	8	north	sheltered	S2	VC1
A10234	41.7298409	79.8729419	3482	102	15	south	exposed	S1	VC2
A10200	41.7337124	79.8652578	3483	102	9	south	exposed	S2	VC2
A10204	41.7309998	79.8742672	3520	92	13	south	exposed	S1	VC1
A5021C	41.7356712	79.8685891	3523	2	8	west	exposed	S1	VC1
A10226	41.7350265	79.8695480	3533	102	9	north	sheltered	S1	VC1
A50226	41.7362485	79.8678168	3542	2	22	south	exposed	S1	VC1
A1022E	41.7343655	79.8749204	3558	82	9	west	sheltered	S1	VC1
A10223	41.7313905	79.8837561	3571	102	6	west	exposed	S1	VC1
A50214	41.7352515	79.8749080	3577	2	11	west	exposed	S1	VC1
A1021E	41.7321844	79.8871211	3587	82	14	south	exposed	S1	VC1
A1023D	41.7339144	79.8792360	3594	102	9	south	exposed	S1	VC1
A50224	41.7331012	79.8825064	3607	2	19	south	exposed	S2	VC2
A5020C	41.7347671	79.8815866	3633	2	8	south	sheltered	S1	VC1
A1021D	41.7367759	79.8758854	3637	102	18	south	exposed	S3	VC3
A50223	41.7340210	79.8883989	3650	2	25	south	exposed	S1	VC1
A10214	41.7375919	79.9026136	3680	72	10	south	exposed	S2	VC2
A1020C	41.7388500	79.8792733	3681	102	7	north	sheltered	S1	VC2
A1024C	41.7368723	79.8785087	3681	122	17	south	exposed	S1	VC1
A1023B	41.7361852	79.8836737	3683	112	12	south	exposed	S2	VC3
A1021C	41.7384719	79.8758946	3690	92	8	west	exposed	S1	VC2
A5020D	41.7386842	79.8770435	3696	2	12	north	sheltered	S1	VC1
A10241	41.7393497	79.8779916	3698	92	4	west	sheltered	S1	VC1
A5021B	41.7393831	79.8791749	3702	2	5	south	exposed	S2	VC2
A1021A	41.7351469	79.8875524	3703	82	12	south	sheltered	S2	VC3
A10236	41.7389655	79.8795334	3703	22	9	north	sheltered	S2	VC2
A10243	41.7397745	79.9055959	3710	125	7	south	sheltered	S2	VC2
A1023E	41.7401831	79.8818815	3720	102	8	north	sheltered	S1	VC1
A10240	41.7382082	79.8791272	3733	112	4	west	exposed	S2	VC2
A50215	41.7414876	79.9091790	3755	2	7	west	exposed	S3	VC3
A10216	41.7423208	79.8845190	3758	102	9	west	sheltered	S3	VC3
A1024A	41.7428770	79.9085172	3781	52	11	south	exposed	S3	VC3
A50203	41.7399466	79.9117710	3782	2	3	west	exposed	S3	VC3
A10215	41.7423059	79.8914819	3784	102	7	south	exposed	S1	VC1
A5020E	41.7406713	79.9110039	3784	2	8	west	exposed	S3	VC3
A1020A	41.7438242	79.8856031	3785	102	9	west	sheltered	S3	VC3
A10244	41.7416101	79.8850251	3793	122	11	north	sheltered	S3	VC3
A10235	41.7446559	79.9057984	3796	102	8	north	sheltered	S1	VC1
A5020F	41.7462163	79.8872406	3797	2	8	west	sheltered	S1	VC1
A50204	41.7459851	79.9054496	3805	2	14	west	exposed	S2	VC2
A50206	41.7463661	79.8863626	3807	2	17	east	exposed	S3	VC3
A1020D	41.7465483	79.9045368	3818	102	13	east	sheltered	S3	VC3
A10239	41.7429988	79.8865194	3825	122	8	west	exposed	S3	VC3

A10237	41.7468746	79.8948346	3849	125	9	east	sheltered	S3	VC3
A1023A	41.7487984	79.9006356	3850	102	6	east	sheltered	S1	VC1
A1021B	41.7490215	79.9051654	3859	102	7	east	sheltered	S2	VC2
A50213	41.7507668	79.9091331	3887	2	24	west	exposed	S1	VC2
A1023F	41.7484799	79.8913099	3920	122	10	west	exposed	S1	VC2
A10245	41.7521370	79.8923966	3929	122	25	west	sheltered	S1	VC1
A1024B	41.7539628	79.8997882	3936	72	13	south	exposed	S2	VC1
A10211	41.7559356	79.9069011	3971	122	11	south	sheltered	S2	VC1
A10248	41.7580795	79.9081776	4049	122	14	south	sheltered	S1	VC1
A10232	41.7555921	79.8936496	4060	102	7	west	sheltered	S2	VC3
A50212	41.7607235	79.9021953	4129	2	21	south	sheltered	S1	VC1
A10203	41.7328316	79.8817390	3600	temperature sensors exposed to surface due to animal disturbance or erosion ➔ corrupt data					
A10209	41.7427797	79.8869842	3810						
A10217	41.7374637	79.8881982	3730						
A10227	41.7344989	79.8775012	3609						
A10228	41.7356202	79.8731427	3571						
A5020A	41.7286416	79.8650141	3419						
A50202	41.7539876	79.9100062	3940						
A50217	41.7607027	79.9021813	4127						

However, in 2011 policies and regulations in Xinjiang Province concerning foreign research in border areas and in particular international river catchments, like the Aksu, changed dramatically. Consequently, permission to access the Gukur research area was denied on short notice and field work in 2011 had to be cancelled. As a result, the whole AKSU-TARIM research bundle decided to shift all fieldwork to the Kyrgyz part of the Aksu catchment, where such research restrictions did not exist. Therefore, in August 2012 a general survey of permafrost features and ground ice occurrence was conducted in several areas of the Kyrgyz Central Tian Shan (Ak-Syjrjak, Sary Dzaz and Enyl Cek area). Data of temperature loggers in the Gukur catchment were generously read out by the research team of our project partners Prof. Li Zhongqing and Prof. Gao Qiangzhao (Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou, China) and Dr. Sun Zhandong (Nanjing Institute of Geography and Limnology, CAS, Nanjing, China) in August 2011 and September 2012.

Permafrost distribution modelling

Modelling of mountain permafrost distribution started in the mid 1970's and has made great progress since. It is an indispensable tool, because permafrost generally cannot be seen in the terrain and there are few indicators of subsurface frozen grounds or ground ice (e.g. active rock glaciers). In the following paragraphs the methodical background for permafrost distribution modelling in mountainous areas will be described. In general, existing models can be divided into process based models and empirical-statistical models.

Process based models were mainly developed by the permafrost research groups at the Swiss Federal Institute of Technology Zurich (ETH Zurich) and the Zurich University (Funk & Hoelzle 1992, Haeberli et al. 1996, Imhof 1996, Frauenfelder 2004). These models exploit energy exchange processes between earth surface and atmosphere to calculate of the soil surface and the soil temperatures, depending on slope, exposure, snow cover, vegetation, and substrate. The necessary input parameters need to be obtained with reasonable accuracy to favour a reliable permafrost distribution modelling (Mittaz 1998, Hoelzle et al. 2001, Stocker-Mittaz et al. 2002). Due to the lack of detailed input data, a process based distribution model is not suitable for remote areas such as the Central Tian Shan.

A first empirical approach for developing and testing permafrost models was done by Haeberli (1973, 1975) who used the measurement of BTS temperatures (basal temperature of the snow cover) to prove permafrost occurrences in the field, and subsequently to test this empirical distribution model (rule of thumbs). Hoelzle (1992, 1994, 1996, Hoelzle et al. 1993, 2001) further developed this empirical approach by relating the BTS to the mean annual air temperature (MAAT) as well as the potential direct solar radiation - derived from a Digital Elevation Model (DEM). The program PERMAMAP (within an Arc/Info GIS) allowed distinguishing between areas with probable and with non-probable permafrost. The program approach PERMAMAP was supplemented by Keller (1992) and his program PERMAKART, differentiating between areas of probable, possible and non-permafrost occurrences depending on altitude, slope and exposure. These GIS based modelling approaches (Keller 1992, 1994, Keller & Gubler 1993, Hoelzle 1994, Noetzli 2003) formed the first steps for modelling larger mountain areas (Keller et al. 2008).

The quality of the modelling highly depends on the quality of the DEM as well as on the reliability of the field data (Imhof 1996). BTS measurements are relatively a reliable and often used method for verifying permafrost existence, used recently also in North America

(Lewkowicz & Ednie 2004, Zhang et al. 2001). However this method is dependent on the existence of a reasonably thick snow cover (~ 70 cm) and extensive field measurements in late winter before snow melt starts. However, in the Central Tian Shan, drift snow is common feature, which results in a thicker snow cover at foot slopes, small depressions and lee positions. Wind exposed locations in contrast stay snow free for most of the winter (see Publication 1). Therefore BTS is not feasible to use as an indicator for permafrost in the study area. MAGST on the other hand is not dependable on a homogenous snow cover and a reliable and common indicator for permafrost and subsurface thermal conditions (e.g. Cremonese et al. 2011)

An excellent overview on the general modelling background, the development of spatial models (including specialties for mountain permafrost models), and a detailed discussion of the state of the art is given by Riseborough et al. (2008). The basic requirements for all these models are, as mentioned above, the availability of an accurate digital representation of surface elevation data. Appropriate Digital Elevation Models (DEMs) have been generated during the past years through new remote-sensing programs for many remote regions of the earth. The Shuttle Radar Topography Mission (SRTM) of NASA or, more relevant in this study, the along-track stereo sensor of the imaging instrument ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) are the most popular choices. By making use of the latter a high resolution 30 m DEM is developed for the research area.

For a detailed explanation of the high resolution empirical-statistical model presented in this dissertation, see the methodology chapter in Publication 1 for fundamental analysis of the ground surface temperatures and according chapter in Publication 2 for derivation and discussion of input parameters and development of model design.

3 Overview of publications

In this chapter, short summaries of the published articles are presented to understand the discussion of the results in chapter 4. For full information on data and methodology, statistical analysis of ground temperature data, developed models and resulting permafrost distribution maps, see the original publications in Appendix A – C

Table 3: List of publications and indication of own contribution to individual chapters of the publications (● = single contributor; ◕ = main contributor; ◑ = equivalent contribution by co-authors)

Publication 1: “Spatial and Temporal Variability of Mean Annual Ground Surface Temperatures (MAGST) in the Gukur Catchment, Central Tian Shan” In: Neo Geographia (2013), Volume 2, Issue 1, p. 1 – 18. (peer reviewed) Authors: Stephan Imbery, Murataly Duishonakunov, Zhandong Sun, Lorenz King			
Introduction ◑	Methodology ●	Results ●	Discussion ◕
Publication 2: “Empirical-Statistical Approach for Modelling of Mountain Permafrost Distribution in the Central Tian Shan Using Detailed Analysis of Mean Annual Ground Surface Temperatures (MAGST)” In: Neo Geographia (2013), Volume 2, Issue 2, p. 11 – 20. (peer reviewed) Authors: Stephan Imbery, Murataly Duishonakunov, Zhandong Sun, Lorenz King			
Introduction ◕	Methodology ●	Results ●	Discussion ◕
Publication 3: “Rock Glaciers and Permafrost in the Central Tian Shan” In: Proceedings of the International Scientific Conference on "Environment and Global Warming" (2011), Tbilisi, Georgia, p. 160 - 165. Authors: Stephan Imbery			
Introduction ●	Methodology ●	Results ●	Discussion ●

3.1 Publication 1: Data and analysis

"Spatial and Temporal Variability of Mean Annual Ground Surface Temperatures (MAGST) in the Gukur Catchment, Central Tian Shan"

Neo Geographia (2013), Volume 2, Issue 1, p. 1 – 18.

Mean annual ground surface temperature (MAGST) is one of the main parameters for assessment of the thermal state of permafrost and identification of its spatial distribution (Cremonese et al. 2011, Guadong & Dramis 1992). High resolution temperature sensors (PT1000, DALLAS DS1820) and wireless mini data loggers (M-Log5W) were installed in the exemplary Gukur catchment (130 km²) in August 2010 ensuring high data resolution as well as data security. The temperatures were monitored at an hourly interval over two consecutive years (August 16th 2010 to August 15th 2012)

With a correlation coefficient of $r = -0.68$, $p < 0.001$ for the first year ($n = 61$) and $r = -0.76$, $p < 0.001$ for second year ($n = 55$) of monitoring, altitude has the highest influence on MAGST in the research area. This also corresponds very well with similar studies in the European Alps using BTS measurements (e.g. Gruber & Hoelzle 2001, Hoelzle et al. 2001).

Investigating further factors affecting MAGST, the relationship of MAGST/MAAT and altitude needs to be considered (Figure 4 in Appendix A: Publication 1 shows relevant factors in relation to altitude and MAGST).

A major finding of this publication is the importance of snow for both spatial and interannual variations of MAGST. Besides altitude, slope and aspect, stressed in numerous studies as the main factors for variations in the ground thermal regime (e.g. Riseborough et al. 2008, Gruber & Hoelzle 2001), the snow cover is often difficult to assess. In this study, variations of daily ground surface temperatures were used to calculate snow covered days per year - making use of the insulating effect on the ground below, due to the low thermal conductivity of snow (e.g. Smith 1975, Goodrich 1982, Keller & Gubler 1993, Zhang et al. 1996, Ishikawa 2003, Zhang 2005). In accordance with similar approaches (Rödder & Kneisel, 2012, Schmidt et al. 2009, Danby & Hik, 2007, Schmid et al. 2012) a threshold of $\sigma \leq 0.2$ °C was chosen for the daily standard deviation of GST to identify days with a considerable insulating snow cover. These findings are most striking when comparing sites in close proximity (less than 350 m apart) with similar conditions (vegetation cover, substratum...) and same altitude. Figure 5 in

Publication 1 (Appendix A) presents daily temperature variation at two exemplary sites. The insulating effect of snow during the winter month results in a difference in MAGST of 4.02 °C at these two locations.

Examining the interannual variation of MAGST the importance of snow cover and snow redistribution by wind is furthermore endorsed. With topographic factors, vegetation cover and substratum being constant, major variations in MAGST can only be attributed to changes in MAAT and snowfall. MAGST decreased on average by 1.1 °C from first to second year at all monitored locations. In contrast, MAAT increased by 0.43 °C in the same time period at reference locations. Also onset of snowfall can be suspended, as ground surface temperature and date of the first snowfall were incidentally identical for both years. Only the change in duration of a considerable snow cover correlates significantly ($r = 0.72$, $p < 0.001$) with the change in MAGST (see Figure 6 in Publication 2).

In conclusion, this publication provides a unique data on ground surface temperatures unprecedented in the Central Tian Shan. It proves the high spatial variability of the ground thermal regime that has been identified in other alpine areas (Gubler et al. 2012). Furthermore, the paper stresses the regional approach. Local conditions, like duration of snow cover and drift snow, common in the arid environment of the Central Tian Shan, hugely influence the permafrost distribution. All in all, the presented original data, new approaches of analysis and results provide invaluable input to the current discourse on permafrost to the scientific community working in Central Asia and mountainous regions across the world.

3.2 Publication 2: Permafrost distribution modelling

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

Neo Geographia (2013), Volume 2, Issue 2, p. 11 – 20.

The modelling approach is a key component for the assessment of thermal state and distribution of permafrost. It is furthermore a methodological challenge in remote areas, where direct observations and the availability of basic input data (e.g. MAAT) are limited or not available. While process based models need large amounts of input data for computation, empirical-statistical models are less demanding. In this paper, an empirical-statistical model is developed based on the evaluation of MAGST in the first publication. By analysing correlations between MAGST and satellite derived data products, two modelling approaches were developed:

[1] $MAGST = -0.005909 * altitude + 9.065E - 07 * PISR + 0.02787 * NDVI + 18.33$
($R^2 = 0.642$; R^2 adjusted = 0.621)

[2] $MAGST = -0.006227 * altitude + 9.418E - 07 * PISR + 19.23$
($R^2 = 0.637$; R^2 adjusted = 0.623)

PISR = Potential Incoming Solar Radiation;
NDVI = Normalized Differential Vegetation Index

As described before, altitude most prominently affects MAGST and therefore has the highest correlation. In order to incorporate other topographic parameters like slope, aspect and shielding, potential incoming solar radiation (PISR) is used as a compound parameter. Attempts by Gruber & Hoelzle et al. (2001) to enhance this compound parameter by including a summer albedo map were not significant and hence omitted in this approach. PISR was calculated in ArcGIS at a resolution of 30 m based on the 30 m ASTER DEM.

As a third parameter, normalized differential vegetation index (NDVI) was incorporated into the model. NDVI is a simple but highly suitable quantitative indicator and was computed by the use of the near infrared and visible infrared band of a snow and cloud free Landsat ETM+ image (recorded on the 5th of October 2002) at a resolution of 30 m:

Vegetation cover significantly affects the ground thermal regime (e.g. Hoelzle 1994) and was consequently expected to improve the model output. However, despite the high coefficient of correlation between MAGST and NDVI (r = 0.45), model output [1] was not improved as compared to the results omitting NDVI [2]. This can be explained due to high inter-correlations between altitude and NDVI (r = -0.47) that has also been reported in as study by Gruber & Hoelzle et al. (2001). As a result, the simpler approach [2] was used to model MAGST for the whole Gukur catchment and adjusting areas at a 30 m resolution. In a next step, the simulated mean annual ground surface temperatures is used to classify permafrost as recommended by Cremonese et al. (2011) into four categories: (1) “permafrost presence (medium certainty)”, MAGST < −2 °C; (2) “permafrost presence (low certainty)”, −2 °C < MAGST < 0 °C; (3) “permafrost absence (low certainty)”, 0 °C < MAGST < 2 °C; (4) “permafrost absence (medium certainty)”, MAGST > 2 °C.

Explaining 62% of the variance of MAGST, the empirical-statistical approach presented in this paper proved to be very effective for the application in the Central Tian Shan. The resulting permafrost distribution map (Figure 7 in Appendix B: Publication 2) is a unique assessment of permafrost at this resolution (30 m) in the region. In contrast to existing maps on permafrost in the Chinese part of the Central Tian Shan, like “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), individual catchments can now be analysed in great detail. This will be of great importance for the assessment of water resources stored in the periglacial belt in this arid environment.

The success of the empirical-statistical model used in this study furthermore demonstrates the advantages of this approach in remote and mountainous environments. It therefore confirms the findings of Riseborough et al. (2008) and the results of Gruber & Hoelzle (2001), who had a similar approach using BTS-measurements in the European Alps. Although the model can be applied in other areas of the Central Tian Shan within certain geographical limits, new training data and in situ validation are needed to further improve and adapt the model to other climatic and geological conditions.

3.3 Publication 3: Study area

“Rock Glaciers and Permafrost in the Central Tian Shan”

Proceedings of the International Scientific Conference on "Environment and Global Warming" (2011), Tbilisi, Georgia, p. 160 - 165.

This conference proceeding can be seen as an introduction and to the research presented in this dissertation. It gives additional background knowledge and includes a literature review and a detailed portrayal of selected permafrost features based on in situ assessments in the Gukur catchment.

The paper starts with a brief introduction on permafrost research in the greater Tian Shan region. This covers a description of general permafrost distribution, thermal state of the permafrost environment as well as measured and expected tendencies under climate change conditions. Stressing their importance for the water cycle, a special focus is given to rock glaciers and ice cored moraines.

The second part is based on the field investigations conducted during the first field work in the Gokur catchment in August 2010. Three exemplary rock glaciers as well as ice-cored moraines are described in detail. They are used as examples to show the different types of rock glaciers (active/inactive) in the research area and furthermore discuss formation and disputed definitions of these permafrost features.

4 Discussion and outlook

The monitored ground temperatures emphasize the high spatial variation of MAGST even in close proximity and on same altitudinal levels. With many parameters (e.g. substratum, aspect) strongly affecting the ground surface temperatures, thickness and duration of snow cover were identified as key factors. Depending on the season, a thick snow cover has different effects on the ground below (e.g. Bartlett et al. 2004). In late spring, snow cover cools the ground below, by shielding it from direct solar radiation and fast increasing air temperatures. In winter however, it insulates the ground from cold air temperatures. Both effects were detected in the monitored ground temperature data, but the insulation and shielding of cold air temperatures during the winter proved to be more significant for the mean annual ground temperatures in the Central Tian Shan (see Figure 5 in Publication 1). Thus, a thinner snow cover and shorter snow season generally leads to lower ground temperatures and therefore a shallower active layer.

These findings are of great importance for the overall understanding of the ground thermal regime and the behaviour of permafrost under climate change conditions in the region. But unfortunately, these findings cannot be applied directly to a permafrost distribution model. This is partly because of the high variations in MAGST even inside small test plots (e.g. Gubler et al. 2012). But more importantly, not all necessary parameters can be provided in such a high resolution (e.g snow distribution, substratum) on a catchment scale, particularly in remote areas. This is especially true because many parameters act as compound parameters that cannot be clearly identified and separately assessed (e.g. publication 1, Gruber & Hoelzle et al. 2001). Therefore, resolution of the permafrost model and necessary input parameters needs to be feasible and sensibly adjusted to the question at hand and the scale of the research area. For the assessment of permafrost on a subcatchment to catchment level, the resolution of 30 m proved to be very successful. The availability and integration of remotely sensed data products makes this approach feasible for the whole Central Tian Shan and the resolution is still more than sufficient for the in depth assessment of permafrost as a key component for the future freshwater availability in the region. Therefore, the presented results also stress the importance of scale and feasibility.

Figure 8: Permafrost indicators in the field: inactive rock glacier (left) and solifluction lobes (right) in the Aksu catchment

The detailed investigation on permafrost indicators – like rock glaciers and solifluction lobes - in the field (Figure 8) along with the installation of a temperature monitoring network, the identification of significant parameters and the development of an empirical-statistical model for permafrost distribution presented in this thesis, is the first in depth research on permafrost in these remote parts of the Central Tian Shan of its kind. The 30 m permafrost map (see Figure 2 and Figure 3 in Publication 2) corresponds very well with identified altitudinal levels for continuous permafrost in other parts of the Tian Shan defined by Gorbunov et al. (1996).

The developed model is not only used for the detailed high resolution assessment of permafrost in exemplary subcatchments of the Aksu, but also as a validation basis for coarser resolution permafrost models for the entire region (subproject: Aksu-Tarim-RS, Technical-University Dresden). Furthermore, the overall findings provide key input parameters for the development of a comprehensive runoff model (subproject: Aksu-Tarim-Melt, Ludwig-Maximilians-University Muenchen, Commission for Glaciology of the Bavarian Academy of Sciences and Humanities) and is therefore an integral part of the Aksu-Tarim research bundle.

Additionally, the results presented in this dissertation stress the importance of permafrost for the overall hydrological regime in the region. The highly continental climate and an abundance of debris lead to a strong interaction of the glacial and permafrost environment (see chapter 1.2 *cryosphere* and King 1984). Figure 10 shows the close proximity of (debris covered) glaciers, rock glaciers and ice-cored moraines in the Gukur research area. Through the processes of conservation and refreezing, large amounts of glacial ice and water can be preserved and retained under the thick debris cover (e.g. Harris & Murton 2005).

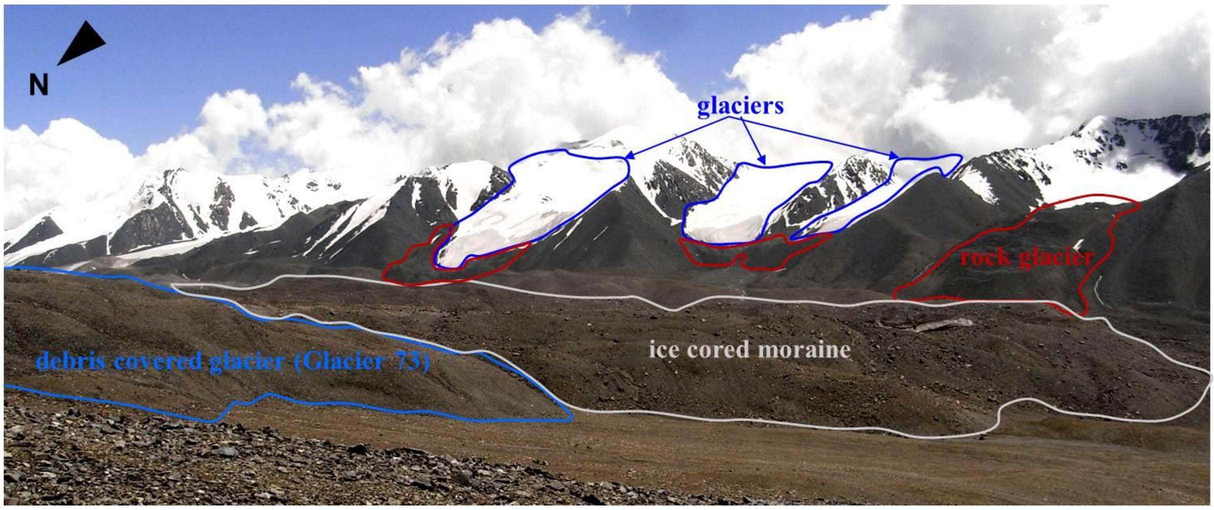

Figure 9: Interaction of the glacial and periglacial environment in the Gukur catchment research area

Exemplary analysis of boreholes and geophysical data in comparable areas of the European Alps and Andes in South America show high and wide ranging ice contents in rock glaciers from 20 % to almost 100 % (e.g. Barsch et. al. 1979, Francou et al. 1999, Haeberli et al. 2006, Hausmann et al. 2007). In addition, large amounts of glacial ice are preserved in ice-cored moraines. While their formation is by definition bound to the activity of glaciers, the conservation of ice-cored moraines depends solely on the permafrost environment (see King 1986). Circulation of cold air in the coarse moraine deposits favours the occurrence of permafrost. Temperatures in coarse debris bodies are typically 2.5 - 4 °C colder than the surrounding mean annual air temperature (Gorbunov et al. 2004). Therefore, the ice core is preserved over long time periods.

Besides these clearly visible and evident features (rock glaciers, ice cored moraines), ground ice should not be ignored. While ice content in coarse substrates in general ranges from 30 % to 50 % of the total volume, ice lenses and massive ground ice can form in fine grained substratum (Haeberli et al. 1993). In general, meltwater can percolate freely through the predominantly coarse debris at steep slopes. Fine grained material and shallow slopes on the other hand favour the oversaturation of the ground (see Woo et al. 1994) and therefore the formation of massive ground ice. Impressive outcrops of massive ground ice were found in this survey in the Ak-Syjrjak area on altitudes of around 3,800 m a.s.l. (Figure 10). These exemplary outcrops are a clear evidence for the extraordinary high ground ice content in the region.

Figure 10: Exemplary outcrop of massive ground ice in the Ak-Syjrjak area (3,800 m a.s.l.)

Crucial for the conservation and formation of ground ice is the stability of the active layer thickness. In the Gukur catchment an approximation of active layer thickness was calculated by regression analysis based on annual maximum temperatures at different depth below the surface. As a result, average active layer thicknesses of 120 to 250 cm can be expected at the 28 locations equipped with temperature measurement strings. The propagation of the diurnal temperature signal depends - besides substratum and snow distribution - largely on the water/ground ice content. Due to the release of latent heat in the freezing process of water, the duration of zero curtain periods is an excellent indicator for water/ground ice content. In the Gukur catchment, extensive zero curtain periods were identified in deeper depth of the active layer (> 100 cm) at all monitored locations (e.g. Figure 11). Accordingly, high amounts of ground ice are expected in both, coarse and fine grained sediments in the whole Aksu catchment.

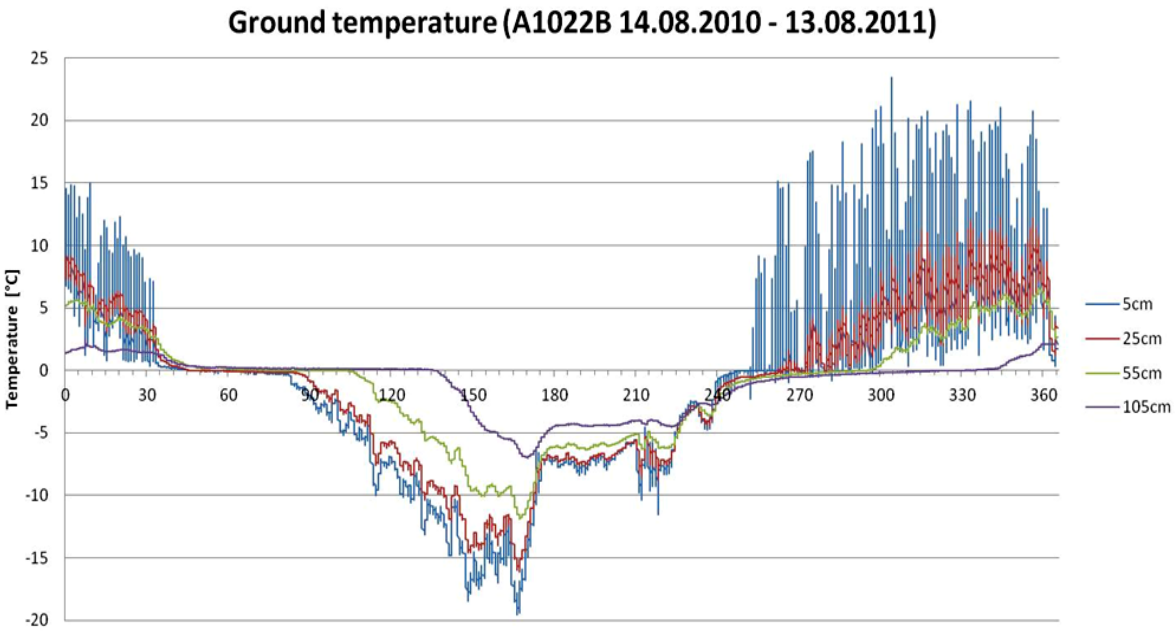

Figure 11: Ground temperature measurements at different depth of the active layer at an exemplary location. Extensive zero curtain periods at 105 cm below surface, indicate high water/ground ice content.

To predict the reaction time of the active layer thickness under climate change conditions, long term monitoring data is necessary. However, with the main parameters affecting the variability of the subsurface thermal regime identified in this study (e.g. snow cover and thickness), new models can be developed, including scenarios and data from regional and global climate models to predict future changes. Hence, the general trend of winter precipitation in the form of snow (onset, increase/decrease) and the development of new snow distribution models (including redistribution by wind) will be a major concern for the Tian Shan area in addition to general temperature trends.

Under climate change conditions, a changing permafrost environment affects the region on both, short and long term basis. On an annual basis, the earlier thawing and increasing depth of the active layer will increase the water storage capacity and percolation of meltwater into deeper parts of the ground and thus also alter the proportioning of surface and subsurface flow in spring and summer (e.g. Woo et al. 1994). On a long term basis, the runoff fraction from the permafrost environment will increase due to the clearly shorter response time of glaciers to climate warming compared to the periglacial systems. With a high density of rock glaciers and ice cored moraines, a general high ground ice content and the existence of massive ground ice, the contribution from permafrost to the overall runoff of the Central Tian Shan will play a key role for the economic development (e.g. extraction of natural resources and yields in agriculture) and sustainability of Tarim basin and the region that cannot be underestimated.

With original monitored field data and highly significant modelling results, this study - and the AKSU-TARIM project as a whole - establishes a comprehensive research foundation in the area. The results presented here contribute largely to the ongoing SuMARiO-project (Sustainable Management of River Oases along the Tarim River, BMBF-funded) and future research by the AKSU-TARIM project partners and external scientists (e.g. Sun et al. 2014). The permafrost distribution maps and field surveys furthermore provide key data and background knowledge for stakeholders and policy makers. Considering the rising demand for water in the surrounding arid lowlands, the results are a unique contribution to one of the most pressing challenges in the region under climate change conditions.

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Appendix A: Publication 1

Spatial and Temporal Variability of Mean Annual Ground Surface Temperatures (MAGST) in the Gukur Catchment, Central Tian Shan

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Abstract

Permafrost temperatures in mid-latitudinal mountain ranges like the Central Tian Shan are predominantly warm and therefore susceptible to climate change. However, only little information exists concerning the distribution and thermal state of the permafrost in the Chinese part of the Central Tian Shan. In this study a dense network of 69 temperature logger was installed in the 130 km² Gukur catchment to monitor Ground Surface Temperatures (GST) over two consecutive years and assess the thermal state of the permafrost underneath. Results therefore improve the scientific knowledge on spatial and temporal variation of Mean Annual Ground Surface Temperatures (MAGST) as an indicator for permafrost. Besides topographic parameters like altitude ($r= -0.68$, $p < 0.001$ first year; $r= -0.76$, $p < 0.001$ second year), snow cover emerged as the dominant factor for spatial variability of MAGST. Thus variations of more than 4°C are common within short distances (< 350 m) and on same altitudinal levels. The insulating effect of snow shields the ground from cold air temperatures during winter. Furthermore, inter annual variations of MAGST correlate significantly ($r= 0.72$, $p < 0.001$) with variations in duration of the insulating snow cover. Thus, snow distribution could be identified as the main factor for inter annual variations of MAGST

1 Introduction

Detailed investigations on permafrost distribution and permafrost temperatures under climate change conditions are one of the key research topics in densely populated mountainous areas like the European Alps for natural hazard assessment and challenges in engineering (e.g. Haeberli 2013, Harris et al. 2001). Despite the low population density in the alpine areas of the Chinese Tian Shan, information on permafrost gets increasingly important for the region, as the main interest is not infrastructures or rockfalls, but water discharge in this arid continental climate (Bolch & Marchenko 2006). Climate change actually leads to an accelerated ablation and retreat of high mountain glaciers in most parts of the world, and to a runoff increase of the related rivers in the short to middle term. Whereas this is a well-known fact, the additional runoff supplied by slowly melting ground-ice and perennial snow fields is almost unknown. However, this periglacial contribution is significant. Marchenko et al. (2005) estimate the total volume of ice in permafrost to be similar to the volume of glaciers in the region. In extremely arid mountainous areas like the Central Tian Shan, the water of rivers form the vital source for the economic development of the Taklamakan basin, rich in natural resources and strongly suffering from water shortage. With a contribution of more than 70 % to the total runoff of the Tarim River, the Aksu has by far the largest impact on the water resources and the future development of this region under climate change conditions. Ground thermal regime and frozen ground are the result of energy and moisture exchange between atmosphere and the ground surface. The key variable resulting from these exchange processes is the ground surface temperature (GST), which is transmitted into subsurface temperatures through topography, surface characteristics and ground thermal properties. The presence of frozen ground, both seasonally and perennially, in turn influences the ecological site conditions depending on its local characteristics.

The variation of frozen soil depth is closely related to varying air temperature and solar radiation. At present, these relationships are quite well understood in polar lowlands (e.g. Washburn 1979, Williams & Smith 1989, French 1996), while still little is known about the function of correspondent processes under the more pronounced topography and characteristic forms of high mountain environments (King 1984, 2000, Tenthorey 1992, Keller 1994, Hoelzle et al. 1999, Hoelzle et al. 2001, Mittaz 2002). This especially concerns the depth change of permafrost, where temperature change is decelerated for very long periods (Chen 1997).

While a wide range of low resolution maps on permafrost exist for most parts of the region, detailed investigations on small scale distribution of permafrost in the Central Tian Shan is absent (e.g. Ran et al. 2012). The availability of even basic data (e.g. mean air temperature, snow thickness etc.) is very scarce. But small scale influences cannot be neglected, as considerable changes of MAGST and permafrost temperatures are common in high mountains, even in close proximity (Gubler at al. 2011). Hence, the main scientific tasks of this study include an improvement of knowledge on the variability of ground surface temperatures and permafrost distribution as well as deriving the factors having the largest effect on these parameters. These results are also fundamental to better understand the contribution of permafrost and snow to the water discharge in the Aksu catchment and the Central Tian Shan.

2 Study area

The Tian Shan, situated in Central Asia, extends some 2,500 km from east to west. It is one of the highest mountain ranges in the world and can be divided into a Western, Inner, Northern, Central and Eastern Tian Shan. Maximum altitudes range from more than 7,000 m a.s.l. in the Central Tian Shan to about 6,000 m a.s.l. in the Inner and 5,000 m a.s.l. in the other parts of the Tian Shan, respectively. The climate can be described as highly continental, with decreasing precipitation from northwest to southeast. Therefore the average annual precipitation in the Central Tian Shan is very low, even in high altitudes. The altitudinal lower limits of continuous permafrost in the region have been identified at 3,500 m a.s.l. for the Northern and Eastern, 3,600 m a.s.l. for the Inner and 3,800 m a.s.l. for the Western Tian Shan (Gorbunov et al. 1996). Furthermore geothermal observations show an increase in temperature between 0.3 °C and 0.6 °C for the last 30 years (Marchenko et al. 2007). As permafrost warms up and the active layer is thickening – by about 23 % since the early 1970s (Marchenko et al. 2007) - seasonally frozen ground has decreased by 7% in the northern hemisphere since 1900 and the annual average of snow cover in the period of 1988- 2004 shows a reduction by 5% compared with the period of 1967-1987 (Lemke et al. 2007).

Stretching across the China-Kyrgyzstan border, the Aksu catchment is located in the highest parts of the Central Tian Shan between 41°10’N-42°50’N and 78°30’E-80°30’E. The largest glaciers are mainly originating from the vicinity of Tomur Peak, with 7,435 m a.s.l. the highest mountain of the Tian Shan. The presence of large amounts of debris on top and surrounding these glaciers are typical for the region (Wang et al. 2011). This leads to a close interaction of the glacial and permafrost environment. Debris covered glaciers, ice cored moraines and rock glaciers are very common in the Aksu catchment. Detailed field investigations are carried out in the 130 km² Gukur catchment (Figure. 1) and started in August 2010. The catchment, sited in the vicinity of Tomur Peak, is a direct tributary to the Aksu 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) and are surrounded by an extensive periglacial area.

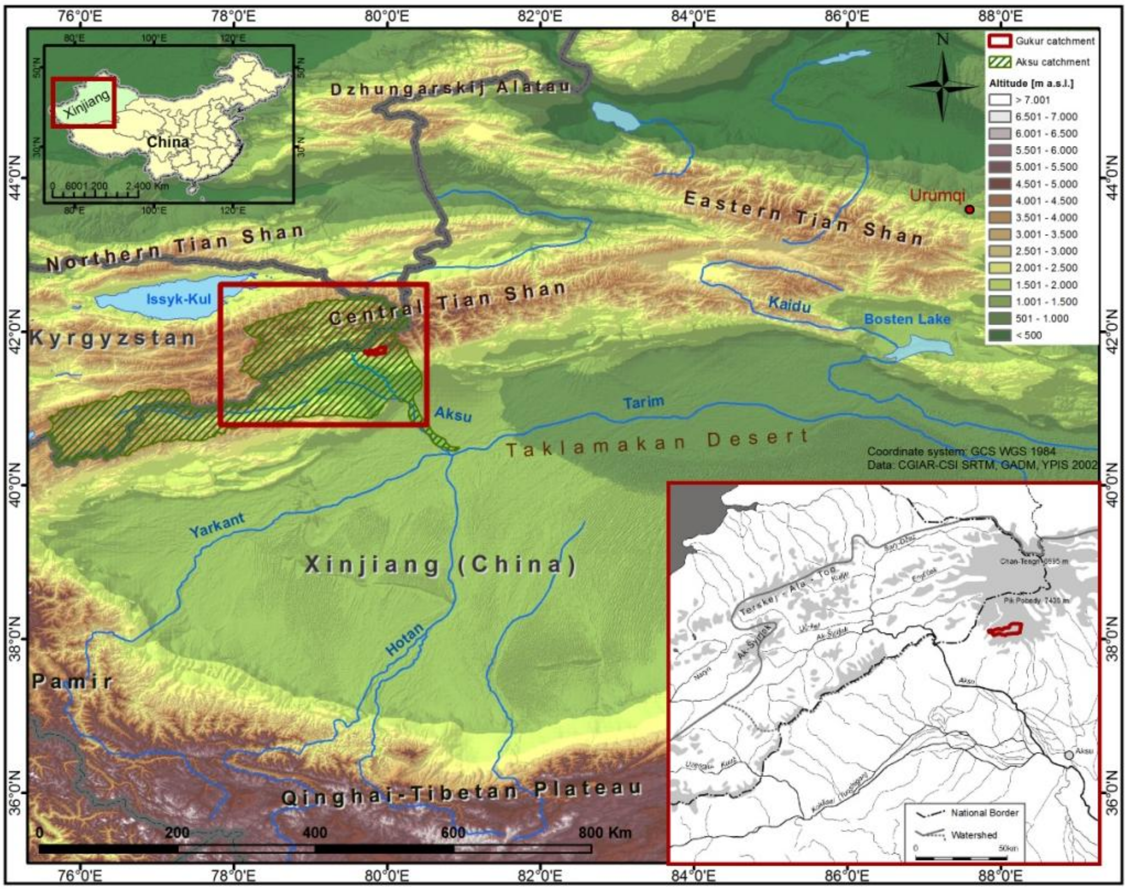

Figure 1: Regional overview and location of the research area (Gukur catchment) within the Aksu catchment, Central Tian Shan.

3 Data and methodology

3.1 Instruments

A dense network of 46 high resolution thermistor strings and 23 mini temperature data loggers were installed at a total of 69 locations in the Gukur catchment. The commercial M-Log5W (GeoPrecision, www.geoprecision.com) wireless mini data loggers with inbuilt PT1000 sensors are used to measure the ground surface temperature (GST). They have a high memory capacity (2048 kB), low energy consumption and come in a small, but waterproof housing. The inbuilt PT1000 temperature sensor has a high resolution of 0.01 °C and an overall accuracy of ± 0.1 °C. These features minimize the maintenance to a minimum (battery change every 5 to 10 years, depending on temperature conditions) and are thus ideal for continuous temperature monitoring in remote areas. Furthermore, the wireless interface with an operating range of up to 100 m (433 MHz) allows reading-out data remotely by laptop and a USB-dongle.

For the temperature measurements at multiple depths in the active layer, the same M-Log5W wireless mini data loggers are used. But, instead of an inbuilt temperature sensor, they can be attached to thermistor strings (Figure 1). For maximum cost benefits, the thermistor strings were designed and manufactured at the Institute for Physics at the University of Giessen with the help of GeoPrecision. The chosen DALLAS DS1820 temperature sensor has a lower resolution (0.065 °C) and accuracy (± 0.25 °C) in the expected temperature range, but is cheap and easy to handle. The unique 64-Bit serial code allows multiple DS1820 sensors to function on the same 1-Wire bus and can therefore be controlled with an M-Log5W. For each string, five DS1820 sensors were used with intervals of 20 cm, 20 cm, 30 cm and 50 cm, adding up to a total length of 120 cm. Some extra cable ensures that the attached M-Log5W can be buried safely and hidden from any human or animal disturbances. The temperature strings are waterproof and resistant to tensile stress.

3.2 Experiment design

For best representation of GST, the upper most sensor of the thermistor string as well as the M-Log5W with inbuilt sensor are buried at a depth of about 2-3 cm below the surface to prevent the sensor from direct surface exposure. Temperatures are recorded at an hourly interval at all locations. In order to identify the factors having the largest influence on GST and active layer depth, the 69 locations were carefully chosen to represent the local conditions in terms of altitude, topography, substrate and vegetation cover as well as probable thickness of snow pack and duration of snow over (Figure 2). Depending on local conditions, the depths of the deepest sensor of the thermistor strings range from 52 cm to 125 cm below surface.

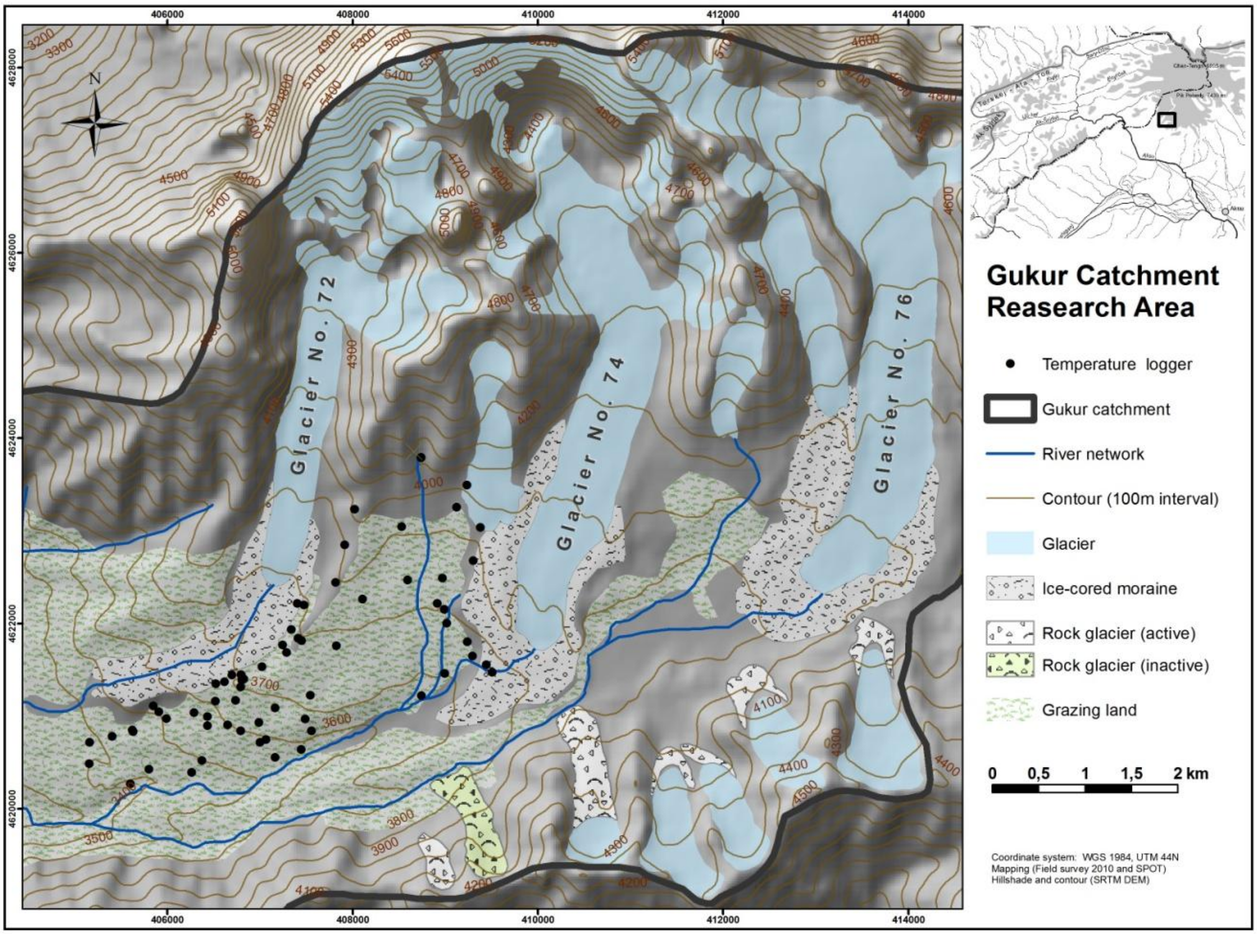

Figure 2: Position of all 69 temperature loggers in the Gukur catchment research area.

Topographic factors

To obtain a reliable temperature gradient, altitudes of logger positions range from 2,476 m to 4,129 m a.s.l.. The majority of loggers are placed between 3,400 m and 4,000 m a.s.l. as this is considered the altitudinal band, where the lower limit of continuous permafrost is expected (Gorbunov et al. 1996). For further analysis slope is categorized in “flat“ (≤ 8°), “medium” (8° - 16°) and “steep” (>16°), aspect in the four major geographic directions north, east, south and west.

Substrate and vegetation cover

In the given altitudinal range, vegetation cover is limited to graze land and depends strongly on the substrate. Thus, vegetation cover (VC) is grouped into the three classes: (VC1) dense grass cover, (VC2) sparse grass cover and (VC3) total absence of grass cover. Similarly the substrate can be divided according to ISO 14688-1 into (S1) fine grained, mostly silty material, $d < 2$ mm; (S2) a matrix (silt) supported gravel, $d < 63$ mm and (S3) larger open work debris (mostly cobbles) at talus slopes and young moraine deposits $d > 63$ mm. Singular cobbles and larger boulders are randomly enclosed in all categories.

Snow cover and wind exposure

Due to the remoteness and inaccessibility of the study area, there is no direct information on snow thickness and snow distribution. Snow has a significant insulating effect on the ground below, due to its low thermal conductivity (e.g. Smith 1975, Goodrich 1982, Zhang et al. 1996, Ishikawa 2003, Zhang 2005). Therefore, daily GST variation can be used to identify the onset and duration of a substantial snow cover. Daily temperature amplitudes (Rödder & Kneisel 2012) or thresholds for daily standard deviation are proposed in various studies ranging from 0.09 °C for hourly temperature intervals (Schmidt et al. 2009) to 1 °C for sampling intervals of 4 hours and a snow thickness of at least 2.5 cm (Danby & Hik 2007). Schmid et al. (2012) propose a more complex approach using different thresholds for positive (0.1 °C) and negative (0.3 °C) temperatures.

Obviously, the duration of snow cover is slightly underestimated with this method. A snow cover is only identified if snow depth is sufficient to alter the daily temperature amplitude. But this is by no means a drawback, but rather intended in this study, as only a snow depth that considerably insulates the ground from air temperatures is relevant for further investigation in this study. After analysis and interpretation of the dataset and taking into account the accuracy and resolution of the temperature loggers, a threshold of $\sigma \leq 0.2$ °C was chosen for the daily standard deviation of GST in this study.

Additionally the position was described in situ as being “exposed” to or “sheltered” from wind. This factor describes the immediate local condition like ridges or small depressions and does not correspond to general wind directions.

Zero curtain

Zero curtain periods are calculated using a threshold for temperature deviation from 0 °C. Following the approach by Gubler at al. (2011) the final threshold was chosen by testing a very small threshold and stepwise increasing it until homogeneous results were produced. The resulting threshold of ≤ 0.12 °C and ≥ -0.12 °C thus is also an indication for data accuracy of the instruments in the given temperature range.

Due to the release of latent heat in the freezing process of water, the duration of zero curtain periods in different depth of the active layer can further be used to identify locations with higher water content in the catchment.

4 Results

4.1 Data quality

The instruments proved to be highly reliable and easy to handle. Time consuming recovery of data loggers is not applicable due to the wireless data interface. Operation range of the wireless data transmission is in general less than 10 m due to the burial of the loggers below the ground. Although being less than the 100 m stated above, it is more than sufficient for this application. If necessary, larger operating ranges can be achieved using a directional antenna. Still, eight loggers showed clear indications of animal disturbance. This resulted in corrupt measurements as sensors were dug out and exposed to the surface or complete failure in two locations, where thermistor strings were bitten through. Furthermore, six loggers could not be approached in 2012 due to harsh weather conditions during field work. This leaves a total of 61 loggers for the time frame of August 16th 2010 to August 15th 2011 and 55 for August 16th 2011 to August 15th 2012.

Analysis of zero curtain periods (see above) furthermore indicates, that accuracy of the DALLAS DS1820 temperature sensors are probably around 0.12 °C in the relevant temperature spectrum and therefore much higher than the 0.25 °C stated above.

4.2 Site specific parameters

The main site specific parameters, which are not altered considerably within the time period of a year, are shown in Figure 3. Slopes vary between less than 3° and up to 25° while aspect shows a slight tendency of over presenting south and west exposed locations, giving credit to the main orientation of the Gukur catchment (see Figure 2). Same is applicable for vegetation cover which represents the extensive grazing areas between glacier No. 72 and glacier No. 74 with its fine grained silty substratum.

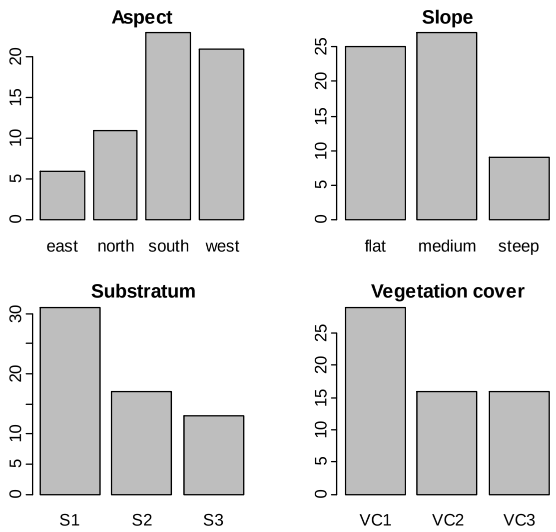

Figure 3: Number of temperature loggers representing site specific parameters (substratum: S1 = fine (d < 2 mm), S2 = medium (d between 2 mm and 63 mm), S3 = coarse (d > 63 mm); vegetation cover: VC1 = dense grass cover, VC2 = sparse grass cover, VC3 = total absence of grass cover)

4.3 Ground surface temperatures

Table 1 lists all temperature loggers and thermistor strings that were installed in the catchment together with MAGST and calculated snow covered days for the two years monitored (if available) and all metadata recorded in the field. The measured temperatures (MAGST) range between 4.86 °C and -3.28 °C for the first and 4.82 °C and -4.74 °C for the second year. Extensive variations in MAAT can be expected at the different locations due to the altitudinal differences of more than 1,600 m (between 2,476 m and 4,129 m a.s.l.). As a result, altitude is the factor having the highest correlation with MAGST ($r= -0.68$, $p < 0.001$ for first year, $n = 61$; $r = -0.76$, $p < 0.001$ for second year, $n = 55$). Looking for other factors effecting MAGST this correlation and the difference in altitude of the locations needs to be incorporated.

Table 1 (next page): Metadata of all installed temperature loggers in the Gukur catchment (MAGST and snow cover for the two years of measurement, (1) = 16/08/2010 – 15/08/2011, (2) = 16/08/2011 – 15/08/2012; substratum: S1 = fine (d < 2 mm), S2 = medium (d between 2 mm and 63 mm), S3 = coarse (d > 63 mm); vegetation cover: VC1 = dense grass cover, VC2 = sparse grass cover, VC3 = total absence of grass cover).

Logger ID	Altitude [m a.s.l.]	Slope [°]	Aspect	Substrate	Vegetation cover	MAGST [°C]			Snow cover [days]	
						(1)	(2)	$\bar{x}$	(1)	(2)
A50222	2476	7	north	S1	VC1	4.86	4.82	4.84	3	5
A5021D	2826	5	west	S1	VC1	3.98	3.68	3.83	21	13
A50208	3213	11	west	S2	VC2	2.15	1.62	1.89	27	26
A10212	3406	9	north	S2	VC2	-1.75	-1.76	-1.75	28	25
A10229	3416	5	east	S1	VC1	2.20	1.77	1.99	31	48
A1022A	3439	7	south	S3	VC3	2.62	2.07	2.34	198	139
A1022B	3442	10	north	S1	VC1	-1.34	-1.62	-1.48	112	110
A5021F	3477	8	north	S2	VC1	-0.32	-1.36	-0.84	244	248
A10234	3482	15	south	S1	VC2	1.64	1.53	1.58	31	19
A10200	3483	9	south	S2	VC2	2.72	2.24	2.48	36	16
A10204	3520	13	south	S1	VC1	2.05	1.64	1.84	34	21
A5021C	3523	8	west	S1	VC1	0.80	0.42	0.61	49	32
A10226	3533	9	north	S1	VC1	-0.39	-0.98	-0.69	163	128
A50226	3542	22	south	S1	VC1	3.03	2.18	2.60	7	10
A1022E	3558	9	west	S1	VC1	0.59			207	
A10223	3571	6	west	S1	VC1	-1.68	-1.43	-1.56	60	39
A50214	3577	11	west	S1	VC1	-0.90	-1.63	-1.27	84	29
A1021E	3587	14	south	S1	VC1	0.27			41	
A1023D	3594	9	south	S1	VC1	0.62	-0.77	-0.08	23	12
A50224	3607	19	south	S2	VC2	-0.77	-1.33	-1.05	7	8
A5020C	3633	8	south	S1	VC1	1.30	-0.33	0.48	205	79
A1021D	3637	18	south	S3	VC3	0.68	0.19	0.44	66	34
A50223	3650	25	south	S1	VC1	0.77	-0.11	0.33	13	13
A10214	3680	10	south	S2	VC2	-0.80	-1.14	-0.97	31	18
A1020C	3681	7	north	S1	VC2	-1.11	-2.32	-1.71	218	209
A1024C	3681	17	south	S1	VC1	0.87	0.15	0.51	49	33
A1023B	3683	12	south	S2	VC3	0.43	0.25	0.34	49	29
A1021C	3690	8	west	S1	VC2	-1.51	-1.54	-1.53	78	52
A5020D	3696	12	north	S1	VC1	-0.83	-2.55	-1.69	225	190
A10241	3698	4	west	S1	VC1	-1.38	-2.66	-2.02	192	123
A5021B	3702	5	south	S2	VC2	0.14	-0.11	0.02	37	19
A1021A	3703	12	south	S2	VC3	0.26	-1.54	-0.64	236	78
A10236	3703	9	north	S2	VC2	1.06	-0.17	0.45	234	239
A10243	3710	7	south	S2	VC2	0.76	-0.38	0.19	219	100
A1023E	3720	8	north	S1	VC1	-0.16	-3.15	-1.65	229	60
A10240	3733	4	west	S2	VC2	-2.14	-4.74	-3.44	58	25
A50215	3755	7	west	S3	VC3	0.83	0.42	0.63	13	14
A10216	3758	9	west	S3	VC3	1.05	-1.75	-0.35	235	212
A1024A	3781	11	south	S3	VC3	-0.86	-1.15	-1.01	93	34
A50203	3782	3	west	S3	VC3	-2.48	-3.88	-3.18	130	34
A10215	3784	7	south	S1	VC1	-0.42	-1.91	-1.17	150	38
A5020E	3784	8	west	S3	VC3	-0.39	-0.32	-0.36	12	3
A1020A	3785	9	west	S3	VC3	0.26	-2.49	-1.12	235	62
A10244	3793	11	north	S3	VC3	-1.33			167	
A10235	3796	8	north	S1	VC1	-0.77	-3.09	-1.93	218	68
A5020F	3797	8	west	S1	VC1	-1.85	-3.12	-2.49	150	150
A50204	3805	14	west	S2	VC2	-0.82	-4.20	-2.51	213	13
A50206	3807	17	east	S3	VC3	0.34	-2.59	-1.13	213	0
A1020D	3818	13	east	S3	VC3	0.80	-0.40	0.20	144	28
A10239	3825	8	west	S3	VC3	-3.28	-3.31	-3.30	30	14
A10237	3849	9	east	S3	VC3	0.74	-1.89	-0.58	232	84
A1023A	3850	6	east	S1	VC1	-1.88	-3.85	-2.87	203	96
A1021B	3859	7	east	S2	VC2	-0.20	-1.22	-0.71	243	243
A50213	3887	24	west	S1	VC2	-2.02	-2.86	-2.44	167	20
A1023F	3920	10	west	S1	VC2	-3.13	-3.28	-3.20	66	45
A10245	3929	25	west	S1	VC1	-1.31	-2.96	-2.14	158	20
A1024B	3936	13	south	S2	VC1	-0.62	-2.64	-1.63	225	51
A10211	3971	11	south	S2	VC1	-0.11	-3.08	-1.59	247	153
A10248	4049	14	south	S1	VC1	-1.03			248	
A10232	4060	7	west	S2	VC3	-2.56			109	
A50212	4129	21	south	S1	VC1	-1.44			238	

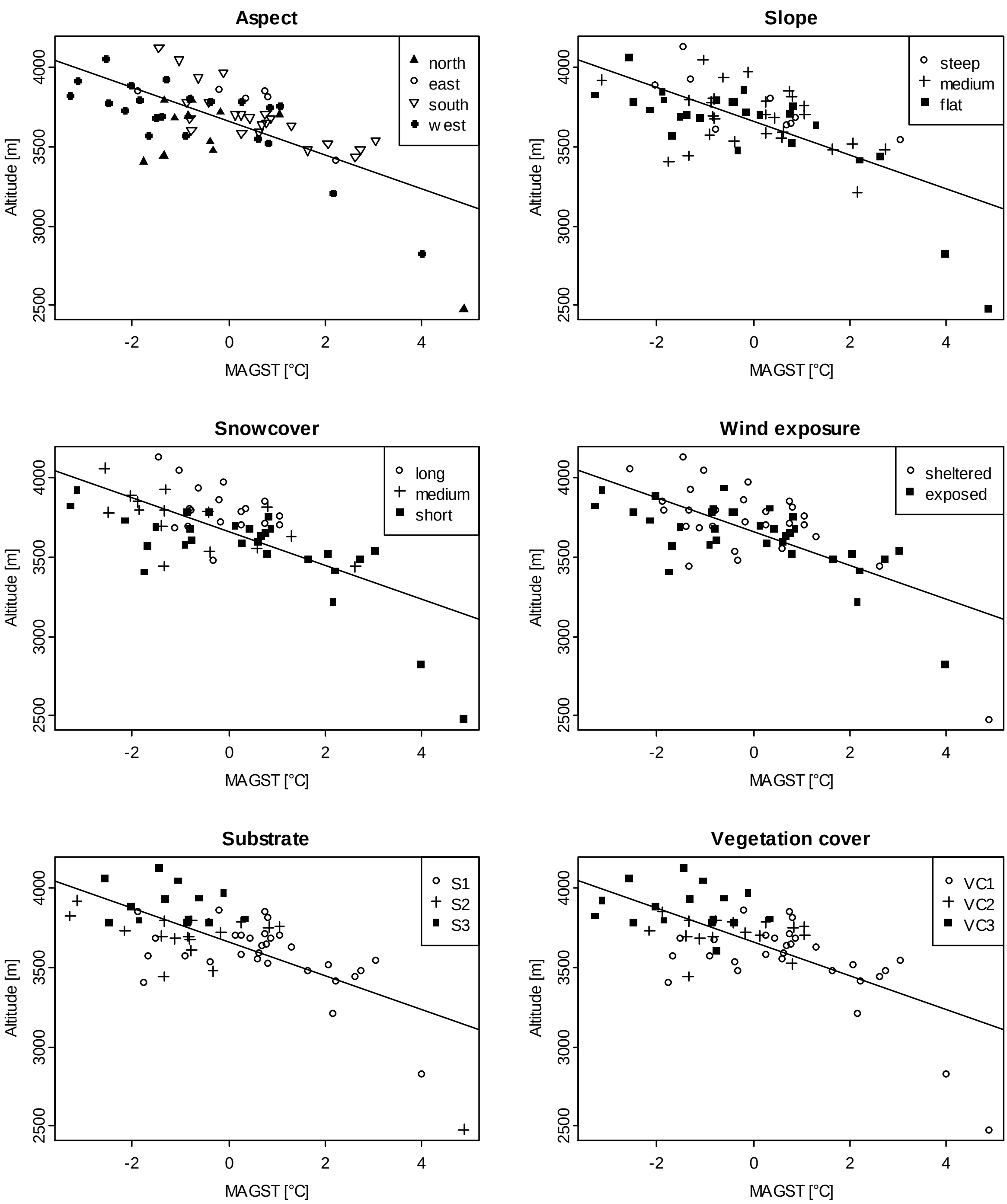

Figure 4: Selected parameters in relation to MAGST and altitude for the period 16/08/2010 – 15/08/2011 (linear regression of MAGST and altitude: $y = -106.56x + 3661.9$; $r= -0.68$, $p < 0.001$).

Figure 4 gives an overview of relevant parameters in relation to MAGST and altitude for the first year of monitoring. It clearly indicates that MAGST is most significantly influenced by the factors aspect and snow cover. While slope, substrate and grass cover show clear tendencies, the effect is overlain by the aforementioned more dominant factors.

5 Discussion

5.1 Spatial variation of MAGST

Snow distribution

Besides thickness of snow pack, the onset and duration of a considerable snow cover is of great importance for the MAGST (e.g. Bartlett et al. 2004). Due to the close proximity, the onset of snow is at the same date at all given locations. The difference in duration of snow cover can be explained due to melting and more importantly the redistribution of snow by wind. Drift snow is an important and common factor in cold and arid environments and results in a thicker snow cover at foot slopes, small depressions and lee positions and considerably affects the thermal state of the permafrost in the region.

Coldest MAGST were measured at wind exposed positions (e.g. ridges) which remain snow free for most of the winter (< 30 days snow covered). Wind sheltered locations on the other hand show a much longer duration of snow cover on same altitudes and close proximity. Figure 5 gives the daily variation of GST for two exemplary locations less than 350 m apart. The thick and long duration of snow cover at location A10237 shields the ground from the cold air temperatures during winter while location A1023F is exposed throughout the winter. This insulating effect is the main factor for the significant difference in MAGST of 4.02 °C at these exemplary two locations.

On the other hand, snow cover will have a cooling effect on the subsurface especially in spring time. Snow has a high albedo and shields the underlying ground from direct solar radiation. Furthermore, a longer duration of snow cover results in a more profound zero curtain period in spring due to percolation of meltwater through the snow pack and the release of latent heat during refreezing at or near the ground surface. Although this effect is visible in Figure 5, it is more profound in lower altitudes, where ground temperatures recorded at snow patches have considerable cooler spring temperatures than surrounding snow free areas.

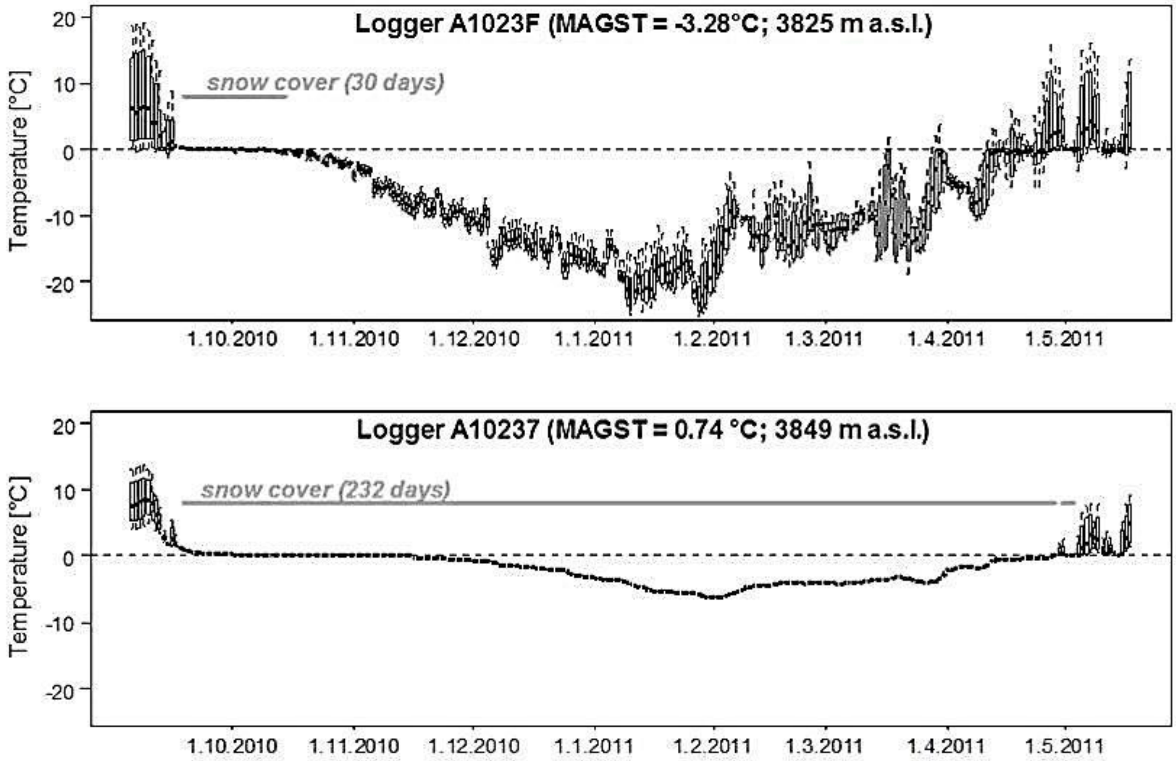

Figure 5: Daily variation of GST for two exemplary sites in close proximity (< 350 m) and same altitudinal levels (< 24 m apart) for the winter period (5.9.2010 – 15.5.2011); duration of snow cover is indicated in grey.

However, the results in this study clearly point out that the insulating effect in winter time is more dominant than the cooling effect in spring, especially at higher altitudes. This relationship of MAGST and duration of snow cover is highly significant. Therefore a longer duration of snow cover results on average in warmer MAGST on same altitudinal levels. These findings furthermore underline the significance of snow distribution and drift snow for permafrost distribution in the Central Tian Shan.

Topographic parameters

As mentioned above, significant variations in MAAT can be expected at individual locations due to the difference in altitudes. This is clearly reflected in the measured MAGST. Besides altitude, slope and aspect are identified as important factors in many studies on permafrost distribution (e.g. Riseborough et al. 2008, Gruber & Hoelzle 2001) as they are key factors for the amount of incoming solar radiation. Results in this study stress the significance of aspect, as north exposed locations show considerably cooler MAGST as compared to south exposed locations (Figure 4).

Besides the direct influence resulting from different exposure to solar radiation, slope and aspect are important factors for depth and duration of a substantial snow cover. Due to higher incoming solar radiation, south exposed slopes show in general a shorter duration of substantial snow cover than north exposed slopes. However, findings in this study suggest that the redistribution of snow by wind considerably alters the general north-south assumption. Snowdrift in this cold and dry environment therefore is of great importance for the snow distribution in the study area. Local wind conditions and small scale topography (e.g. depressions) can result in a thick snow cover even on south exposed slopes in the catchment till late spring while north exposed slopes and ridges can stay snow free even during winter time. Visual interpretations of satellite imagery (LANDSAT, SPOT) of exemplary parts of the whole Aksu catchment as well as interviews of the local population confirm these findings.

Substratum and vegetation cover

Influence of substratum and vegetation cover on MAGST in this study is to a large extend overlain by the more dominant topographic factors and snow cover. On the other hand its contribution should not be underestimated. A cover of large blocky debris material favors the occurrence of permafrost, as cold air can circulate freely between the large blocks. Due to the surface roughness it is less likely for a consistent and insulating snow cover to form. Therefore, temperatures in coarse debris with air filled voids are typically 2.5 - 4 °C colder than the surrounding mean annual air temperature (MAAT) (Gorbunov et al., 2004). This is of great importance for the study of rock glaciers and ice cored moraines in the region, as permafrost can occur in coarse blocky material even at lower altitudes, where the MAAT exceeds 0 °C.

5.2 Inter annual variation of MAGST

The dataset shows significant differences in MAGST from the first to the second year. Taking all 55 loggers with continuous measurements from August 2010 to August 2012 into account, the MAGST decreased 1.1 °C on average between the two years. Therefore, MAGST are significantly cooler in the second year of measurement as compared to the first. With topographic and other site specific factors (e.g. substratum, vegetation cover) being constant, the difference thus results from changes in air temperatures or snow.

To eliminate the temperature factor, a reference logger (Altitude: 1,538 m a.s.l; latitude: 41.57370044°; longitude: 79.701906°) is installed in close proximity to the Gukur catchment. At an altitude of 1,538 m a.s.l. influence of snow on MAGST is negligible as in both years, as a considerable snow cover is limited to two or three days per year. With a MAGST of 13.68 °C in the first and 14.11 °C in the second year, it clearly indicates, that general cooler temperatures in the second year are not the explanation for the significantly colder MAGST measured in the Gukur catchment. This is also confirmed by loggers, where a short duration of snow cover has been calculated for both years. Here, only minor changes in MAGST from first to second year occurred. Furthermore general cooler temperatures would have a more evenly distributed cooling effect at all locations. But while the temperatures decreased on average by -1.1 °C from first to second year, the variation is striking. With a standard deviation of 0.95 °C, changes in MAGST range from fairly detectable up to 3.39 °C at individual locations. Onset of snowfall can also be neglected, as no significant difference in air temperature before snowfall or starting date can be detected (with 16.08.2010 and 16.08.2011 being incidentally the same day of the year).

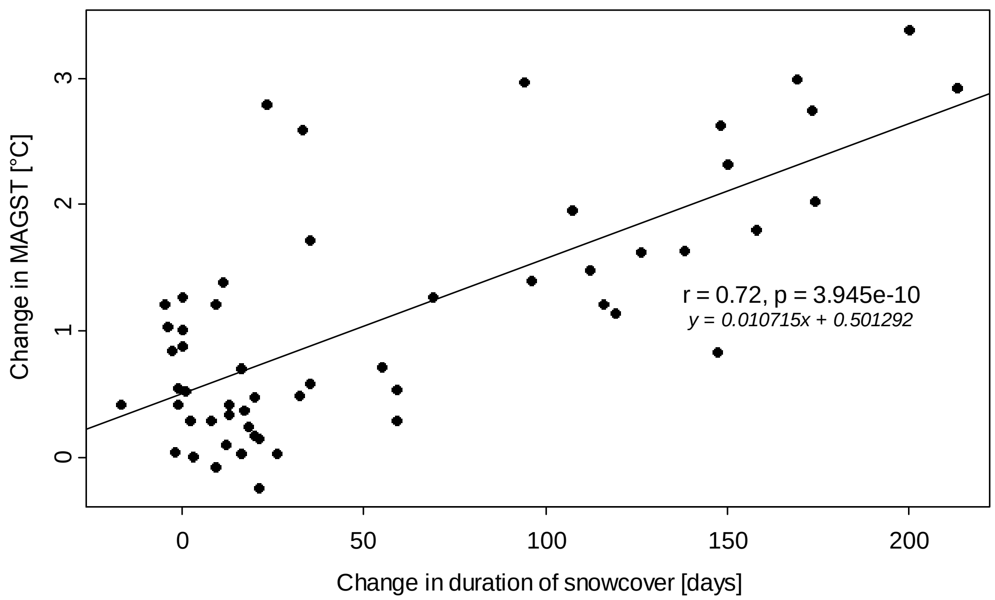

Figure 6: Linear relationship between change in MAGST [°C] and change in duration of snow cover [days] from second year (16/08/2011 – 15/08/2012) to first year (16/08/2010 – 15/08/2011) of measurements.

On the other hand, the change in duration of snow cover correlates significantly (r= 0.72, $p < 0.001$) with the change in MAGST (Figure 6) between the two years and can therefore be considered the single most important factor for inter annual variations of MAGST in the research area for the two monitored years. Another implication stressing the importance of the duration of a snow cover is the overall decline of variation of MAGST at same altitudinal levels from the first to the second year (compare Figure 4 and Figure 7). This is further indorsed by a higher correlation coefficient in the second year as compared to the first year of temperature recording (r= --0.66, $p < 0.001$ for first year, n= 55; r = -0.76, $p < 0.001$ for second year, n = 55). With less snow fall and an on average shorter duration of a considerable snow cover in the second year, spatial variations in MAGST are less profound and more directly correlated to the change in MAAT and therefore altitude.

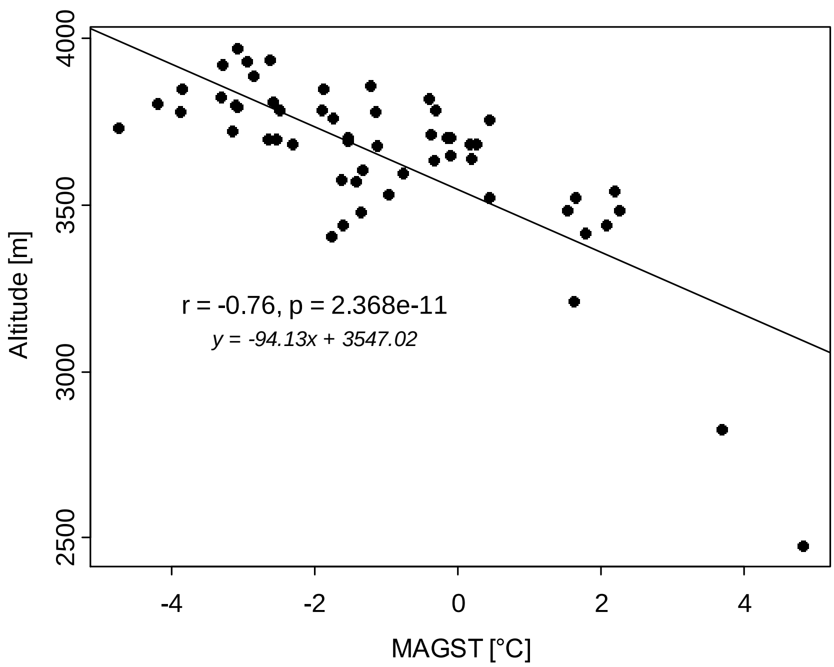

Figure 7: Linear relation between altitude [m a.s.l.] and MAGST [°C] for the time period 16/08/2011 – 15/08/2012.

6 Conclusion and outlook

The main findings of this study include:

- Altitude is identified as the most dominant factor for MAGST in the study area ($r = -0.68$, $p < 0.001$ first year; $r = -0.76$, $p < 0.001$ second year)
- MAGST can vary considerably (> 4 °C) even in close proximity and on same altitudinal levels.
- Distribution of snow has the most significant influence on the thermal state of underlying frozen soils on same altitudinal levels
- Extensive spatial variations in thickness and duration of snow cover occur in the study area due to redistribution by wind common in cold and arid regions
- Variation in MAGST between the two monitored years is > 1.1°C on average and up to 3.39 °C at individual locations
- Inter annual variations in MAGST for the two years can be largely explained by the difference in snowfall and hence, the duration of a considerable snow cover at given locations
- While the probability of permafrost occurrence is highest at altitudes of 3,700 m a.s.l. and above, permafrost presence can be expected in favoured positions at altitudes as low as 3,400 m a.s.l. (MAGST = -1.75 °C)

Results presented here will be used to establish a statistical-empirical model for permafrost distribution in the Chinese part of the Central Tian Shan. Besides the factors analyzed in this paper, DEM and satellite derived parameters will be incorporated to extrapolate the results over a larger area.

While this study gives great insight into the state of the ground thermal regime, a longer time series would help to better understand the influence of climate change on this regime as well as the state and distribution of permafrost. The durability, accuracy and easiness to handle, make the instruments used in this study ideal for the necessary monitoring of ground temperatures over long periods of time.

Acknowledgments

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Appendix B: Publication 2

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 subcatchment of the central Tian Shan.

1 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 Asia (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.

2 Study area

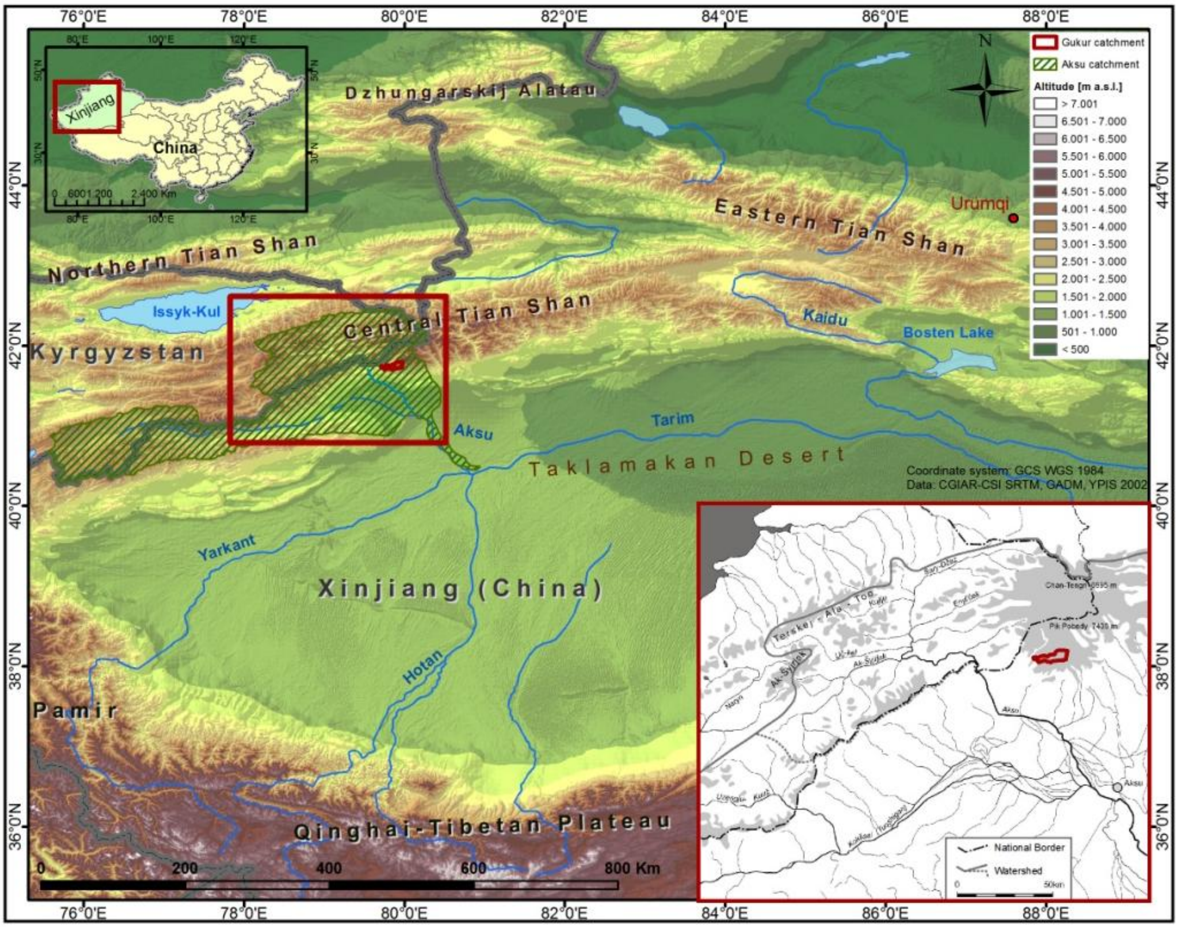

Figure 1: Regional overview and location of the research area (Gukur catchment) within the Aksu catchment, Central Tian Shan.

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.

3 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 (Geographic Information System) derived parameters from Digital elevation models are tested and incorporated in the model. Each relevant parameter tested for the model will be described briefly.

3.1 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).

3.2 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).

3.3 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 (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.

3.4 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.

4 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 $R^2 = 0.637$ is marginally lower than in the first model, while the adjusted $R^2 = 0.623$ 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: Coefficients of correlation for the monitored temperatures (MAGST), 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

5 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.

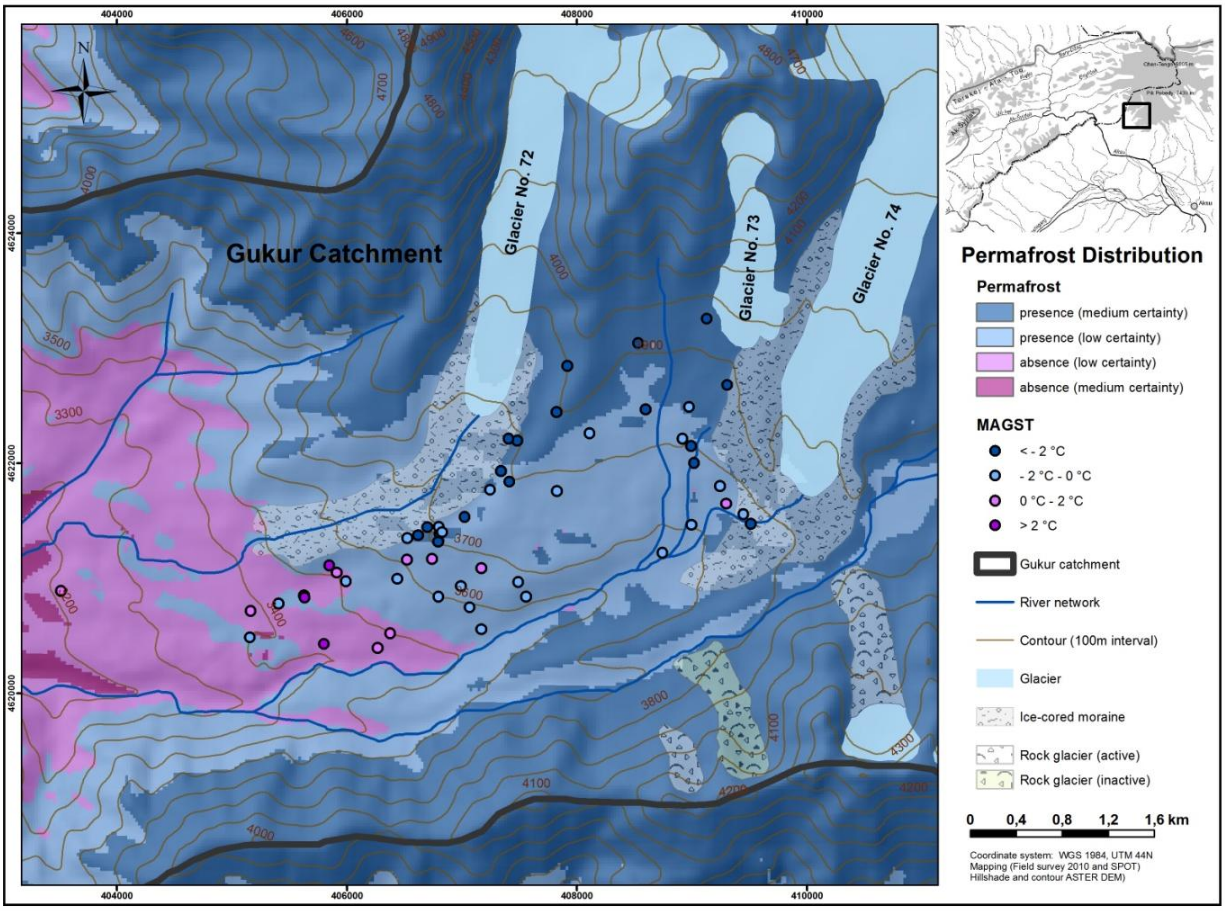

Figure 2: Permafrost distribution map for the focus area, using continuous modelled MAGST as a means of classification into four categories (permafrost presence: MAGST < −2 °C medium certainty; −2 °C < MAGST < 0 °C low certainty; permafrost absence: 0 °C < MAGST < 2 °C low certainty; MAGST > 2 °C medium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

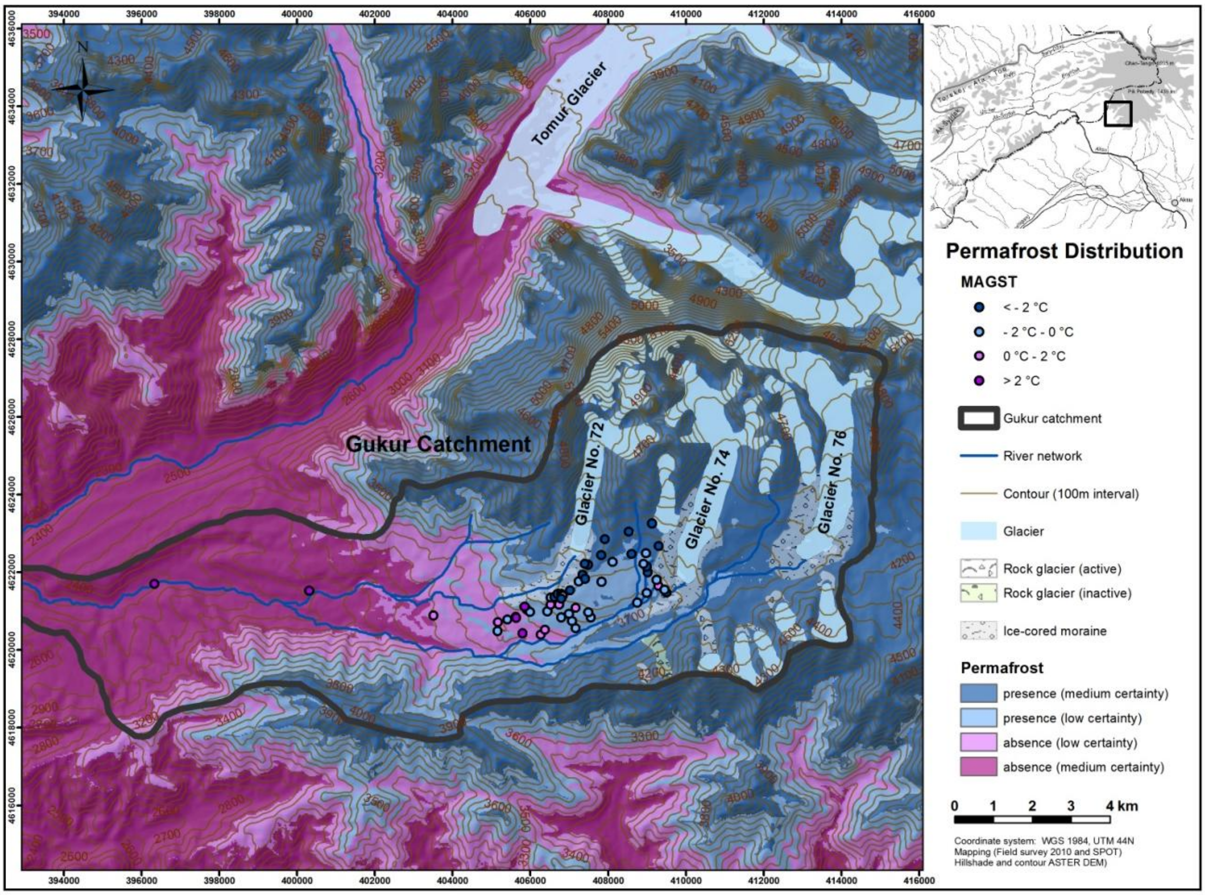

Figure 3: Permafrost distribution map of the greater Gukur research area, using continuous modelled MAGST as a means of classification into four categories (permafrost presence: MAGST < −2 °C medium certainty; −2 °C < MAGST < 0 °C low certainty; permafrost absence: 0 °C < MAGST < 2 °C low certainty;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

6 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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Appendix C: Publication 3

Rock Glaciers and Permafrost in the Central Tian Shan

Proceedings of the International Scientific Conference on "Environment and Global Warming" (2011), Tbilisi, Georgia, p. 160 - 165.

Stephan Imbery (Department of Geography, Justus Liebig University Giessen, Germany)

Abstract

In highly continental climates the mountain permafrost zone has the largest extend as the lower limit of glaciation is at higher altitudes compared to more maritime climates. This certainly applies for the high mountain ranges of the Central Tian Shan, where a strong interaction of glaciers and permafrost processes can be observed. It is therefore an ideal place to study the dynamics and temperature regime of rock glaciers and ice-cored-moraines under climate change conditions.

1 The Tian Shan

The Tian Shan, located in Central Asia, stretches some 2,500 km from east to west. It is one of the highest mountain ranges in the world and can be divided into a Western, Inner, Northern, Central and Eastern Tian Shan (Figure 1). Maximum altitudes range between more than 7,000 m a.s.l. in the Cetral Tian Shan to about 6,000 m a.s.l. in the Inner and 5,000 m a.s.l. in the other parts of the Tian Shan respectively. The highest mountains, Pik Pobedy (7,439 m a.s.l.) and Khan Tengri (7,010 m a.s.l.), are also the most northerly peaks over 7,000 m a.s.l. in the world. Apart from the southwest, where it is bordering the Pamir Mountains, the Tian Shan is surrounded by (semi-) arid lowlands. The climate can be described as highly continental, with decreasing precipitation from northwest to southeast. Therefore the average annual precipitation in the Central Tian Shan is very low, even in high altitudes (311 mm at “Tian Shan” climate station, 3,600 m a.s.l.). The annual average temperature at “Tian Shan” climate station is -7.6 °C, with particular cold winters (-21.5 °C January average) due to its high valley location.

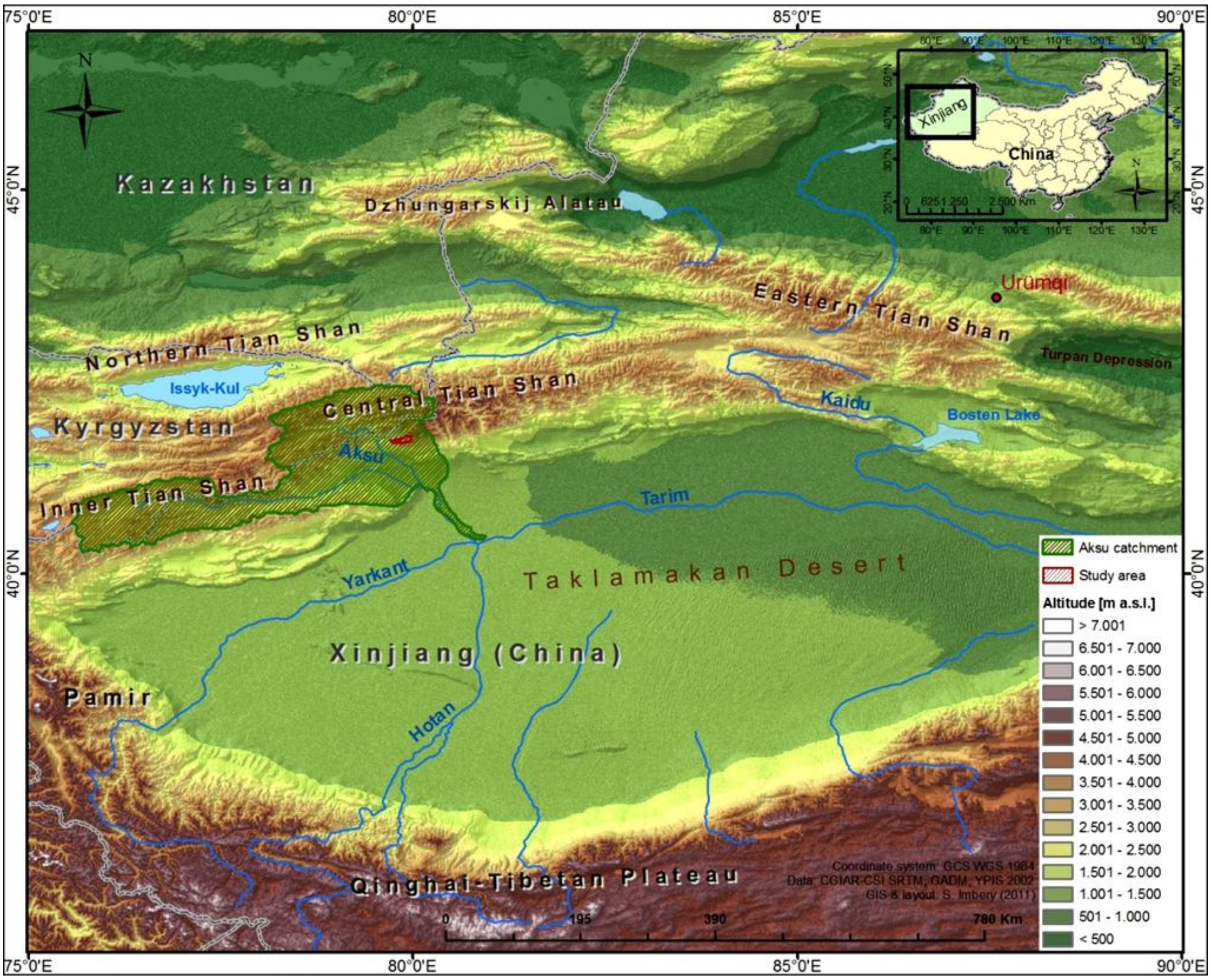

Figure 1: Location and structure of the Tian Shan and the Aksu catchment

2 Permafrost

The altitudinal lower limits of continuous permafrost in the region have been identified at 3,500 m a.s.l. for the Northern and Eastern, 3,600 m a.s.l. for the Inner and 3,800 m a.s.l. for the Western Tian Shan (Gorbunov et al., 1996). Furthermore geothermal observations show an increase in temperature between 0.3 °C and 0.6 °C for the last 30 years (Marchenko et al., 2007). As permafrost warms up and the active layer is thickening – by about 23 % since the early 1970s (Marchenko et al., 2007) - seasonally frozen ground has decreased by 7% in the northern hemisphere since 1900 and the annual average of snow cover in the period of 1988-2004 shows a reduction by 5% compared with the period of 1967-1987 (Lemke et al. 2007).

In the year 1983, the area of frozen ground in the Chinese Tian Shan Mountains was 63,000 km^2, and the maximum measured thickness of frozen ground in this region was 174 m (Qiu 1983). The temperature of mountain permafrost is an important aspect of climate change research in mid Asia Mountains. On the basis of the Sino-Russia cooperation, combined with the Sino-Japan monitoring programme of temperature along the 43°N meridian, a continuous six years of in-situ observation of ground temperature was conducted at the river head of the Urumqi River during 1990-1995, including Borehole No. 5 (43° 06′ N, 86° 50′) at the Ice Pass, with an altitude of 3,900 m a. s. l. the highest borehole in the Tian Shan Mountains. The results showed that permafrost temperatures between 0.5 to 2.0 meters depth indicate a clear rising trend at all sites. At the source of the Urumqi River at 3,300 m a. s. l. the temperatures at 10 m and 18 m depth however declined gradually (Jin et al. 1997). During the 20th century, the lower limit of permafrost in the Tian Shan might have shifted upwards by about 150 – 200 m (Marchenko et al., 2007).

But researches show, that the temperature in coarse debris are typically 2.5 - 4 °C colder than the surrounding mean annual air temperature (MAAT) (Gorbunov et al., 2004). This is of great importance for the study of rock glaciers in the region, as permafrost can occur in coarse blocky material at lower altitudes, where MAAT exceeds 0 °C.

3 Rock glaciers

To avoid any confusion regarding the terminology of rock glaciers, the following descriptions follow the definition given by Barsch (1988; 1992) which focuses on process (creep of supersaturated mountain permafrost), material (unconsolidated debris) and form (depending on whether the flow is extending or compressing). As the unconsolidated debris can be derived from different sources, Barsch (1988) furthermore distinguishes between talus rock glaciers and (glacial- or morainic-) debris rock glaciers. A comprehensive roundup concerning the internal structure and flow of rock glaciers is given by Haeberli (1985).

Rock glaciers can be found in most major mountain systems in the world. In principle, only permafrost and an adequate supply of debris and ice is required for the formation of rock glaciers. But favorable conditions are in continental climate, as the glaciation limit is increasing with a more continental climate and the mountain permafrost zone has the largest extend (see King 1984). This makes the Tian Shan an ideal place to study these creeping permafrost bodies. In the investigated valleys in the Northern Tian Shan, Bolch and Marchenko (2006) showed that rock glaciers cover about 13% of the glaciated area.

Although researches have been done in the Northern Tian Shan (e.g. Gorbunov 1967, 1970, 1983, Gorbunov et al. 1992, Bolch & Marchenko 2006), very little is known about rock glaciers in the Central Tian Shan and the Chinese part of the Aksu catchment in particular. Beside their geomorphologic role and potential source of palaeoclimatic information (Humlum 1998), rock glaciers are very important for the water discharge in this arid region under climate change conditions (Bolch & Marchenko 2006).

First field investigations in the ca. 130 km² Gukur catchment (Figure 2), a tributary of the Aksu, started in 2010. The catchment, sited in the vicinity of Tomur Peak, is a direct tributary to the Aksu 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) and are surrounded by an extensive periglacial area.

Remarkably, the rock glaciers in this study area are only occurring at north facing slopes, with a lower limit of about 3,700 m a.s.l.. Despite their close proximity, also in altitude, they have very distinct morphological features. Three exemplary rock glaciers will be shortly described below.

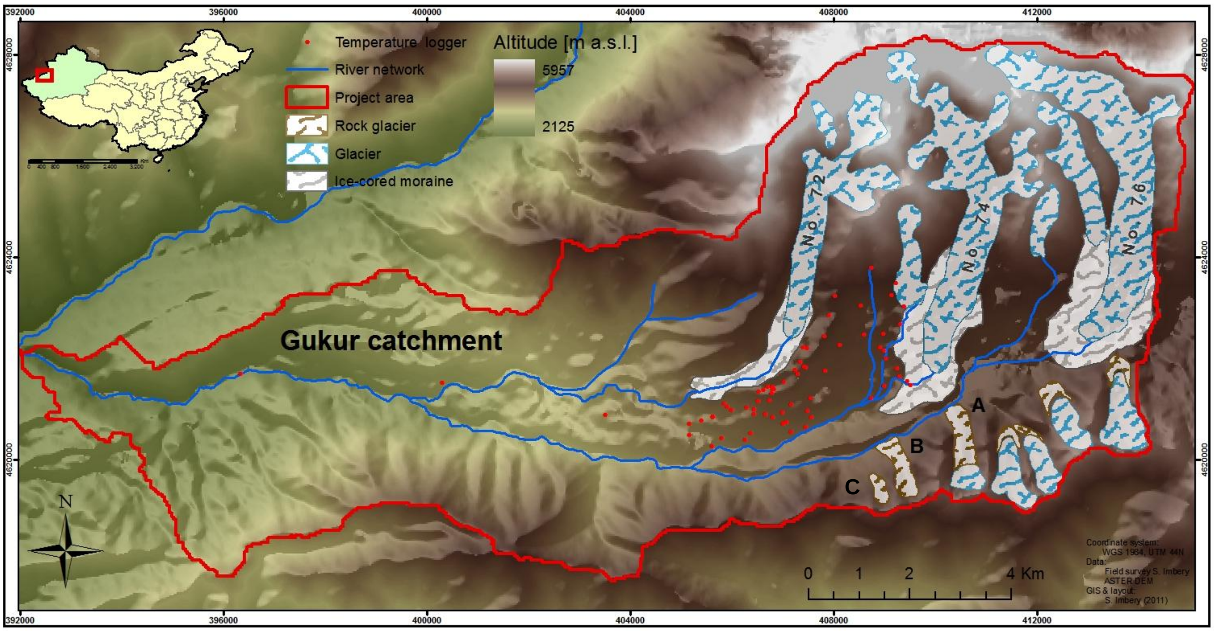

Figure 2: Location of rock glaciers (A, B and C), ice-cored moraines and glaciers in the Gukur catchment, Central Tian Shan.

Rock glacier A

This rock glacier covers an area of about 0.48 km^2. The debris is mainly derived from moraine material of a glacier, which is now limited to the small cirque (ca. 0.27 km^2), at the top of the rock glacier. The very steep slopes at the front of the rock glacier (ca. 3,850 m a.s.l.) as well as ridges and furrows provide a clear evidence of movement. It can therefore be stated, that the rock glacier is still active. So far, no measurements have been done concerning the actual speed of the movement, but will be part of the ongoing research. Four more, much smaller, active debris rock glaciers can be found in the study area at higher altitudes (rock glacier front at ca 3,950 m a.s.l).

Figure 3: Rock glacier A; active debris rock glacier with steep front.

Rock glacier B

The front of rock glacier B (ca. 0,44 km^2) is at ca. 3,700 m a.s.l. and is very flat, compared to rock glacier A. Furthermore patches of vegetation can be seen on the front. These indicators imply that the rock glacier is inactive. An inactive rock glacier still has a core of permafrost and ice (unlike relict rock glaciers), but shows no signs of movement. This can be due to dynamic or climatic reasons. The small cirque at the top indicates that the rock glacier once formed out of moraine derived debris, while at present the supply of debris is limited due to warming and the melting of the glacier.

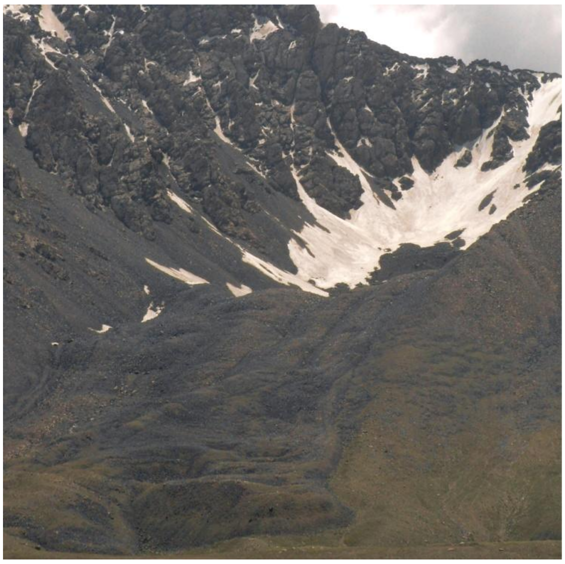

Figure 4: Rock glacier B; inactive debris rock glacier with shallow and overgrown front.

Rock glacier C

This rock glacier is considerably smaller (ca. 0.15 km²) compared to the aforementioned rock glaciers. It also differs in form and shape, as it is not one cohesive compound, but a succession of small creeping permafrost bodies at a very steep slope. Here, Avalanches could play a major role as a supplier of rock debris and ice. The importance of avalanches for the formation of rock glaciers could be shown for a small rock glacier on Svalbard (Humlum et al 2007). The main ridge is at an altitude of about 4,000 m a.s.l. The incised erosion line indicates the occurrence of small landslides in summer month, due to the steep slope and the thawing of the active layer of the permafrost.

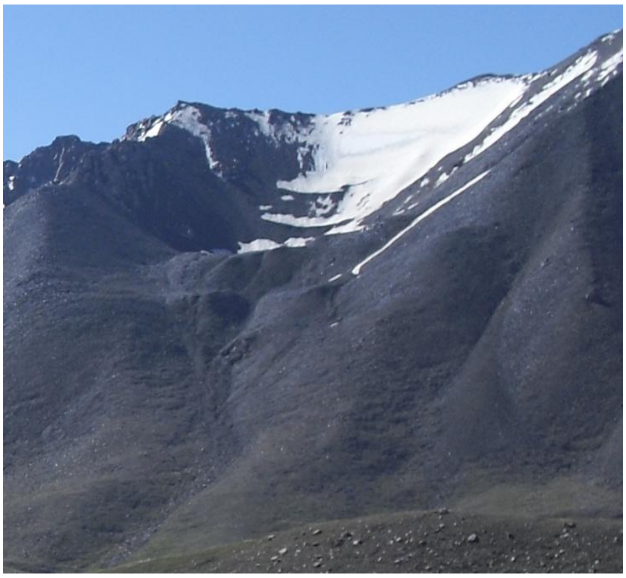

Figure 5: Rock glacier C; succession of small creeping permafrost bodies.

Ice-cored moraines

Although Barsch (1971) uses the term ice-cored moraines synonymously to rock glaciers, it is here used following Østrem (1971; Østrem & Arnold 1970) in the sense of unconsolidated debris which show no signs of movement as they accumulated on flat terrain. These large morainic permafrost bodies are surrounding the larger glacier tongues on the south facing slopes. In some places it is very hard to distinguish between debris covered glaciers and the ice-cored moraines. To better understand and define the ice-cored moraines close to the glaciers, more research needs to be done concerning movement and connectivity to the glacier.

While the conservation of ice-cored moraines depends on permafrost environment, their formation is by definition bound to the activity of glaciers (King 1986). According to King (1986), moraines with degrading ice-cores in a non-permafrost environment should be termed moraines with dead ice instead of ice-cored moraines, to avoid confusion. To investigate the temperature regime in these debris bodies, several temperature sensors were installed at different depth for continuous measurements.

Figure 6: Ice-cored moraine at the south facing slope, below Glacier No. 74.

Summarizing the first observations of rock glaciers in the Gukur catchment, the lower limit of active rock glaciers is estimated to be at about 3,850 m a.s.l, while rock glaciers at lower altitudes seem to be inactive. But fieldwork in the Gukur catchment just started, and further investigations and continuous data on the temperature regime and active layer dynamics in the coarse debris of rock glaciers and ice-cored moraines, as well as in the finer grained surrounding material, will allow a more detailed and profound understanding of the geomorphologic processes and relevance for runoff in the catchment and the Central Tian Shan.

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Appendix D: Publications

Scientific papers (peer reviewed)

Imbery, S., Duishonakunov, M., Sun, Z.D., King, L. (2013): Empirical-Statistical Approach for Permafrost Distribution Modelling in the Central Tian Shan Using Detailed Analysis of Mean Annual Ground Surface Temperatures (MAGST). Neo Geographia, 2, 2, 11 – 20.

Imbery, S., Duishonakunov, M., Sun, Z.D., King, L. (2013): Spatial and Temporal Variability of Mean Annual Ground Surface Temperature (MAGST) in the Gukur Catchment, Central Tian Shan. Neo Geographia, 2, 1 – 18.

Duishonakunov, M., Imbery, S., Narama, S., Mohanty, A., King, L. (2013): Recent Glacier Changes and Their Impact on Water Resources in Chon and Kichi Naryn Catchments, Kyrgyz Republic. Water Science & Technology: Water Supply, IWA Publishing 2013 doi:10.2166/ws.2013.217.

Sun Z.D., Imbery S., King L. (under review). Dynamics of Land Surface Temperature (LST) in the high mountain regions of Central Tianshan, and possible implications. Mountain Research and Development.

Conference contributions and other publications

King, L., Duishonakunov, M., Imbery, S. (2014): Influences of Climate Warming and Facility Management on Continuous Permafrost at Matterhorn Glacier Paradise, Zermatt, Swiss Alps. - Geophysical Research Abstracts, Vol. 16, EGU2014-2489-3, EGU General Assembly 2014.

Imbery, S., Sun, Z.D., Duishonakunov, M., Gao, Q.Z., King, L. (2012): Spatial variability of ground temperatures and active layer thickness in the Central Tian Shan. Tenth International Conference on Permafrost, Salekhard, Russia.

King, L., Imbery, S., Hasler, M., Julen, P., Lauber, A. (2012): New constructions in continuous permafrost regions of Zermatt at Matterhorn glacier paradise, Swiss Alps. Tenth International Conference on Permafrost, Salekhard, Russia.

Duishonakunov, M., Imbery, S., King, L., Usubaliev, R. (2012): Hydrological regime of glacial rivers of the Naryn basin and their role for Toktogul water reservoir. IWA 4th Eastern European Young and Senior Water Professionals Conference 2012, St. Petersburg, Russia

Usubaliev, R.A., King, L., Duishonakunov, M., Imbery, S., Asissov, A. (2012): Auswirkungen des Klimawandels auf den Wasserhaushalt des Naryn-Einzugsgebietes (Kyrgyzstan). XV Glaciological Symposium, Archangelsk, Russia. (in Russian)

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Imbery, S. (2011): Rock glaciers and permafrost in the Central Tian Shan. Proceedings of the International Scientific Conference on "Environment and Global Warming" 2011, Tbilisi, Georgia, 160-165.

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Appendix E: Erklärung

Ich erkläre: Ich habe die vorgelegte Dissertation selbständig und ohne unerlaubte fremde Hilfe und nur mit den Hilfen angefertigt, die ich in der Dissertation angegeben habe. Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichten Schriften entnommen sind, und alle Angaben, die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht. Bei den von mir durchgeführten und in der Dissertation erwähnten Untersuchungen habe ich die Grundsätze guter wissenschaftlicher Praxis, wie sie in der „Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis“ niedergelegt sind, eingehalten.

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