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Article

# Glaciers, Permafrost and Lake Levels at the Tsengel Khairkhan Massif, Mongolian Altai, During the Late Pleistocene and Holocene

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**Abstract:** Understanding paleo—and recent environmental changes and the dynamics of individual drivers of water availability is essential for water resources management in the Mongolian Altai. Here, we follow a holistic approach to uncover changes in glaciers, permafrost, lake levels and climate at the Tsengel Khairkhan massif. Our general approach to describe glacier and lake level changes is to combine traditional geomorphological field mapping with bathymetric measurements, satellite imagery interpretation, and GIS analyses. We also analysed climate data from two nearby stations, and measured permafrost temperature conditions at five boreholes located at different elevations. We identified four glacial moraine systems (M4–M1) and attribute them to the period from the penultimate glaciation (MIS 4/5) until the Little Ice Age (MIS 1). During the Local Last Glacial Maximum (LLGM; MIS 2), a glacier reached down into the western Kharganat Valley and blocked it, resulting in the formation of the endorheic Khar Lake basin. Subsequently, the lake was fed mainly by precipitation and permafrost meltwater. In recent years, glaciers have been in strong recession, yet Khar Lake levels have remained relatively stable, which is in contrast to mainly decreasing lake levels in other regions throughout Mongolia. While temperatures in the Altai are increasing (leading to increasing evaporation), precipitation in higher elevations has increased, which—in addition to increased glacier and permafrost melting—would counteract the increasing aridity effects. A systematic and holistic monitoring of glaciers, permafrost, lake levels and climate in the Mongolian Altai is necessary, and results from (sub-)disciplines need to be correlated.

**Keywords:** environmental change; climate; glacier; Holocene; lake; Mongolian Altai; permafrost; Pleistocene

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## 1. Introduction

Understanding paleo- and recent environmental changes and the dynamics of individual drivers of water availability is essential for water resources management in the Mongolian Altai. Mongolia's water resources are limited and unevenly distributed, and are related to three dominant drainage basins: Arctic Basin, Pacific Basin, and Central Asian Internal Basin. The latter includes in the far west the Mongolian Altai Mountains and Great Lakes Depression with its largest lakes Uvs, Khar, Khar-Uvs, and Khyargas. For the 1980s, the total water resources of Mongolia had been estimated at 599 km<sup>3</sup>, of which 83.7% was found in the ~3500 lakes, 10.5% in the 262 glaciers of the

Altai, and 5.8% in the 3811 rivers [1]. Batnasan [2] believed that these water resources are highly vulnerable to several drivers including climatic changes, overgrazing, deforestation, mining, and several hydropower development projects. For example, he attributed the rise of lake levels by 1–2 m at Uvs Nuur (“nuur” = lake) and Khyargas Nuur between 1963 and 1995 to the melting of mountain glaciers, while simultaneously levels of lakes without significant glacier melt inflow dropped. Furthermore, Batbold et al. [3] estimated that nearly 20% of surface water bodies in Mongolia are already permanently saline with a larger portion of these in the western and southern regions.

The objective of this paper is to describe paleo- and recent environmental changes at Tsengel Khairkhan Uul (“uul” = mountain) including: (1) changes in total glacier area; (2) recent permafrost conditions; (3) changes in lake levels; and (4) recent climatic changes. Its purpose is to describe the dynamics of environmental drivers that are crucial for water availability.

## 2. Background

Relatively little is known about paleo- and recent glacier fluctuations in the Altai Mountains and even less is known about the drivers that influence these changes [4–7]. For the combined Altai and Western Sayan Mountains estimates for the “past” maximum glacier coverage range between 35,000 and 80,000 km<sup>2</sup> [8–11]. For the Mongolian Altai, Lehmkuhl et al. [12] identified glacier advances during MIS 4 (74–71 ka) and MIS 2 (25–20 ka and 18–17 ka). Pan et al. (in review) [13] found that as of 2016 glaciers covered an area of 334 km<sup>2</sup>, which is a remarkable reduction by 35% since 1990. Within the Altai, eighteen mountain ranges are considered to being glaciated. These glaciers have been characterized as mountain-slope glaciers (75%), valley glaciers (21%), and flat-top glaciers (4%) [14]. Baast [15] noted that the glaciers form at elevations from 2800 to 374 m and are of the deep-freeze cold type, which are indicative to the regional continental climate. Based on two Representative Concentration Pathways (RCPs) climate scenarios, 53% of Mongolian glaciers are expected to disappear by 2100 [16]. Furthermore, given the nature of limited precipitation and high rates of evaporation in Mongolia, glacier melt provides a significant contribution to total water resources and has been estimated to approximately 10% [1]. As glaciers in the Altai continue to retreat, they will continue to supply water to regional lakes; however, if these glaciers were to disappear, the lakes which were dependent on meltwater will likely follow in the glaciers’ footsteps.

Permafrost studies for the Mongolian Altai are rare [17–19]. The distribution of permafrost in Mongolia is only mosaic-like owing to the fact that the country is located at the southern boundary of the Siberian permafrost. Permafrost predominantly occurs in the Altai, Khangai, Khentii and Khuvsgul mountains and their surroundings. Generally, the thickness of the active layer and seasonally frozen ground show large spatial variations depending on microclimatic conditions, driven by topography, thermal soil properties, and vegetation cover on local scales [17–21]. Permafrost in the Khangai, Khentii and Khuvsgul mountains usually occur under forested regions [18,21,22], while in the Altai Mountains it occurs under alpine grassland. For the Altai, studies on permafrost, particularly its thermal regimes, are rare owing to the Altai’s remote location that in turn makes in situ ground temperature monitoring difficult. Relevant climatic parameters for periglacial processes are the frost change frequency days, soil moisture, precipitation, humidity and wind, but micro-climatic studies are not available for the entire Altai. In this article, we present results from borehole temperature readings between 2010 and 2016 at Tsengel Khairkhan Uul, located within the continuous and discontinuous permafrost zones.

Studies on paleo- and recent lake level oscillations within the Altai Mountains are more or less not available, while results are available from other regions in Mongolia. It is assumed that large paleo-lakes existed as a result of an extensive transgression phase during the Middle Pleistocene: the current lakes Airag, Durgon, Khara, Khar-Uus and Khyargas within the Great Lakes Depression east of the Altai were part of a combined paleo-lake with a maximal level at 1265 m a.s.l. and total surface area of 23,158 km<sup>2</sup> [23], and also the lakes within the ‘Valley of the Lakes’ in the Gobi Desert formed one large paleo-lake [24]. For the Great Lakes Depression, several authors showed that level

transgressions with higher levels correlate with the two Pleistocene glacier regressions during MIS 3 and MIS 2 [25–28]. Walther (1999) [29] found a shoreline at 80 m above the recent one at Airag Nuur and Uvs Nuur, and one at +40 m at Airag Nuur and Bayan Nuur that dates into the period between 13,200 and 11,200 BP. For northwestern Mongolia, Walther [29,30] described dropping lake levels during the Preboreal and Boreal (until ~8000 BP) followed by higher levels of between 3 and 10 m during the Atlantic (~8000–5500 BP), and again higher levels during the mid-Subboreal (~2900 BP). Fedotov et al. [31] concluded that at Hovsgul Nuur in north-central Mongolia, levels dropped by 100 m at end of the Pleistocene owing to low regional precipitation at only 110 mm. Schwanghart et al. [32] and Walther et al. [33] studied Ugii Nuur in central Mongolia and found low lake level conditions during the Early Holocene (10,600–7900 BP) and generally higher lake levels during the mid-Holocene (7900–4200 BP).

For recent times—between the 1980s and 2010—Tao et al. [34] showed that 63 (17.6%) of all lakes >1 km<sup>2</sup> throughout entire Mongolia disappeared. Kang and Hong [35] reported that for 73 lakes >6.25 km<sup>2</sup> throughout Mongolia, the total surface area decreased by 9.3% at an annual rate of 53.7 km<sup>2</sup> from 2000–2011. Szumiński [36] and Walther et al. [28] found shrinkage between 1974 and 2013 at two lakes in the “Valley of the Lakes”: the surface area of Boon Tsagaan Nuur decreased by 14% and that of Orog Nuur by 51%; Orog Nuur disappeared entirely in some years. Such recent lake level oscillations have been largely attributed to changes in precipitation [34,36,37], but also to increasing water demand from mining activities [28]. However, for Hovsgul Nuur in north-central Mongolia, Kumagai et al. [38] attributed 70–80% of the water loss between 1963 and 2003 to increased (35%) evaporation, whereas rainfall, surface inflow and outflow had remained almost constant, and ground water inflow increased by 50%. Some authors pointed out that caution is required when interpreting paleo-shorelines, since geomorphological events such as the influx of dune sand, landsliding, and blockage by glaciers and rock glaciers can significantly alter a lake’s level [26,29,30].

For the Great Lakes Depression, Walther [29] described an stadial-interstadial climate cycle including four paleo-climatic phases for the Late Pleistocene (<126 ka): (i) decreasing cool temperatures paired with increasing precipitation (“moist-cool conditions”), which resulted in rising lake levels and glacier advances; (ii) consistently decreasing cold temperatures and increasing precipitation (“moist-cold conditions”); (iii) dramatically decreasing precipitation that led to the lowest lake levels and maximum glacier extent (“dry-cold conditions”); and (iv) increasing temperatures with increasing precipitation resulting in rising lake levels (“moist-cold/cool conditions”). This climate cycle occurred several times, and regional differences in intensity and local environmental conditions controlled local lake levels and glacier fluctuations.

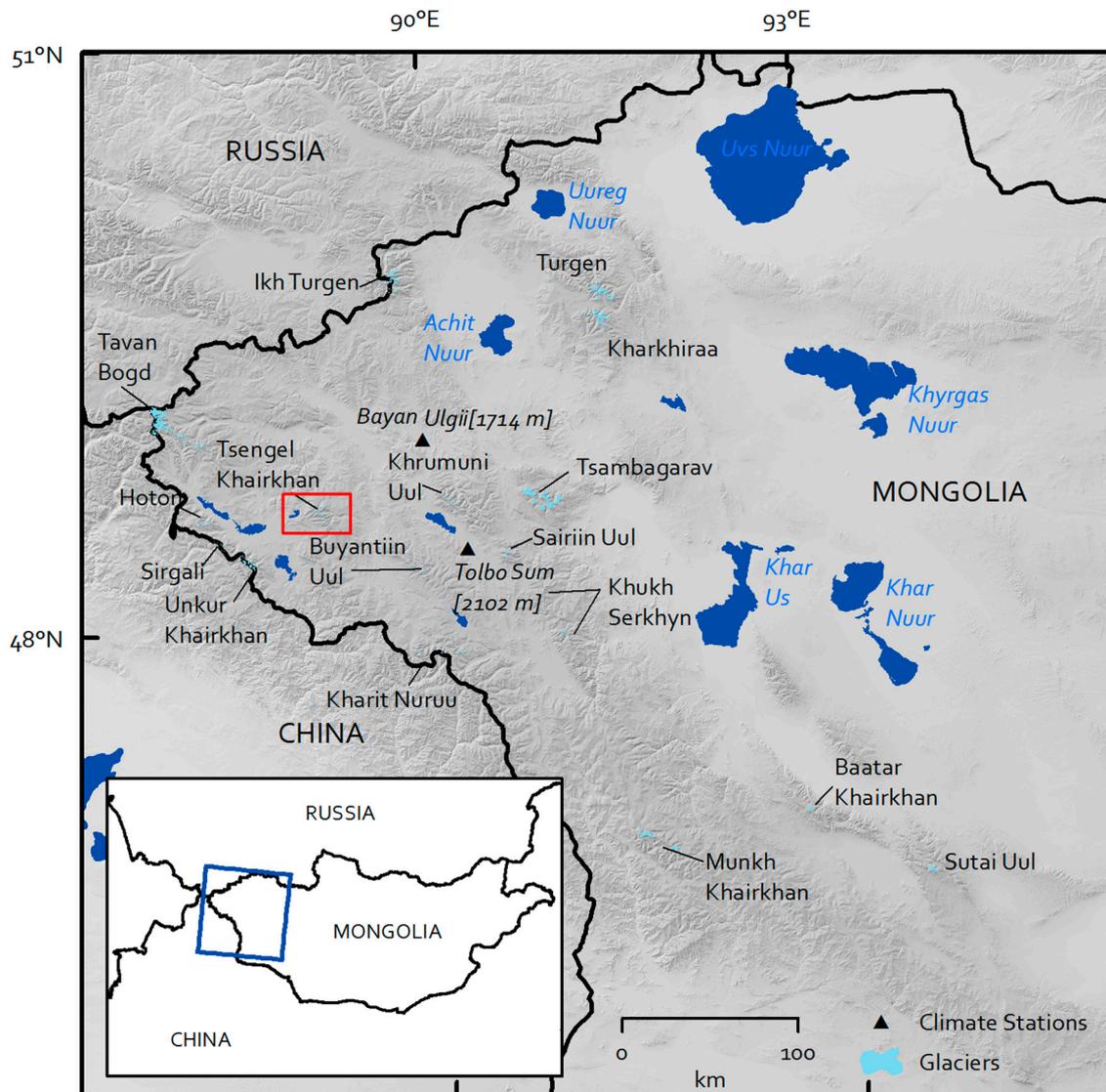
For western and northern Mongolia, palynological data controlled by radiocarbon datings describe the following picture of paleo-vegetation changes: before 9000 BP, steppe vegetation occurred and was followed by forest steppe from 9000 to 8500 BP; between 8500 and 4000 BP, wet conditions allowed the existence of forests and forest-steppe eventually, after 4000 BP, drier conditions changed the landscape again into steppe [25,39–43].

Most recently, between the 1940s and the early 1990s, the mean annual temperature in Mongolia increased by 1.56 °C; winter temperatures increased by 3.6 °C [44]. From 1961 to 2001, the warming was 4 °C in winter and 0.9 °C in summer in Khovd (1405 m a.s.l.) east of the Altai [45]. Within the Altai itself, Heat Wave Duration (HWD) increased by 10 days from 1940 to 2001, and annual precipitation increased by 2–60 mm between 1971 and 2001 [45].

### 3. Study Area

The study area with its center Tsengel Khairkhan Uul (3943 m a.s.l.; 48°38.865' N, 89°9.344' E) is part of the Mongolian Altai Mountains in western Mongolia (Figure 1). The transboundary Altai Mountains reach their highest elevation of 4506 m a.s.l. at Belukha Uul at the border between Kazakhstan and Russia, while the highest peak in the Mongolian Altai is Khuiten Uul at 4374 m a.s.l. in the Tavan Bogd massif at the border between China and Mongolia. From here, the Mongolian Altai stretches over a distance of around 1200 km towards the southeast before

terminating in the Gobi Desert. Besides its widely mountainous landscape, western Mongolia is also characterized by wide endorheic basins of mainly tectonic origin. In the study area, Khar Nuur, at the border between Tsengel and Ulaanhus Sum, with an area of 14.2 km<sup>2</sup> and a shoreline length of 20.4 km, is the most important lake [46]. The 516 km-long Khovd River, flowing west of the study area, originates in Tavan Bogd massif in the northwest and eventually enters Khar-Uus Nuur.



**Figure 1.** Study area of Tsengel Khaikhan Uul in the Mongolian Altai Mountains. (Note: the Khar Nuur east of the Altai Mountains is not the Khar Nuur of this study).

The climate is of cold desert type (BWk) following Köppen's climate classification: summers are warm or hot and dry, while winters are cold with rare snow; the annual precipitation is between 25 and 200 mm, and the "rainy" season occurs during the summer. In the valleys, typical mean monthly temperatures are around  $-30\text{ }^{\circ}\text{C}$  in January and less than  $15\text{ }^{\circ}\text{C}$  in July [45]. In Ulaangom (939 m a.s.l.), located in the Uvs Nuur Basin in the northeast foreland of the Altai, mean annual temperatures are  $-4\text{ }^{\circ}\text{C}$  [47]. Usually, the first snow falls in mid-October, and the snow cover persists until late April [45].

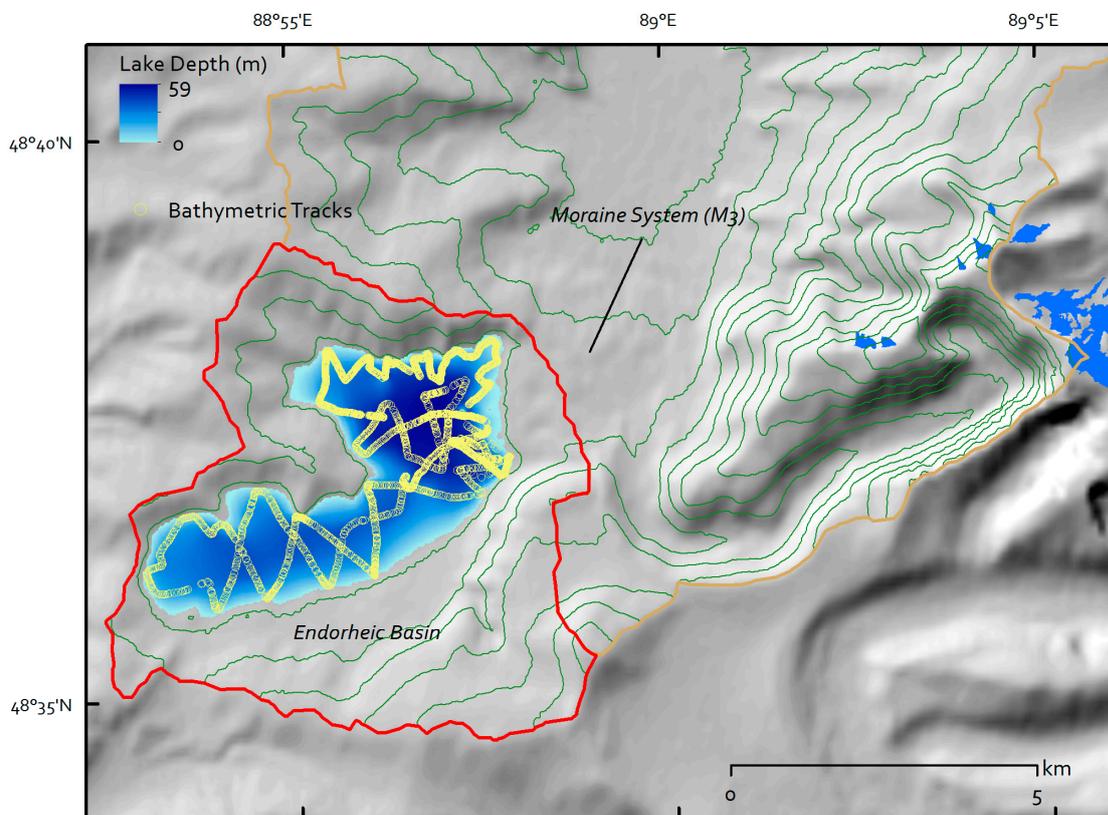
Most of the study area is covered by nivale and alpine vegetation; in edaphically advantaged locations dwarf shrubs are common.

#### 4. Methods

Our general approach to develop a chronology of glacier and lake level changes is to combine traditional geomorphological field mapping with bathymetric measurements, satellite imagery interpretation, and GIS analyses. Since no funding was available for absolute dating of sediments or rocks, we compared our relative chronology to absolute chronologies from Lehmkuhl et al. (2016) [12] for Tsengel Khairkhan Uul and other studies in the Mongolian Altai.

Our geomorphological maps result from the interpretation of our field maps and observations, and satellite imagery interpretation. In addition to the mapping of older lake shorelines in the field, we estimated lake levels from several sources including a Soviet topographic map 1:100,000 from 1948/1970 (see below), Google Earth imagery from 2006, Digital Globe imagery from 2010, and a digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM). The Soviet topographic map from 1970 is only an updated version of the original one from 1948. Unfortunately, we do not know which of the two years the lake extent in the map represents. Hence, we use “1948/1970” throughout our paper.

Bathymetric measurements at Khar Nuur (Figure 2) were taken using a Garmin echoMAP CHIRP 73 dv. This echo sounder sends a continuous sweep of frequencies ranging from low to high, and interprets frequencies individually upon their return. The sensor was located approximately 15 cm below the water surface, and this was corrected for during post-processing of measured data. Samples were automatically collected every 15 m during the early morning hours to avoid choppy water surfaces. Each of the 396 bathymetric measurements includes geographic coordinates and water depth. To determine recent changes at Khar Nuur, we mapped the lake area for 2006, 2010, and 2016, using a simple Normalized Difference Water Index (NDWI). Lake levels for each year were determined by converting the lake polygon for a given year to points, and then extracting elevations values to these points. Finally, the mean of all of extracted point values are presented as a representative lake level proxy.



**Figure 2.** Track of the 396 bathymetric measurements (light yellow) at Khar Nuur west of the glaciated Tsengel Khairkhan Uul. The red line defines the endorheic Khar Nuur catchment.

Kamp and Pan [6] generated glacier outlines for 1990, 2000, and 2010 for the entire Mongolian Altai; from this inventory, we acquired glacier outlines for Tsengel Khairkhan Uul, which are available from the Global Land Ice Measurements from Space (GLIMS) database. The inventory includes only debris-free glacier parts; however, Earl and Gardner [7] determined that in the Altai debris-covered glacier parts accounted for only 3.6% of the total glacier area. To retain glacier inventory integrity, we mapped the 2016 outlines of the debris-free glaciers using a Sentinel-2A MSI image acquired on 3 September 2016 (T45UWQ), downloaded from the USGS via its Global Visualization viewer, following the approach of Kamp and Pan [6]. However, as a slight modification, we qualitatively determined the image thresholds rather than applying one of 2 as has been recommended by several authors [48,49]. We determined this threshold visually following the criterion to be as low as possible to include slightly dirty ice margins [50]. A  $3 \times 3$  median filter was applied to the Near Infrared/Shortwave Infrared band ratio thresholding results to remove misclassified isolated pixels before being converted to vector polygons that were then aggregated; we applied a size threshold of 0.01 km<sup>2</sup>. The glacier polygons were intersected with DEM-derived ice divides to segregate the entire debris-free glacier cover into individual glaciers [51]. After intersecting, the debris-free glaciers were manually edited to merge sliver polygons to larger adjacent glacier entities [52–54]. Where it was possible, we manually digitized glacier extents during the Little Ice Age (LIA) again by visual inspection of satellite and topographic data.

The Equilibrium Line Altitude (ELA) was calculated using the “toe-to-ridge altitude method” (TRAM) after Höfer [55]: the median elevation of the former glacier (MEG) is placed midway between its toe, as indicated by its terminal moraine, and the mean of the highest summits of the surrounding ridge. Another good method for calculating the ELA in the Altai Mountains would be the “square calculation method” [56,57], since reconstructed glacier area during the Pleistocene is often unknown. Furthermore, the “lateral moraine method” [58] could be applied to the historical glacier advances such as the LIA.

In addition to the mapping of geomorphological features, we collected ground temperature data between 2010 and 2016 in the surroundings of Tsengel Khairkhan Uul from 5 boreholes (Table 1) for our studies on recent permafrost conditions. Two of the 5 boreholes are positioned in valley locations, and three exist at similar elevations but possess different slope/aspects around the massif. The boreholes are equipped with HoboU-12 data loggers; soil temperature sensors have been installed in depth-intervals of 1 m or 2 m. From our measurements, we calculated the following values: (i) mean ground surface temperature (MGST); (ii) mean annual ground temperature (MAGT) at depths of 9–10 m; (iii) freezing degree days (FDD), i.e., the daily degrees below freezing summed over the total number of days the temperature was below freezing; and (iv) thawing degree days (TDD), i.e., the daily degrees above freezing summed over the total number of days the temperature was above freezing. Furthermore, we calculated also (v) the active layer thickness (ALT) as a linear interpolation of soil temperature profiles between two neighboring measurements at the time of maximum thawing of the active layer.

Climate data from 2005 to 2015 were downloaded for two weather stations, namely Bayan Ulgii (WMO-ID 442140) and Tolbo Sum (WMO-ID 442170), from the National Center for Environmental Information (NCEI) at the National Oceanic and Atmospheric Administration (NOAA) (CDO02617233, CDO3058607077733). The station at Bayan Ulgii (48°58'47" N, 89°58'47" E) is located 68 km northeast of the Khar Nuur area at 1714 m a.s.l.; Tolbo Sum station (48°24'47" N, 90°17'13" E) is located 87 km to the southeast at 2101 m a.s.l., i.e., Tsengel Khairkhan Uul is situated more or less in the middle of these two climate station locations.

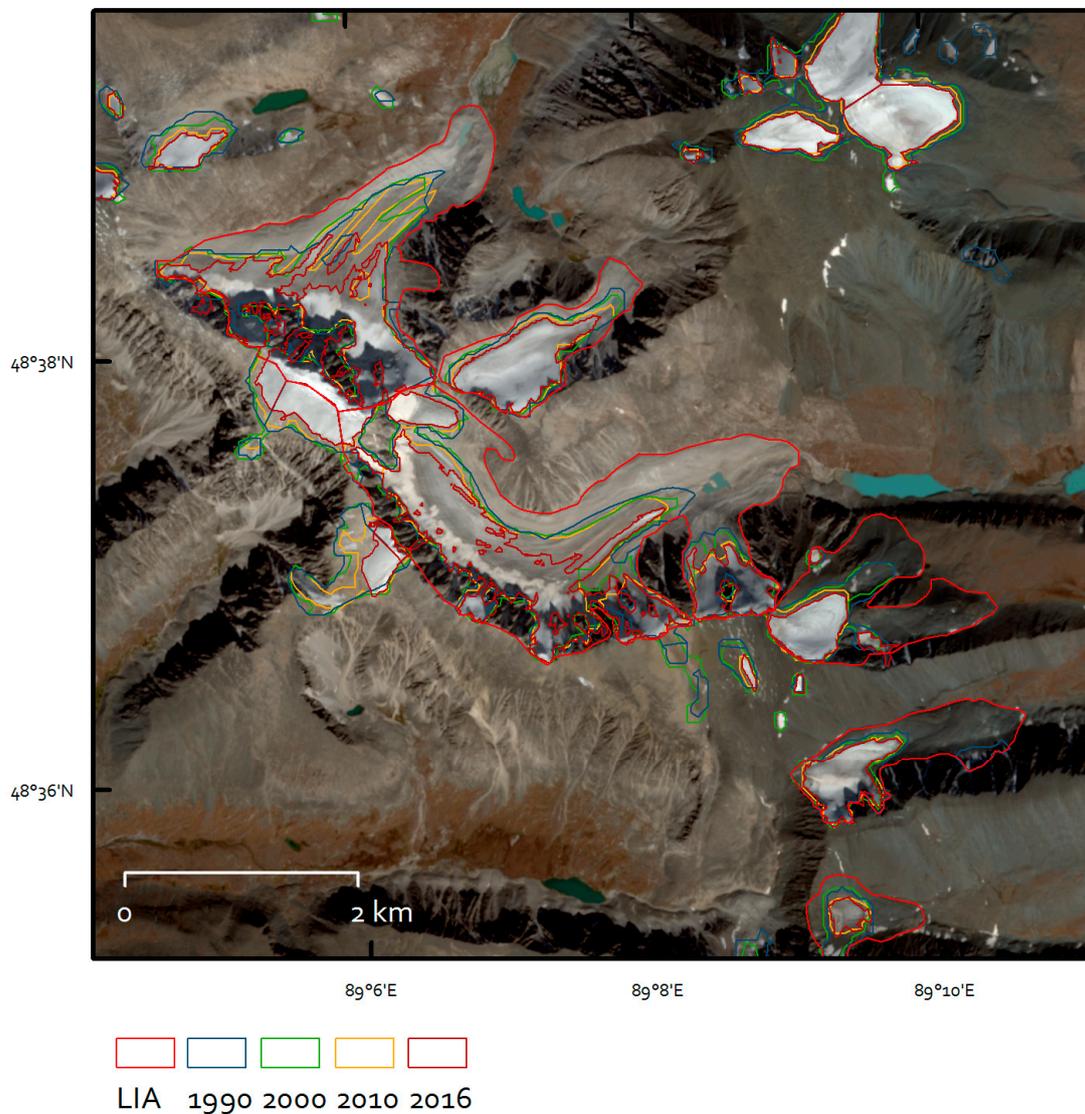
**Table 1.** Characteristics related to permafrost conditions at five boreholes at Tsengel Khairkhan Uul. (MGST: mean ground surface temperature; MAGT: mean annual ground temperature at 9–10 m depth; ALT: active layer thickness; FDD: freezing degree days; TDD: thawing degree days).

Borehole	Location	Slope	Elevation (m a.s.l.)	Ground Surface Conditions	Dominant Ground Material and Depth	Sensor Depths (m)	MGST (°C)	MAGT (°C)	ALT (m)	FDD	TDD
TS-2	48°46'23" N 89°06'33" E	valley (3–5°)	2240	poorly vegetated; pebbles and debris	dry sandy gravels (0–5 m), silt with less gravels (5–10 m)	0, 1, 2, 3, 4, 6, 10	–1.0 to 1.0	–0.1 to –0.3	5.9–6.0	–1998 to –2459	2211 to 2276
TS-3	48°42'36" N 89°02'27" E	valley (3–5°)	2338	poorly vegetated; pebbles and debris	dry sandy gravels (0–6 m), silt with less gravels (6–10 m)	0, 1, 2, 3, 4, 6, 8, 10	–0.8 to 2.4	–2.3	3.4–3.7	–1950 to –2455	1778 to 1836
TS-4	48°35'53" N 88°55'32" E	N-slope (3–5°)	2500	poorly vegetated; pebbles and debris	silt with less gravels (0–10 m)	0, 1, 2, 3, 4, 6, 10	–2.7 to –4.2	–3.3	2.2–2.4	–2249 to –3001	1303 to 1517
TS-5	48°35'00" N 88°53'10" E	SE-slope (5–7°)	2567	more heavily vegetated; debris	sandy gravels (0–4.7 m), silt with less gravels (4.7–10 m)	0, 1, 2, 3, 4, 6, 8, 10	–2.2 to –2.4	–2.3 to –2.4	2.0–2.3	–2093 to –2366	1311 to 1587
TS-6	48°35'00" N 88°53'31" E	S-slope (5–7°)	2556	more heavily vegetated; debris	sandy gravels (0–1 m), silt with less gravels (1–10 m)	0, 1, 2, 3, 4, 6, 8, 9	–2.6 to –3.0	–2.4	2.1–2.2	–2253 to –2393	1291 to 1305

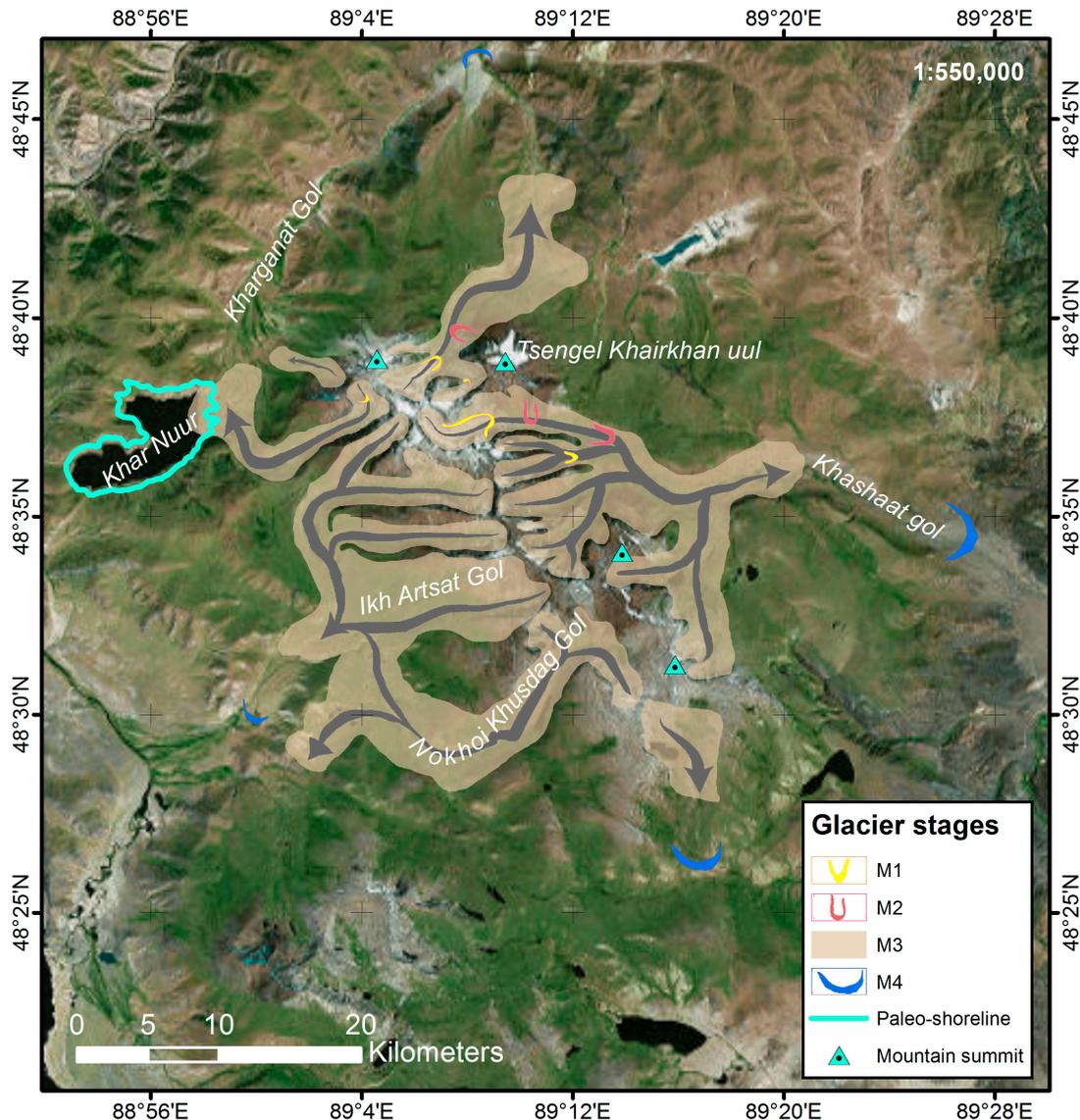
## 5. Results

### 5.1. Geomorphology and Glaciers

Today, Tsengel Khairkhan Uul is covered by a small ice cap (“flat top glacier”) in the north and valley glaciers in eastern and southern aspects (Figure 3). Our mapping of the glaciers for 2016 revealed a surface extent of 8.2 km<sup>2</sup>. Based on geomorphological criteria, we identified four moraine systems in the study area, of which the sequence in the eastern Khashaat Gol (“gol” = valley), tributary of the Sakzay Gol, is the best-preserved one (Figure 4). Here, moraine systems can be found—in order from old to young—at 2256 m a.s.l. (M4), 2421 m a.s.l. (M3), 2732 m a.s.l. (M2), and 2907 m a.s.l. (M1). The recent glacier terminus is located at 3050 m a.s.l. The M3 environment is characterized by the presence of hummocky surfaces, erratic boulders and kettle holes. In a distance of 1.5 km up-valley from the M3 moraine system, numerous eskers cover the valley bottom. The steep moraine ridges of the M1 stage are barren of vegetation; a rock glacier was found 1 km down-valley from these moraines.



**Figure 3.** Glacier extents during the LIA and for 1990, 2000, 2010 and 2016 at Tsengel Khairkhan Uul.



**Figure 4.** Paleo-glaciations at Tsengel Khairkhan Uul: M4: penultimate (MIS 4/5); M3: LLGM (MIS 2); M2: Younger Dryas/Early Holocene (MIS 1); and M1: LIA (MIS 1). The paleo-shoreline at Khar Nuur is 14 m above the recent lake level and is correlated to the M3 moraine system from the LLGM.

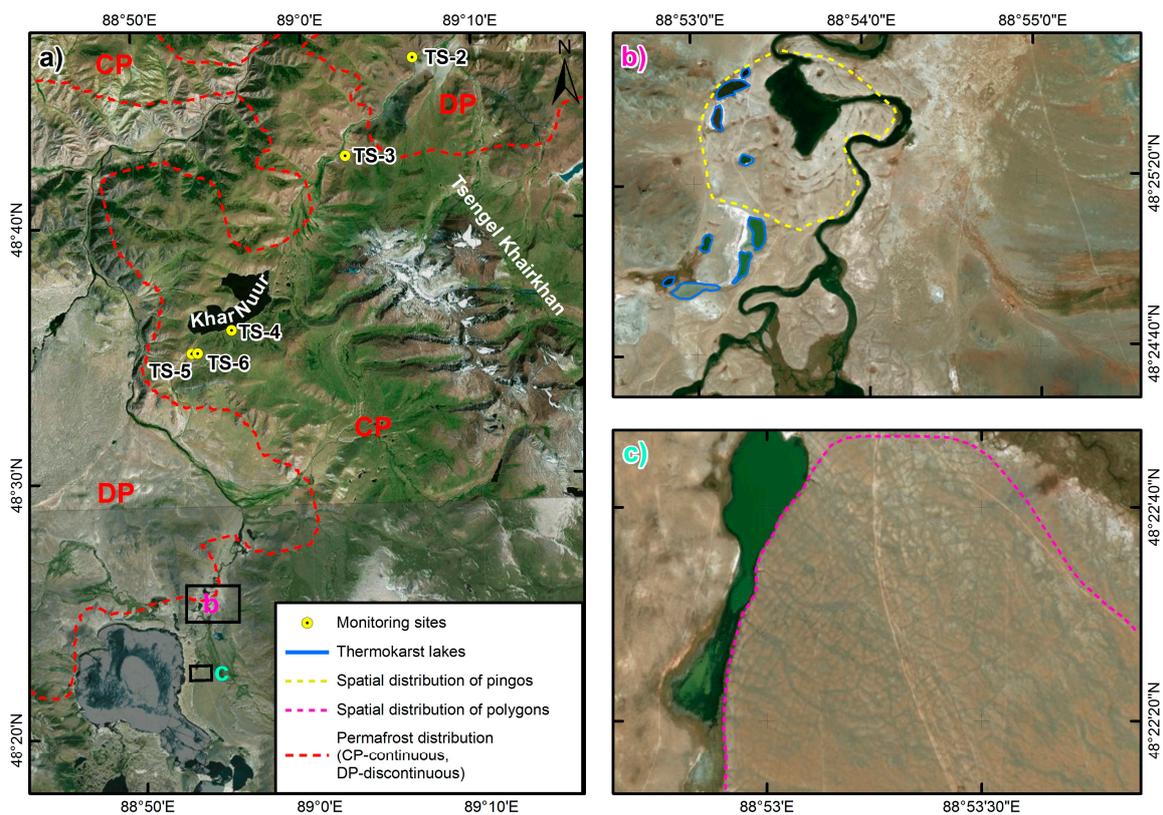
While in the eastern Khashaat Gol only relics of the M4 moraines are preserved, large boulders and outwash plains in the Ikh Artsat Gol in the southwest provide further evidence of this stage. Here, a rock glacier originates in a cirque glacier, and the distinct M3 moraines are covered with eolian deposits, and fluvial sediments have been deposited in between the individual M3 moraine ridges. Lateral and terminal M3 moraines are also preserved in the western Kharganat Gol and effectively blocked the Kharganat River. Following this blockage, water began to fill the Khar Nuur basin during or shortly after this M3 advance. At the north side of the massif, numerous larger erratic boulders occur at around 2190 m a.s.l.

The recent ELA at Tsengel Khairkhan Uul is located ca. 3300 m a.s.l., which results in a depression during the M1 stage between 11 and 41 m depending on aspect. During the M2 stage, the depression was between 245 and 389 m, and it was between 367 and 406 m during the M3 stage.

## 5.2. Permafrost

Permafrost is widespread in the study area and occurs as different ground thermal regimes. For the period 2010–2016, the MGST ranged from 1.0 °C at TS-2 (2240 m a.s.l.) to −4.2 °C at TS-4 (2500 m a.s.l.); from TS-2 to TS-4, we calculated an elevation lapse rate of −1.2 °C/100 m (Table 1). Surprisingly, we measured the lowest temperatures at TS-4, although TS-5 (2567 m a.s.l.) and TS-6 (2556 m a.s.l.) are located in slightly higher elevations; we attribute this to the locations' aspects—TS-4 is situated on the northern slope. The MAGT at 10-m borehole depth in TS-2 was between −0.1 °C and −0.2 °C, whereas in all other locations it ranged from −2.6 to −3.3 °C at depths of 9–10 m. The ALT varied from 3.4–6.0 m at the two valley locations TS-2 and TS-3, and from 2.0–2.4 m at the three mountain sites TS-4 to TS-6. The FDD increased from −1950 to −3001 with increasing elevation and was the highest in northern aspects, while the TDD decreased from 2276 to 1291 with increasing elevation and was the lowest in northern aspects.

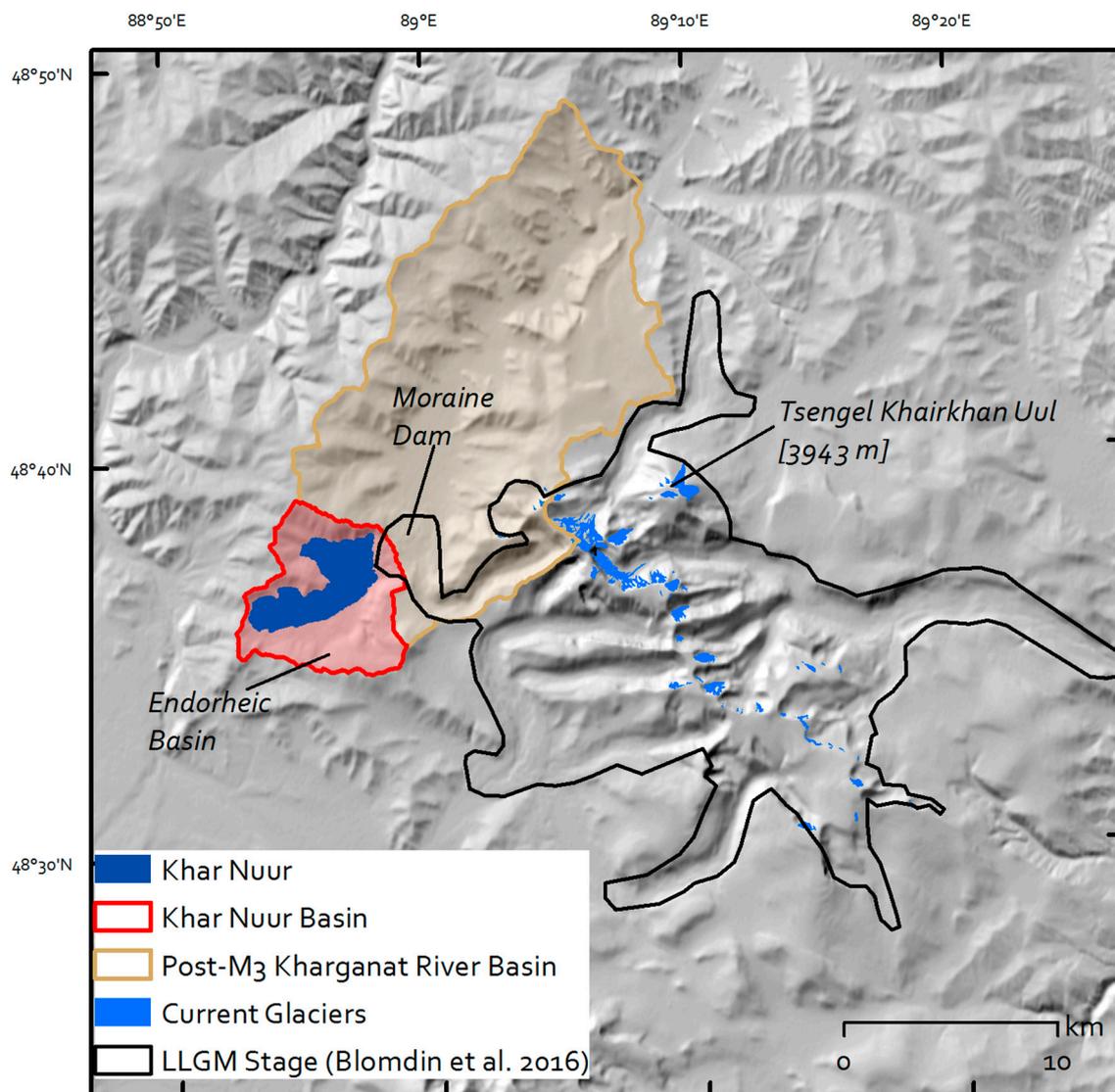
We observed several periglacial features such as hummocks, patterned ground, pingos, stone polygons, solifluction, and thermokarst lakes (Figure 5). Patterned ground and stone polygons are common in plan positions like in the surrounding of Dayan Nuur, a lake 20 km south of Khar Nuur, where soil is fine-grained and wet. At the same time, stone stripes occur mainly on slopes. Solifluction is widespread and exists in nearly all expositions, although it is clearly present in northern aspects. Pingos and thermokarst lakes are common in the upper part of the Godon Gol. The tops of the pingos are mostly smooth, and no active degradation is noticeable. In the Godon Gol, the thermokarst lakes have an area of between 0.5 and 10.7 ha and are actually shrinking; we did not find any recently formed ones.



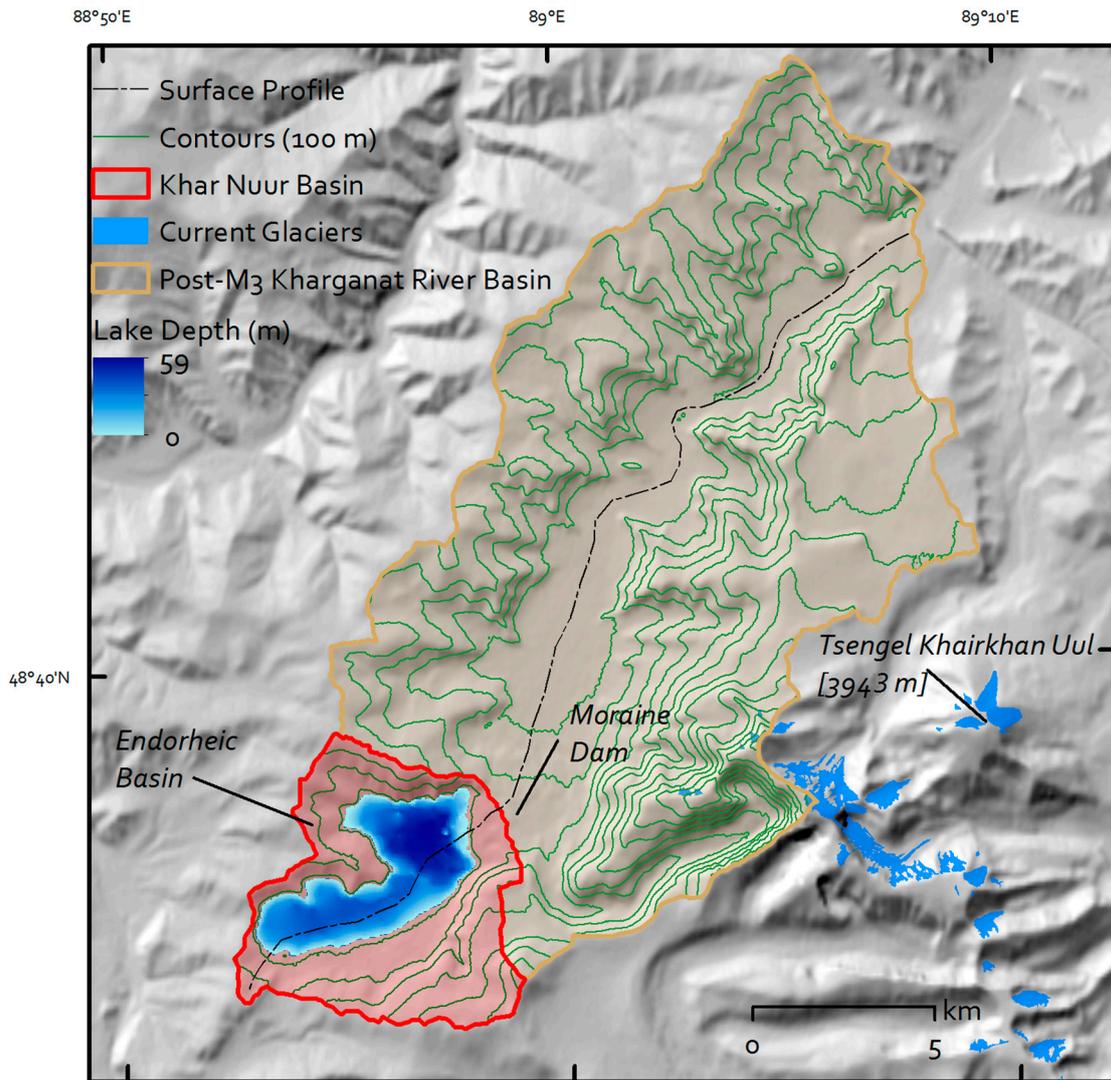
**Figure 5.** Permafrost in the Tsengel Kharikhan Uul study area: (a) distribution of continuous and discontinuous permafrost after Jambaljaw et al. (2016) [59] and locations of our permafrost borehole stations; (b) pingos in the upper Godon Gol; (c) polygons east of Dayan Nuur.

### 5.3. Khar Nuur Characteristics

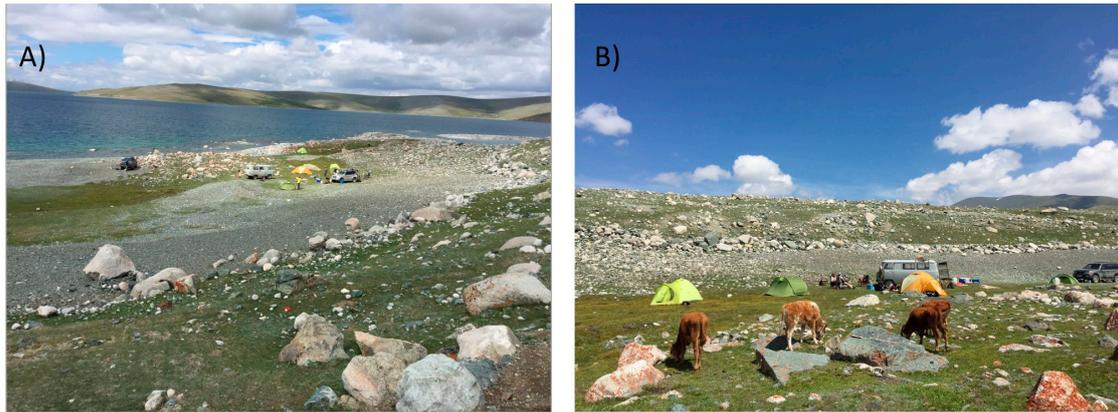
Khar Nuur, west of the Tsengel Khairkhan Uul, is located up-valley from a larger moraine system of the M3 stage that blocked the Kharganat Gol (Figures 6–8). The lake is nourished by water that runs through only short creeks. A submerged hummocky moraine relief with numerous bays and bars characterizes the north end of the lake. In 2016, the lake had a surface area of 13.8 km<sup>2</sup> that covered ~30% of its catchment of only 44.8 km<sup>2</sup>. The lake's maximum depth was 58 m in the northwest, while it is shallower in the southwest; its mean depth was 28 m. By using the bathymetric chart, we calculated a water volume of 0.36 km<sup>3</sup>. During our field investigations, we identified several older shorelines at 14 m, 8 m, 5 m, and 3 m above the recent one. We could not find any former spillways in the moraine systems. We estimated recent lake level elevations as follows: 2488 m a.s.l. in 1948/1970, 2487 m a.s.l. in 2006, 2486 m a.s.l. in 2010, and 2487 m in 2016 (Table 2).



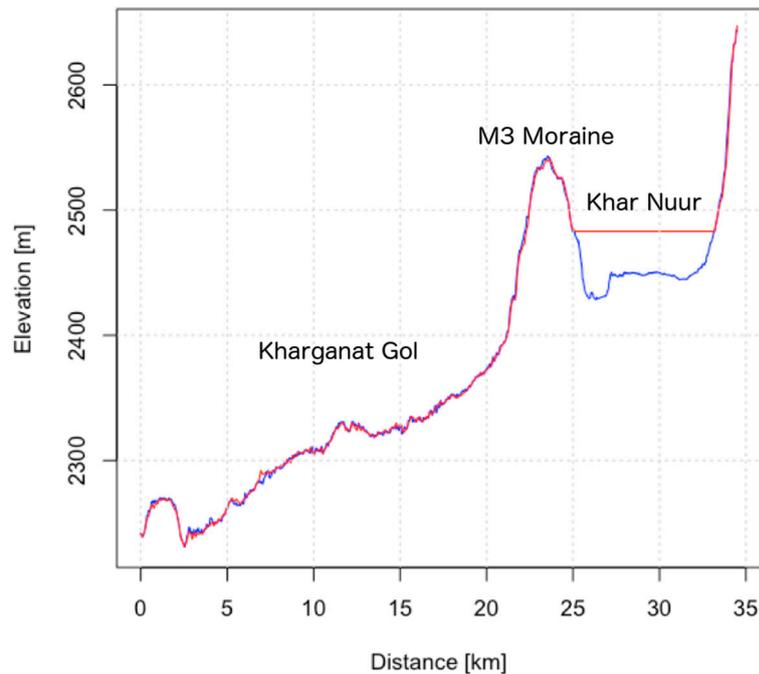
**Figure 6.** Impact of a glacier advance during the period between the LLGM and the Late Glacial on the hydrography in the Kharganat Gol: the glacier in the west of Tsengel Khairkhan Uul reached into the valley, generated the moraine system M3, and blocked the Kharganat River resulting in the formation of the endorheic Khar Nuur Basin. Since then, glacier meltwater from the massif feeds into a “Post-M3” Kharganat River basin.



**Figure 7.** Bathymetric chart of Khar Nuur west of the glaciated (light blue) Tsengel Khairkhan Uul. The red line defines the Khar Nuur catchment, while the orange line bounds the “Post-M3” Kharganat River basin. The moraine system M3 is from the period between the LLGM and the Late Glacial and blocked the Kharganat Gol resulting in the formation of Khar Nuur. (The longitudinal surface profile is displayed in Figure 9).



**Figure 8.** (A) View from the larger boulder moraine dam (M3 advance) towards the dammed Khar Nuur; the camp is located on the +14 m lake terrace (Photo by Michael Walther, August 2016); (B) View looking towards the boulder moraine dam (Photo by Caleb Pan, August 2016).



**Figure 9.** Longitudinal profile through the Kharganat Gol. A glacier and its moraine system M3 blocked the valley resulting in the formation of Khar Nuur (recent lake level at 2487 m a.s.l.). For location of this surface profile see the dashed line in Figure 7.

**Table 2.** Khar Nuur characteristics from this study and from [46]. \* Tserensodnom (2000) [46] merely wrote that he used data from the “1970s and 1980s”.

Lake Characteristics	This Study	Tserensodnom (2000) [46]
Catchment area	44.8 km <sup>2</sup>	50.0 km <sup>2</sup>
1948/1970, 1970s/1980s *		
Elevation	2488 m a.s.l.	2494 m a.s.l.
Surface area	13.9 km <sup>2</sup>	14.2 km <sup>2</sup>
Maximal depth	-	30 m
Mean depth	-	17 m
Lake volume	-	0.24 km <sup>3</sup>
2006		
Elevation	2487 m a.s.l.	-
Surface area	13.8 km <sup>2</sup>	-
2010		

Elevation	2486 m a.s.l.	-
Surface area	13.5 km <sup>2</sup>	-
2016		
Elevation	2487 m a.s.l.	-
Catchment area	44.8 km <sup>2</sup>	-
Surface area	13.8 km <sup>2</sup>	-
Maximal depth	58 m	-
Mean depth	28 m	-

#### 5.4. Climate

The annual course of temperature and precipitation are very similar for both locations of the considered WMO weather stations (Bayan Ulgii; Tolbo Sum): mean January temperatures are at almost  $-20\text{ }^{\circ}\text{C}$  and increase to almost  $+18\text{ }^{\circ}\text{C}$  in July; mean January precipitation is only a couple of millimeters and increases to around 15 mm in July; May to September is the “wet” season.

The climate data reflect the harsher conditions at higher elevations of Tolbo Sum compared to Bayan Ulgii: the mean temperature is slightly lower and the mean precipitation is slightly higher; mean snow depth is almost three times higher (snow depths of  $>400\text{ cm}$  have been recorded); it has 24 more ice days ( $T_{\max} < 0\text{ }^{\circ}\text{C}$ ) and 31 more frost days ( $T_{\min} < 0\text{ }^{\circ}\text{C}$ ); and it has a much higher frost change frequency (Table 3). Tolbo Sum has also a longer period with ice days from the end of September until end of May compared with a period from mid-October until mid-May in Bayan Ulgii.

**Table 3.** Mean annual climatic parameters at Bayan Ulgii and Tolbo Sum, based on data from 2005–2015.

Station	Elevation (m a.s.l.)	Temperature ( $^{\circ}\text{C}$ )	Precipitation (mm)	Snow Depth (cm)	Ice Days ( $T_{\max} < 0^{\circ}$ )	Frost Days ( $T_{\min} < 0^{\circ}$ )	Frost Change Frequency
Bayan Ulgii	1714	1.5	116.3	88	116	216	101
Tolbo Sum	2102	-2.4	129.4	255	140	247	205

Between 2005 and 2015, the mean annual temperature increased by only  $0.3\text{ }^{\circ}\text{C}$  in Bayan Ulgii and only  $0.2\text{ }^{\circ}\text{C}$  in Tolbo Sum; for both stations, the period 2006–2012 showed relatively small fluctuations. For both stations, no particular trend in annual ice and frost days or frost change frequency was observed. Both stations reveal opposite trends in mean annual precipitation: while at Bayan Ulgii it decreased from 135 to 100 mm, it increased from 100 to 145 mm at Tolbo Sum.

## 6. Discussion

### 6.1. Glacial Chronology

Information about paleo-glaciations in the Mongolian Altai is still rare. Lehmkuhl et al. (2016) [12] presented the first absolute OSL dates for the southern slopes of Tsengel Khairkhan Uul and described three main moraine systems from: (i) the Holocene—and, in particular, the LIA—without any sediment and soil cover; (ii) the Local Last Glacial Maximum (LLGM;  $>10.4 \pm 0.6\text{ ka}$ ) in three sub-stages of larger moraines ( $M_{1a}$ ,  $M_{1b}$ ,  $M_{1c}$ ) further down-valley; and (iii) the penultimate glaciation ( $M_2$ ;  $>97.6 \pm 30.1\text{ ka}$  and  $>71.2 \pm 4.8\text{ ka}$ ) as relics of eroded moraines. Based on the geomorphological interpretation of the moraine stages  $M_1$ – $M_4$  that we found in the eastern Khashaat Gol, the correlation with the moraines on the southern slopes by Lehmkuhl et al. [12] presents the following picture (Table 4):  $M_1$  is from the LIA ( $\sim 1650$ – $1850$ );  $M_2$  is from the Younger Dryas ( $\sim 12,900$ – $11,700\text{ BP}$ ) or the earlier Holocene;  $M_3$  is from the LLGM; and  $M_4$  is from the penultimate glaciation. The existence of numerous eskers up-valley from the  $M_3$  moraine system suggests that the meltwater runoff during the decay phase of the  $M_3$  glaciers must have been excessive. Lehmkuhl et al. [12] further described that in the Mongolian Altai large ice advances occurred during MIS 4 ( $74$ – $71\text{ ka}$ ) and MIS 2a and 2b ( $25$ – $20$  and  $18$ – $17\text{ ka}$ ), whereas no significant ice expansion has been reported during MIS 3. However, Pötsch et al. [60] identified such an ice advance during MIS 3 ( $37$ – $32\text{ ka}$ ) in the Khangai Mountains of Central Mongolia, and Rother et al.

[61] used cosmogenic radionuclides ( $^{10}\text{Be}$ ) dating to identify three glacier advances in the last 50 ka in the Otgon Tenger massif within the Khangai Mountains: late MIS 3 (40–35 ka), MIS 2a (ca. 23 ka), MIS 2b (17–16 ka). Rother et al. [61] put the LLGM into the late MIS 3, when climate conditions were cool and wet.

**Table 4.** Glacial chronology at Tsengel Khairkan Uul. (MIS: Marine Isotope Stage; LLGM: Local Last Glacial Maximum; YD: Younger Dryas; LIA: Little Ice Age). \* OSL dates from [12].

Moraine System	Elevation (m a.s.l.)	ELA (m a.s.l.)	Description	Age	MIS	Lehmkuhl et al. (2016) [12]
M4	2248	2898–2918	maximum extent of Late Pleistocene glaciers; single glacial blocks; connected with outwash plain	>71/>97 ka *	MIS 4/5	M <sub>2a+b</sub>
M3	2473	2950–3059	distinct terminal moraines and lateral moraines; kettle holes; block-rich terminal walls; basal till with hummocky relief; eskers; moraine system blocking the upper Kharganat Gol	>10.4 ka *	MIS 2	M <sub>1a-c</sub> M <sub>1c</sub> : LLGM
M2	2778	3212–3130	different moraine stages down valley of glacier tongue basins and rock glaciers	YD/early Holocene	MIS 1	-
M1	3056	3244–3293	non-vegetated and soil-free distinct terminal and lateral moraines	LIA	MIS 1	LIA

Based on the positions of the M1 glacier termini, we estimate a glacierized area of 16.2 km<sup>2</sup> during the LIA; this area has decreased by ~49% until 2016. For the LLGM, based on supplemental GIS data in Blomdin et al. [11], we calculated a glacierized area of 323 km<sup>2</sup> for Tsengel Khairkhan Uul.

We estimated a recent ELA of 3300 m a.s.l. and a depression of—depending on aspect—11–41 m during the LIA, 245–389 m during the Younger Dryas/early Holocene, and 367–406 m during the LLGM. As a comparison, Lehmkuhl et al. [12] calculated a higher recent ELA of 3420 m a.s.l. and a smaller LLGM depression of 300 m. For the Chinese Altai, Zhao et al. [62] estimated a recent ELA of 3020–3360 m a.s.l., and a ELA depression of 100 m during the LIA and 600–700 m during the LLGM.

It is obvious that the glaciers at Tsengel Khairkhan Uul are recently undergoing a significant recession. As part of their GLIMS inventory of the glaciers in Mongolia, Kamp and Pan [6] also mapped glacier changes in the study area, where, between 1990 and 2010, the glacierized area decreased by ~28% from 14.2 to 10.3 km<sup>2</sup>; this matches the mean of ~28% for the entire Mongolian Altai (Table 5). For 2016, we calculated a glacierized area of 8.2 km<sup>2</sup>, which reflects a reduction of ~42% since 1990 and of ~20% in the only six years from 2010 to 2016. Consequently, the glacier recession during the 2000s and 2010s was three times larger than the one during the 1990s.

**Table 5.** Glacier area and change from 1990–2016 at Tsengel Khairkhan Uul. (Numbers for 1990–2010 from [6]; 2016 numbers from this study).

Glacier Area	1990	1990–2000	2000	2000–2010	2010	2010–2016	2016
(km <sup>2</sup> )	14.2	−0.9	13.3	−3.0	10.3	−2.1	8.2
(%)	-	−6.3	-	−22.6	-	−20.4	-

## 6.2. Recent Permafrost Conditions

Ground temperatures attest that probably both warm and cold permafrost conditions exist within the relatively small Tsengel Khairkhan Uul study area. The mean annual ground temperature (MAGT) at 10-m borehole depth in TS-2 ranged from −0.1 to −0.2 °C indicating warm permafrost at this lowest location in the valley. MAGT at the depths from 9 to 10 m for the other sites ranged from −2.6 to −3.3°C, supporting the interpretation as cold permafrost. Although TS-4 is located at a lower elevation than TS-5 and TS-6, we measured lower temperatures and attribute this

to different incident radiation at both sites. The fact that ALT is decreasing with increasing elevation shows it is dependent on TDD and soil composition. Thermokarst lakes are indicators of permafrost degradation; since in the study area many of them are shrinking and new ones were not found, we conclude that either permafrost degradation is quite slow or soils may have a low ice capacity.

### 6.3. Khar Nuur Level Changes

Tserensodnom [46] published data from the 1970s/1980s on Khar Nuur: the 14.2 km<sup>2</sup> large lake was situated at an elevation of 2494 m a.s.l. within a catchment area of 50 km<sup>2</sup>; the maximum depth was 30 m, and the mean depth was 17 m; based on these data, the water volume was given as 0.24 km<sup>3</sup> (Table 2). These results are different from ours: for 1948/1970, we estimated a lake area of only 13.9 km<sup>2</sup>; furthermore, for 2016, we measured a smaller catchment area of only 44.8 km<sup>2</sup>, a lake depth of up to 58 m, a mean lake depth of 28 m. Based on these data, we estimated a much larger water volume of 0.36 km<sup>3</sup> in 2016. While it is challenging to assess these differences in results, we favour to attribute them to obvious differences in the applied methodological—technological approaches. Therefore, drawing conclusions should be done with care.

During the LLGM (M3), a main valley glacier and its moraines on the western side of Tsengel Khairkhan reached into the upper Kharganat Gol and blocked it, resulting in the formation of Khar Nuur. With ongoing deglaciation, the inflow from glacial water into the lake must have decreased, while a recharge from precipitation and permafrost gained importance.

We found a paleo-shoreline at +14 m above the recent one and like to correlate it to results in Klinge and Lehmkuhl [63], who found three paleo-shorelines at Tsetseg Nuur in the Altai: the highest one at +12 m is from between the LLGM and the Late Glacial (before 13 ka); the one at +7 m is from the mid-Holocene; and the youngest at +1 m is from the Late Holocene. Paleo-shorelines at +14 m and +10 m have been described for Khirgas Nuur and Airag Nuur in the Great Lakes Depression, and at +23 m, +15 m, +11 m, and +3 m at Orog Nuur in the “Valley of the Lakes” [28,64]. Naumann and Walther [26] dated paleo-shorelines at Bayan Nuur and Uvs Nuur in the Great Lakes Depression: the one at +10 m is from ~7310 BP, and the one at +6 m dates to ~5800 BP; they found additional ones at +3 m and +1 m. Walther [29] and Grunert et al. [65] identified very high paleo-shorelines at +48 m at Bayan Nuur and at +40 m at Uvs Nuur and attributed them to the deglaciation phase after the LLGM (M3 stage; MIS 2).

Recent lake levels between 1948/1970 and 2016 suggest that the lake level was more or less stable; it dropped by 1 m between 1948/1970 and 2006, then again by 1 m from 2006 to 2010, and eventually rose by 1 m from 2010 to 2016. This is in contrast to lake level changes in other regions of Mongolia, where levels had dropped, particularly as a result of decreasing precipitation [34–36] or mining activities [28]. For Khar Nuur and potentially other lakes within the Altai Mountains, we assume that other factors are of importance and counteracted those of generally increasing temperature and evaporation: (i) precipitation at Tsengel Khairkhan Uul might have increased like at Tolbo Sum, where from 2005 to 2015 it had increased by ~100–145 mm (this station is at 2102 m a.s.l., while Khar Nuur is located at an even higher elevation of 2487 m a.s.l.); (ii) increasing permafrost melting as a result of increasing temperatures. Furthermore, while the endorheic Khar Nuur Basin is not fed by any glacier meltwater, other lakes in the Altai might reveal even stronger recent lake level rises as a result of the increasing temperatures and increasingly melting glaciers.

### 6.4. Recent Climate Change

Climate data from higher elevation locations are rare for the Mongolian Altai; studies either use data from valley stations within the Altai or extrapolate data from stations in the lowlands. The climate data from the two stations in our study might give a first rough idea of climate conditions and changes at Tsengel Khairkhan Nuur; however, while temperatures increased over the last years at both stations, precipitation decreased at the lower-elevation station and increased at the higher-elevation station. Nevertheless, although the precipitation trend at Tsengel Khairkhan Nuur is uncertain, we could assume that at Khar Nuur—at an even higher elevation than the other two

regional stations—precipitation also increased. This would then have an impact on Khar Nuur's water budget. Of course, temperature and precipitation alone do not necessarily explain changes in glaciers, permafrost and lake levels; other factors must be taken into consideration, for example, elevation, aspect, topography (rain-shadow effect), albedo, debris cover, evaporation and evapotranspiration, ice and snow cover, and groundwater.

## 7. Conclusions

Our picture of Late Pleistocene and Holocene environmental changes in the Mongolian Altai is still only fragmentary. In support of results from other regional studies and research at Tsengel Khairkhan Uul, we identified four individual moraine systems (M1–M4) and correlated them to four glacial stages that occurred from the Late Pleistocene to the LIA: M4—penultimate—MIS 4/5; M3—LLGM—MIS 2; M2—Younger Dryas/Early Holocene—MIS 1; and M1—LIS—MIS 1. During the LLGM, a larger valley glacier at the west side of the massif reached down into the Kharganat Gol and blocked it, which resulted in the formation of Khar Nuur. After this separation of the upper Kharganat Gol, Khar Nuur was fed by precipitation and, during deglaciation, progressively permafrost meltwater. A paleo-shoreline at 14 m above the recent Khar Nuur level indicates the strong inflow into the lake between the end of the LLGM and the Late Glacial. During the following Younger Dryas, glacier meltwater flowed into the lower Kharganat Gol and formed a larger outwash plain. In recent times, since 1948/1970, the lake level was more or less stable, which is in contrast to other regions in Mongolia. This could be attributed to the role of precipitation and permafrost melting in higher elevations of the Altai that counteract the impact of increasing temperature and evaporation. Borehole temperature measurements show that today both warm and cold permafrost types exist at Tsengel Khairkhan, and ground temperature regimes are mainly controlled by elevation and aspect.

Uncovering recent lake level oscillations and causes, such as melting glaciers and permafrost and/or increasing precipitation at higher elevations, is crucial for assessing the role of environmental drivers in regional water budgets that must be understood for water resources management. So far, such studies are more or less non-existent for the Mongolian Altai. Since results from lowlands and other mountainous regions cannot simply be transferred to the Altai, a systematic and holistic monitoring of glaciers, permafrost, lake levels and climate in the Mongolian Altai is necessary. While first related activities are underway (e.g., GLIMS Regional Center for Mongolia since 2009; Mongolian Lake Inventory), they have to be coordinated, and results need to be correlated. Our paper was a first attempt to a holistic interpretation of environmental changes at an individual massif in the Mongolian Altai.

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