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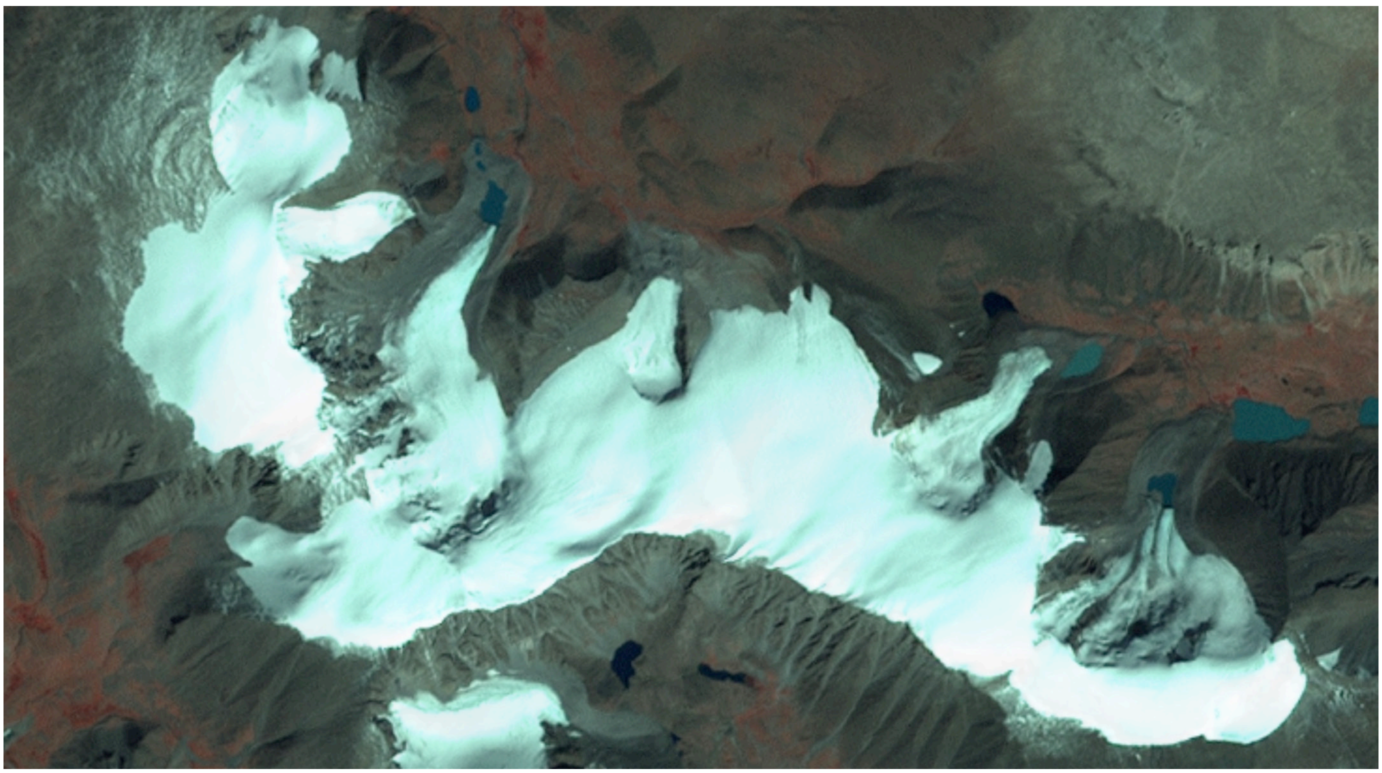

Occasional Paper No. 61
2013
Institute of Arctic and Alpine Research • University of Colorado

The Glaciers of Mongolia

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Occasional Paper 61

2013

INSTAAR/OP-61
ISSN 0069-6145

Abstract

The glaciers of Mongolia have not been well studied; before now, the exact number of glaciers and their extent have not been known, and information about recent glacier fluctuations is sparse. The World Glacier Monitoring Service (WGMS) lists one Mongolian glacier; the Digital Chart of the World outlines only some glaciers in Mongolia; and the World Glacier Inventory (WGI) includes a few glaciers without providing information on when the data were collected. The international program Global Land Ice Measurements from Space (GLIMS) only recently added a so-called Regional Center for Mongolia to its list of regional observation centers, and the inventorying of all Mongolian glaciers has just been finalized. This contribution reviews and summarizes our knowledge about the glaciers, important current climatic conditions, and predicted future climate change in Mongolia. While it presents information from various published sources, it does not aim to evaluate the accuracy of this information or discuss potential disagreements within the scientific community.

Acknowledgments

This project was made possible through the generosity of the University of Montana, the American Alpine Club, and the American Center for Mongolian Studies. Ulrich Kamp thanks the Alexander von Humboldt Foundation, Germany, for awarding a research fellowship. We thank the Global Land Ice Measurements from Space (GLIMS) program for providing Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery free of charge; the Royal Geographic Society, U.K., for providing information and material on the 1910 Carruthers Expedition to Mongolia; and Jeffrey Olsenholler, Texas A & M University, for ASTER digital elevation model (DEM) generation. We appreciate the support of Richard Williams, Jane Ferrigno, and Jan Goodell, U.S. Geological Survey, in preparing the first version of this paper. We also thank Frank Lehmkuhl, University of Aachen, Gregory J. Leonard, University of Arizona, and Alana Wilson, University of Colorado, for many helpful comments on the manuscript. We are thankful to Larry Bowlds, editor of Arctic, Antarctic, and Alpine Research at INSTAAR, for editing and publishing this paper.

Preface

INSTAAR Occasional Paper 61 is an addendum to the U.S. Geological Survey Professional Paper 1386, "Satellite Image Atlas of Glaciers of the World," which contains 11 chapters. While Chapter F, "Asia," includes sections on the glaciers of the Former Soviet Union, China, Afghanistan, Pakistan, India, Nepal, and Bhutan, it does not include the glaciers of Mongolia. This paper on the glaciers of Mongolia had been originally prepared as an online addendum to the USGS PP 1386-F section in collaboration with volume editors Richard Williams and Jane Ferrigno. Although the paper had passed through all publication processes (peer review, revision, and editing) and was turned over to the press, recent budgetary cuts at USGS stalled its publication in the very end. As an alternative, INSTAAR offered to publish the paper in its Occasional Paper series.

The paper reviews our knowledge about the glaciers of Mongolia. Until only recently, the number of glaciers and the area they cover were unknown; data presented in the literature varied within a broad range. In 2010, the international project Global Land Ice Measurements from Space (GLIMS) established its Regional Center for Mongolia at the University of Montana and the National University of Mongolia, and in 2013 the first complete inventory of the glaciers of Mongolia was uploaded to the GLIMS webpage (http://www.glims.org).

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Introduction

The glaciers of Mongolia (Fig. 1) are located between 46°25′ and 50°50′N, and between 87°40′ and 100°50′E at elevations of 2750–4374 m above sea level (a.s.l.) (Davaa and Basandorj, 2005). In general, spatial distribution of the glaciers is sporadic and decreases from northwest to southeast. The glaciers contain approximately 10% of Mongolia's estimated volume of fresh water (Dashdeleg et al., 1983; Baast, 1998; Myagmarjav and Davaa, 1999).

Although a few studies on Mongolian glacier mapping exist, the glaciers of Mongolia are not well studied (Konya et al., 2008; Ohata et al., 2009), and systematic mapping has begun only recently. The World Glacier Monitoring Service (WGMS) lists one Mongolian glacier; the Digital Chart of the World outlines only some glaciers in Mongolia; and the World Glacier Inventory (WGI) includes a few glaciers without providing information on when the data were collected; however, Evans and Cox (2005) reported that no WGI Internet-accessible data existed. In 2010, the international program Global Land Ice Measurements from Space (GLIMS) added the Regional Center for Mongolia (cooperation between the University of Montana and the National University of Mongolia) to its list of observation centers; only recently, the first complete inventory of the glaciers in Mongolia has been compiled and uploaded to the GLIMS website.

FIGURE 1. Location of Khangai Mountains and Altai Mountains with selected subranges within Mongolia.

Thus, until only recently, knowledge about the number and spatial distribution of Mongolia's glaciers was deficient (Fig. 2; Table 1). This is because a comparison of the number of glaciers, glacierized area, rates of areal change, and so forth among individual publications is impossible when methods of glacier mapping, source of data (topographic maps, aerial photographs, and satellite imagery), and (or) date of data acquisition are not mentioned. In addition, from these studies, it is often unclear what the definition of "glacier" was—that is, what was measured in the first place (for example, glacier, snow patch, or both). For example, Selivanov (1972) counted only glaciers that were more than 0.5 km in length, giving the total number at 120 glaciers; Klinge (2001) identified 731 glaciers and glacierized areas; Krumwiede et al. (in press) mapped only glaciers and glacierized areas >0.1 km^2; and Kamp and Pan (in prep.) mapped only glaciers and glacierized areas >0.01 km^2 (Table 1). When four publications were compared (Lehmkuhl, 1999; Klinge, 2001; Davaa and Basandorj, 2005; Khrutsky and Golubeva, 2008) in which results from the Kharkhiraa Range (#6 in Fig. 2) from the budget year 1991/1992 were presented, the number of glaciers varied from 29 to 50, and the glacierized

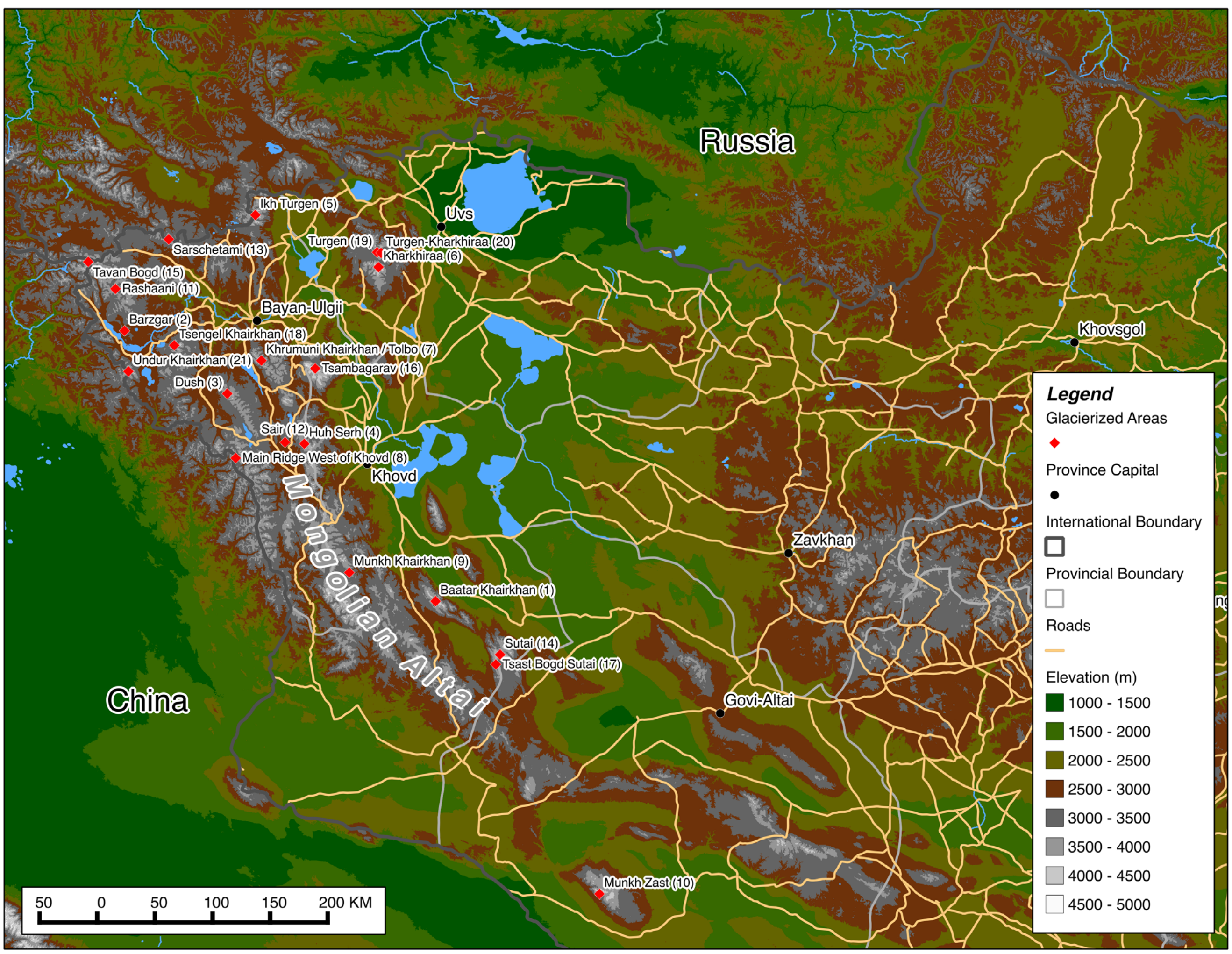

FIGURE 2. Location of selected glacierized regions within the Altai Mountains of Mongolia. See also Table 1 for further details, including geographic names of numbered regions.

area varied between 35 and 57 km^2 (Table 1). But even when one team of scientists employed exactly the same mapping methodology at the same mountain range from two different satellite images of nearly the same date, discrepancies in the quantification of glacier area have occurred. Krumwiede et al. (in press) mapped the area of glaciers in the Munkh Khairkhan Range (#9 in Fig. 2) from two Landsat images of different dates and measured 27.3 km^2 on 11 August 2006 and 26.9 km^2 on 20 August 2006. However, it is very unlikely that this decrease of 0.4 km^2 in glacier area is a result of glacier melt within only 10 days. Last but not least, Lehmkuhl (1998, 1999, 2012) presented varying data for glaciers in the Kharkiraa Mountains, although identical topographic maps (for 1948/1950) and aerial photographs (for 1991) had been used; in these three publications the results are as follows: for 1948/1950, the number of glaciers ranges between 29 and 48, while the glacier area ranges between 53.7 and 58.5 km^2; for 1991, the number of glacier area ranges between 35.9 and 52.1 km^2 (Table 1). With that said, it is important to realize that the numbers of glaciers, glacierized area, changes in glaciers (area, surface elevation, and volume), and estimated climate change from existing studies must be evaluated with extreme caution.

This contribution reviews and summarizes our knowledge about Mongolian glaciers, important current climatic conditions, and predicted future climate change in Mongolia. While it presents information from various published sources, it does not aim to evaluate the accuracy of this information or to discuss potential disagreements about climate and glacier data within the scientific community.

ROMANIZATION OF MONGOLIAN

In the literature on Mongolian glaciers, the use of different transliteration keys produced varying names for individual glaciers or mountain ranges, which challenged the identification and comparison of individual glaciers or locations. Therefore, it is important to cite the applied transliteration key in publications. The Mongolian Cyrillic alphabet contains two characters not present in the Russian alphabet: Ө is transliterated as either U or Ö, and Y is usually transliterated as either U or Ü. Several standards for transliteration and transcription of the Mongolian Cyrillic alphabet into the Latin alphabet exist, including, for example, those from the American Library Association and the Library of Congress (Barry, 1997), United States Board of Geographic Names/Permanent Committee on Geographical Names for British Official Use (BGN/PCGN, 1964), International Organization of Standardization (ISO, 1995), and United Nations Group of Experts on Geographical names (UNGEGN, 2003). Unfortunately, sources such as topographic maps or reports often used different standards or simply followed local pronunciation or spelling. Thus, often more than one spelling of a specific geographic name occurs in the literature. This study follows the spelling conventions for geographic features used by ISO (1995) and the National Atlas of Mongolia (Orshikh et al., 1990).

TABLE 1
Glacierized area and number of glaciers in the Mongolian Altai from published references.

Range	Coordinates (N/E)	ID in Figure 2	Year of Source	Number of glaciers	Glacierized area (km^2)	Data source	Source
Altai Mountains	~45º–50º30′/ ~87º50′–95º		1940s, 1985 (?)	262	659	?	Baast (1998)
			1940s, 1980s, 1990s	731	655	Topo 1:100,000 and aerial	Klinge (2001)[1]
			1947–1950, 1972 (?)	187	540	Aerial	Dashdeleg et al. (1983)
			1947–1950, 1972 (?)	186	540	Aerial and topo	Dashdeleg (1990)
			1948, 1950	—	>300	Topo	Lehmkuhl (1998)
			1970–1971	120	328	Topo 1:100,000	Selivanov (1972)[2]
			1989–1991	691	541	Landsat	Kamp and Pan (in prep.)[3]
			1998–2000	716	429	Landsat	Kamp and Pan (in prep.)[3]
			1999–2002	578	423	Topo and satellite	Yabouki and Ohata (2009)
			2000	~580	423	Topo and satellite	Ohata et al. (2009)
			2010–2011	670	372	Landsat	Kamp and Pan (in prep.)[3]
			?	—	>300	?	Devjatkin (1981)
			?	~250	514	?	Enkhtaivan (2006)
Asgat			1947–1950, 1972 (?)	—	7.0	Aerial and topo	Dashdeleg (1990)
Baatar Khairkhan	46º58′ / 92º44′	1	1940s	9	7.3	Topo 1:100,000	Klinge (2001)[1]
			1947–1950, 1972 (?)	—	5.4	Aerial and topo	Dashdeleg (1990)
			2000	2	5.9	Landsat	Kamp and Pan (in prep.)[3]
			2010	2	5.1	Landsat	Kamp and Pan (in prep.)[3]
Barzgar	48º40′ / 88º27′	2	1940s	30	23.5	Topo 1:100,000	Klinge (2001)[1]
			1947–1950, 1972 (?)	—	1.8	Aerial and topo	Dashdeleg (1990)
Bugat			1947–1950, 1972 (?)	—	18.6	Aerial and topo	Dashdeleg (1990)
Chuche Sain			1947–1950, 1972 (?)	—	11.0	Aerial and topo	Dashdeleg (1990)
Dungerekhijn Zast			1947–1950, 1972 (?)	—	18.6	Aerial and topo	Dashdeleg (1990)
Dush	48º20′ / 89º50′	3	1940s	24	17.1	Topo 1:100,000	Klinge (2001)[1]
			1947–1950, 1972 (?)	—	1.8	Aerial and topo	Dashdeleg (1990)
Huh Serh	48º03′ / 90º52′	4	2007	—	2.2	SPOT	Ladig (2009)
			2008	—	2.1	Field	Ladig (2009)
Ikh Turgen	49º48′ / 89º45′	5	1940s	52	36.8	Topo 1:100,000	Klinge (2001)[1]
			1940s, 1985 (?)	27	39.4	?	Baast (1998)
			1947–1950, 1972 (?)	—	7.0	Aerial and topo	Dashdeleg (1990)
			1998	57	34.0	Landsat	Kamp and Pan (in prep.)[3]
			2011	62	27.8	Landsat	Kamp and Pan (in prep.)[3]
Kharkhiraa	49º34′ / 91º23′	6	1947–1950, 1972 (?)	—	58.2	Aerial and topo	Dashdeleg (1990)
			1948	48	53.7	Topo 1:100,000	Lehmkuhl (2012)
			1948	—	43.0	Topo 1:100,000	Davaa and Kadota (2009)
			1948, 1950	29	58.5	Topo 1:100,000	Lehmkuhl (1998)
			1948, 1950	—	58.5	Topo 1:100,000	Lehmkuhl (1999)
			1969	32	48.8	Topo 1:200,000	Khrutsky and Golubeva (2008)
			1970, 1971	—	50.1	Topo 1:100,000	Kadota and Davaa (2004)
			1988	—	(~36.1)	Aerial 1:44,000	Kadota and Davaa (2004)
			1988, 1991	50	35.0	Aerial 1:45,000	Klinge (2001)[1]
			1989	43	55.3	Landsat	Kamp and Pan (in prep.)[3]
			1991	—	52.1	Aerial 1:45,000	Lehmkuhl (1999)
			1991	35	34.8	Aerial 1:45,000	Jansen (2010)
			1991	39	35.9	Aerial 1:45,000	Lehmkuhl (2012)
			1992	—	57.4	Landsat	Davaa and Basandorj (2005)

TABLE 1 (cont.)

Range	Coordinates (N/E)	ID in Figure 2	Year of Source	Number of glaciers	Glacierized area (km^2)	Data source	Source
			1992	29	36.6	Landsat	Khrutsky and Golubeva (2008)
			2000	—	36.1	Landsat	Kadota and Davaa (2004)
			2001	32	45.5	Landsat	Kamp and Pan (in prep.)[3]
			2002	—	31.3	Landsat	Davaa and Basandorj (2005)
			2002	28	29.3	Landsat	Khrutsky and Golubeva (2008)
			2010	—	30.0	Landsat	Kamp et al. (2013)
			2010	33	31.0	Landsat	Kamp and Pan (in prep.)[3]
Khukh Serkhyn			1963	—	7.0	Topo	Bader et al. (2008)
			2008	—	4.0	Field	Bader et al. (2008)
Khrumuni Khairkhan / Tolbo	48º39′ / 90º10′	7	1940s	26	15.4	Topo 1:100,000	Klinge (2001)[1]
Main Ridge west of Khovd	47º50′ / 90º05′	8	1940s	30	26.7	Topo 1:100,000	Klinge (2001)[1]
Munkh Khairkhan	47º05′ / 91º40′	9	1940s, 1985 (?)	13	77.2	?	Baast (1998)
			1947–1950, 1972 (?)	—	44.0	Aerial and topo	Dashdeleg (1990)
			1989	80	67.1	Aerial 1:45,000	Klinge (2001)[1]
			1990	—	39.2	Landsat and ASTER	Krumwiede et al. (in press)[4]
			1991	35	34.8	Aerial 1:45,000	Jansen (2010)
			1991	108	44.0	Landsat	Kamp and Pan (in prep.)[3]
			1991	—	36.1	Landsat and ASTER	Krumwiede et al. (in press)[4]
			1992	—	37.0	Landsat	Davaa and Basandorj (2005)
			2000	—	28.9	Landsat and ASTER	Krumwiede et al. (in press)[4]
			2001	—	29.2	Landsat and ASTER	Krumwiede et al. (in press)[4]
			2001	54	31.0	Landsat	Kamp and Pan (in prep.)[3]
			2002	—	27.4	Landsat	Davaa and Basandorj (2005)
			2002	—	26.5	Landsat and ASTER	Krumwiede et al. (in press)[4]
			2005	—	28.0	Landsat and ASTER	Krumwiede et al. (in press)[4]
			2006	—	27.3	Landsat and ASTER	Krumwiede et al. (in press)[4]
			2007	—	29.1	Landsat and ASTER	Krumwiede et al. (in press)[4]
			2009	—	26.4	Landsat and ASTER	Krumwiede et al. (in press)[4]
			2010	—	27.9	Landsat and ASTER	Krumwiede et al. (in press)[4]
			2011	49	27.4	Landsat	Kamp and Pan (in prep.)[3]
Munkh Sar'dag			1940s, 1985 (?)	1	0.27	?	Baast (1998)
Munkh Zast	44º48′ / 95º06′	10	1947–1950, 1972 (?)	?	7.0	Aerial and topo	Dashdeleg (1990)
Rashaani	48º59′ / 88º14′	11	1940s	33	30.9	Topo 1:100,000	Klinge (2001)[1]
			1947–1950, 1972 (?)	—	1.0	Aerial and topo	Dashdeleg (1990)
Sair	48º02′ / 90º38′	12	1940s	17	11.8	Aerial 1:45,000	Klinge (2001)[1]
			1947–1950, 1972 (?)	—	11.0	Aerial and topo	Dashdeleg (1990)
			1991	18	9.2	Landsat	Kamp and Pan (in prep.)[3]
			1992	—	11.5	Landsat	Davaa and Basandorj (2005)
			1998	10	7.7	Landsat	Kamp and Pan (in prep.)[3]
			2002	—	6.6	Landsat	Davaa and Basandorj (2005)
			2011	12	5.8	Landsat	Kamp and Pan (in prep.)[3]
Samartai			1947–1950, 1972 (?)	—	1.0	Aerial and topo	Dashdeleg (1990)
Sarschetami	49º28′ / 88º45′	13	1940s	23	12.0	Topo 1:100,000	Klinge (2001)[1]
Sutai	46º37′ / 93º35′	14	1940s	33	16.9	Topo 1:100,000	Klinge (2001)[1]
			1947–1950, 1972 (?)	—	11.0	Aerial and topo	Dashdeleg (1990)
Takhil Desh			1940s, 1985 (?)	36	30.8	?	Baast (1998)
Tavan Bogd	49º09′ / 87º50′	15	1940s	92	119.8	Topo 1:100,000	Klinge (2001)[1]
			1940s, 1985 (?)	88	182.0	?	Baast (1998)
			1947–1950, 1972 (?)	—	12.6	Aerial and topo	Dashdeleg (1990)
			1945	—	88.9	Topo 1:100,000	Kadota and Davaa (2004)
			1988	—	(~79.8)	Aerial 1:44,000	Kadota and Davaa (2004)
			1989	—	213	Landsat	Krumwiede et al. (in press)[4]
			1989	126	115.3	Landsat	Kamp and Pan (in prep.)[3]

TABLE 1 (cont.)

Range	Coordinates (N/E)	ID in Figure 2	Year of Source	Number of glaciers	Glacierized area (km²)	Data source	Source
			1998	97	95.9	Landsat	Kamp and Pan (in prep.)[3]
			2000	—	79.8	Landsat	Kadota and Davaa (2004)
			2009	—	204	Landsat	Krumwiede et al. (in press)[4]
			2011	110	95.0	Landsat	Kamp and Pan (in prep.)[3]
Tsambagarav	48º40′ / 90º50′	16	1940s, 1985 (?)	5	115.9	?	Baast (1998)
			1947–1950, 1972 (?)	—	80.2	Aerial and topo	Dashdeleg (1990)
			1948	—	105.1	Topo 1:100,000	Kadota and Davaa (2004)
			1963	—	(~74.8)	Corona	Kadota and Davaa (2004)
			1987	61	84.8	Aerial 1:45,000	Klinge (2001)[1]
			1991	30	86.6	Landsat	Kamp and Pan (in prep.)[3]
			1992	—	91.0	Landsat	Davaa and Basandorj (2005)
			1998	30	76.6	Landsat	Kamp and Pan (in prep.)[3]
			2000	—	74.8	Landsat	Kadota and Davaa (2004)
			2002	—	71.5	Landsat	Davaa and Basandorj (2005)
			2011	27	69.3	Landsat	Kamp and Pan (in prep.)[3]
Tsast Bogd Sutai	46º32′ / 93º33′	17	1940s, 1985 (?)	5	23.2	?	Baast (1998)
Tsengel Khairkhan	48º38′ / 89º05′	18	1940s, 1985 (?)	20	25.0	?	Baast (1998)
			1947–1950, 1972 (?)	—	2.8	Aerial and topo	Dashdeleg (1990)
			1987, 1988	39	30.7	Aerial 1:45,000	Klinge (2001)[1]
Turgen	49º41′ / 91º20′	19	1947–1950, 1972 (?)	—	48.5	Aerial and topo	Dashdeleg (1990)
			1948	—	50.1	Topo 1:100,000	Davaa and Kadota (2009)
			1948	—	47.0	Topo 1:100,000	Lehmkuhl (2012)
			1948, 1950	29	45.2	Topo 1:100,000	Lehmkuhl (1998)
			1948, 1950	—	44.8	Topo 1:100,000	Lehmkuhl (1999)
			1968	—	43.0	Topo 1:100,000	Kadota and Davaa (2004)
			1969	39	46.8	Topo 1:200,000	Khrutsky and Golubeva (2008)
			1988	—	(~34.7)	Aerial 1:44,000	Kadota and Davaa (2004)
			1988, 1991	40	44.0	Aerial 1:45,000	Klinge (2001)[1]
			1989	71	56.6	Landsat	Kamp and Pan (in prep.)[3]
			1991	—	40.2	Aerial 1:45,000	Lehmkuhl (1999)
			1991	34	35.5	Aerial 1:45,000	Jansen (2010)
			1991	40	33.8	Aerial 1:45,000	Lehmkuhl (2012)
			1992	—	51.0	Landsat	Davaa and Basandorj (2005)
			1992	39	38.6	Landsat	Khrutsky and Golubeva (2008)
			2000	—	34.7	Landsat	Kadota and Davaa (2004)
			2001	51	39.8	Landsat	Kamp and Pan (in prep.)[3]
			2002	—	33.8	Landsat	Davaa and Basandorj (2005)
			2002	39	33.7	Landsat	Khrutsky and Golubeva (2008)
			2010	—	31.8	Landsat	Kamp et al. (2013)
			2010	43	32.4	Landsat	Kamp and Pan (in prep.)[3]
Turgen-Kharkhiraa	49º41′ / 91º23′	20	1940s, 1985 (?)	26	116.7	?	Baast (1998)
			1947–1950, 1972 (?)	—	106.7	Aerial and topo	Dashdeleg (1990)
			1948	—	93.1	Topo 1:100,000	Davaa and Kadota (2009)
			1948	96	100.7	Topo 1:100,000	Lehmkuhl (2012)
			1948, 1950	58	103.7	Topo 1:100,000	Lehmkuhl (1998)
			1948, 1950	—	103.3	Topo 1:100,000	Lehmkuhl (1999)
			1969	71	95.6	Topo 1:200,000	Khrutsky and Golubeva (2008)
			1988	—	(~70.8)	Aerial 1:44,000	Kadota and Davaa (2004)
			1988, 1991	90	79.0	Aerial 1:45,000	Klinge (2001)[1]
			1989	114	111.9	Landsat	Kamp and Pan (in prep.)[3]
			1991	—	92.3	Aerial 1:45,000	Lehmkuhl (1999)
			1991	69	70.3	Aerial 1:45,000	Jansen (2010)
			1991	79	69.7	Aerial 1:45,000	Lehmkuhl (2012)
			1992	—	108.4	Landsat	Davaa and Basandorj (2005)

TABLE 1 (cont.)

Range	Coordinates (N/E)	ID in Figure 2	Year of Source	Number of glaciers	Glacierized area (km^2)	Data source	Source
			1992	68	75.2	Landsat	Khrutsky and Golubeva (2008)
			2000	—	70.8	Landsat	Kadota and Davaa (2004)
			2001	83	85.3	Landsat	Kamp and Pan (in prep.)[3]
			2002	—	65.1	Landsat	Davaa and Basandorj (2005)
			2002	67	63.0	Landsat	Khrutsky and Golubeva (2008)
			2010	—	61.8	Landsat	Kamp et al. (2013)
			2010	76	63.4	Landsat	Kamp and Pan (in prep.)[3]
Undur Khairkhan	48º21′ / 88º36′	21	1940s	29	21.1	Topo 1:100,000	Klinge (2001)[1]
			1940s, 1985 (?)	40	43.3	?	Baast (1998)
			1947–1950, 1972 (?)	—	18.6	Aerial and topo	Dashdeleg (1990)
Zagaan			1947–1950, 1972 (?)	—	5.4	Aerial and topo	Dashdeleg (1990)
Zagaan Khairkhan			1947–1950, 1972 (?)	—	4.0	Aerial and topo	Dashdeleg (1990)

[1] Glacierized area calculated using data and equation from Klinge (2001): "glacier length × 0.7 = glacier area."
[2] Only >0.5-km-long glaciers.
[3] Only glaciers/glacierized area >0.01 km^2.
[4] Only glaciers/glacierized area >0.1 km^2.

Climate and Recent Climate Change

CLIMATE

The general climate of landlocked Mongolia is extreme continental and is characterized by low temperatures, low humidity, high moisture deficit, and low levels of incident energy (Batjargal, 1997). In general, the temperatures increase and the humidity decreases from north to south across Mongolia (An et al., 2008). The mean annual temperature is 0.7 °C, and the temperatures fluctuate over a wide range both seasonally (up to 50 °C) and diurnally (up to 30 °C). In the valleys of the Altai, Khangai, Khuvsgul, and Khentii Mountains, the mean monthly temperature is −30 to −34 °C in January and less than 15 °C in July (Batima et al., 2005). For Ulaangom (939 m a.s.l.; 49°55′N, 92°03′E), located in a basin northeast of the Turgen-Kharkhiraa Mountains (Fig. 1, #20 in Fig. 2), the measured mean annual temperature is −4 °C, and the mean monthly temperature ranges between −32 °C in January and 19 °C in July (Jansen, 2010).

In general, Mongolia's climate is controlled by the Westerlies, which bring precipitation from the Atlantic and the Mediterranean in summer, rather than by the South Asian monsoon, which is partially blocked by the Karakoram and Himalaya (Gillespie et al., 2003). The varying influence of these two systems results in decreasing precipitation from west to east across Mongolia (Lehmkuhl et al., 2004). Average annual precipitation is only 230 mm a^{-1} countrywide, ranging from less than 50 mm in the Gobi Desert to more than 500 mm in some locations in the north; it is concentrated in summer, and less than 10% occurs during the cold season (Batjargal, 1997). In Ulaangom (Fig. 1), the measured mean annual precipitation is 136 mm a^{-1}, with a "rainy season" from June to September (Jansen, 2010) (Table 2). Although annual precipitation is low, its intensity is high, and a rainstorm of 40 to 65 mm may fall in a single hour (Batima et al., 2005). Approximately 90% of the fallen precipitation evaporates back into the atmosphere; of the remaining 10%, 64% becomes surface runoff and only 36% infiltrates the soil (Batjargal, 1997). Winter weather conditions are dominated by the Mongolian anticyclone and are characteristically dry and cold with infrequent precipitation and drying winds, so that fallen snow sublimates rapidly (Khrutsky and Golubeva, 2008). In the Khangai, Khuvsgul, and Khentii Mountains, the mean annual precipitation is 300 to 400 mm a^{-1} (Batima et al., 2005), and in the mountains above 2500 m a.s.l., winter precipitation from snow amounts to 400 to 500 mm a^{-1} (Khrutsky and Golubeva, 2008).

Snowfall contributes less than 20% of the total annual precipitation in Mongolia (Batima et al., 2005). The first snowfall usually occurs sometime between the middle of October and beginning of November, and in the Altai Mountains it often persists as snow cover until late April. In mountainous regions, the duration of stable snow cover is 120 to 150 days (Institute of Meteorology and Hydrology, 1989). The maximum snow depth occurs in January, while the main ablation period is March (Shinoda et al., 2001; Morinaga et al., 2003). In their analysis of data from 1960 to 1992 from 23 climate stations throughout Mongolia, Morinaga et al. (2003) observed the largest snow depth in Ulaangom and found a strong negative correlation for snow depth and temperatures, especially in November and December, which is likely to cause—in combination with economic reasons such as overgrazing—severe mid-winter anomalous snow depth that leads to a significant loss of livestock (so-called white dzud).

TABLE 2

Mean monthly and annual climate data in Ulaangom and the Turgen-Kharkhiraa Mountains (TKM), northern Altai of Mongolia. Abbreviations: haP day^{-1} = hectare Pascals per day; kWh m^{-2}= kilowatt-hours per square meter; m s^{-1}=meters per second; mm °C^{-1} day^{-1}= millimeters per degree Celsius per day. Modified from Jansen (2010).

	Elevation (m)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (ºC)														
Ulaangom[1]	939	−32.4	−29.7	−18.7	−0.4	11.4	17.4	19.1	16.8	10.1	0.4	−10.7	−25.6	−3.5
TKM Recent ice margin[2]	3196	−25.0	−22.9	−15.1	−4.7	3.3	7.0	8.0	6.9	2.2	−4.6	−13.2	−22.9	−6.8
TKM Glacier elevation index[2]	3511	−24.0	−22.0	−14.6	−5.3	2.1	5.6	6.5	5.5	1.1	−5.3	−13.5	−22.5	−7.2
TKM[3]	3825	−23	−21	−14	−6	1	4	5	4	0	−6	−14	−22	−8
Precipitation (mm)														
Ulaangom[1]	939	2.0	1.9	3.6	3.5	6.7	26.6	36.0	23.8	15.3	4.3	7.4	5.3	136.4
TKM[2]	3511	8	8	15	15	83	103	116	106	57	25	43	22	601
Relative Humidity (%)														
Ulaangom[1]	939	73	73	76	51	40	43	41	55	54	62	76	76	61
Water Vapor Pressure Deficit (haP day^{-1})														
Ulaangom[1]	939	0.11	0.14	0.33	2.91	8.1	11.34	10.85	8.62	5.69	2.39	0.65	0.18	4.27
TKM Recent ice margin[2]	3196	1.11	1.17	2.03	3.88	6.79	8.97	8.98	7.44	5.86	3.28	1.93	1.29	---
TKM Glacier elevation index[2]	3511	1.20	1.20	1.98	3.70	6.57	8.62	8.67	7.10	5.78	3.26	1.97	1.37	---
Total Insolation (kWh m^{-2})														
Ulaangom[1]	939	42	68	125	150	185	188	176	154	120	80	40	33	1359
TKM Recent ice margin[2]	3196	59	85	187	206	259	266	241	216	165	112	62	50	1908
TKM Glacier elevation index[2]	3511	61	87	200	213	268	284	250	229	170	115	64	52	1993
Diffuse Radiation (kWh m^{-2})														
Ulaangom[1]	939	17	19	32	59	77	80	79	59	46	32	20	15	536
Wind Speed (m s^{-1})														
Ulaangom[1]	939	0.8	1.0	1.5	2.6	3.0	2.7	2.4	2.3	2.3	2.0	1.6	1.1	1.9
TKM Recent ice margin[2]	3196	5.5	5.8	6.3	7.3	6.4	5.9	5.4	4.8	5.3	6.3	6.7	6.1	6.0
TKM Glacier elevation index[2]	3511	6.5	6.8	7.5	8.5	7.7	6.9	6.3	5.6	6.1	7.3	7.9	7.2	7.0
Positive Degree Days per Day (mm ºC^{-1} day^{-1})														
TKM Recent ice margin[2]	3196	0	0	0	0	3.1	5.9	6.6	5.8	2.3	0	0	0	n/a
TKM Glacier elevation index[2]	3511	0	0	0	0	2.2	4.8	5.5	4.7	1.4	0	0	0	n/a
Positive Degree Days per Month (mm ºC^{-1} day^{-1})														
TKM Recent ice margin[2]	3196	0	0	0	0	95.3	175.5	204.6	179.0	67.5	0	0	0	n/a
TKM Glacier elevation index[2]	3511	0	0	0	0	67.4	144.0	169.7	146.5	42.8	0	0	0	n/a

[1] Calculated data for the period 1952–1995 from Jansen (2010) based on measured weather station data.
[2] Modeled data from Jansen (2010).
[3] Modeled data from Böhner (2006) in Jansen (2010).

RECENT CLIMATE CHANGE

From the 1940s until the early 1990s, the mean annual air temperature in Mongolia increased by 1.56 °C, because winter temperatures increased by 3.6 °C, spring/fall temperatures increased by 1.5 °C, while summer temperatures slightly decreased by 0.3 °C (Dagvadorj et al., 1994; Yatagai and Yasunari, 1994; Dagvadorj and Mijiddorj, 1996; Dagvadorj and Batjargal, 1999; Batima and Dagvadorj, 2000). Batima (2006) extended the time period into the 21st century; he presented an even higher temperature rise of 1.8 °C, with definite warming trends from the beginning of the 1970s intensifying toward the end of the 1980s. The Ministry of Nature, Environment and Tourism (2009) of Mongolia reported 2.14 °C of warming over the last 70 years. This general trend of temperature increase in Mongolia is slightly above the general trend in the Northern Hemisphere (Jacoby et al., 1996, 1999) (Fig. 3). Among the 10 hottest years since the 1940s, 8 occurred after 1995 (Davaa and Kadota, 2009). Batima et al. (2005) calculated that the period 1940 to 2001 had 30 intervals of positive temperature anomaly compared to the normalized anomalies of mean annual temperatures for Mongolia, of which 23 cases occurred after 1970. Furthermore, all 8 intervals that exceeded a 1 °C anomaly occurred after 1990, including 1997, 1998, and 1999. Figure 4 illustrates the temperature trend from 1910 to 2001. Batima et al. (2005) also documented that the number and duration of hot days is increasing, and that the Heat Wave Duration (HWD) increased by 8 to 18 days per year depending on location. The greatest annual HWD increases of 15 to 18 days occurred in the Khan-Khokhii Mountains of the Great Lakes Basin region and in the western part of the Khangai Mountains, while in the Altai Mountains and the Khentii Mountains it increased by 10 to 12 days. In 1998, the warmest year of the last century in Mongolia, the HWD lasted 70 days in high mountain areas and was followed by severe droughts from 1999 to 2002, which affected 50 to 70% of Mongolia's territory. Each of the three summers of drought was followed by a severe dzud—the three most severe ones in recorded history (Natsagdorj, 2002). In contrast, Batima et al. (2005) also showed that the Cold Wave Duration (CWD) has shortened by 13 days per year on average; the highest decrease of 20 days occurred in the Khangai Mountains. However, besides the general warming trend in Mongolia, Morinaga et al. (2003), who analyzed data from 23 climate stations across Mongolia, could not identify any statistically significant trend in the development in normalized snow depth in winter from 1960 to 1992. With regard to this general warming trend for all of Mongolia, Batima et al. (2005) pointed out that such temperature changes varied both in space and time: from 1961 to 2001 the warming was 4 °C in winter and 0.9 °C in summer in Khovd in the Altai Mountains, but only 0.8 °C in winter and 0.5 °C in summer in Dalanzadgad in the southern Gobi (Fig. 1).

For all of Mongolia, Jacoby et al. (1999) observed a slight increase in mean annual precipitation from 1940 to 1995. When analyzing data from 1941 to 2001, Batima et al. (2005) found (i) a slight increase in mean annual precipitation from 1940 to the late 1960s/early 1970s followed by a slight decrease until 2001 (Fig. 5); and (ii) a slight increase (4 to 9%) in autumn and winter precipitation and a slight decrease (8 to 10%) in spring and summer precipitation. However, both groups concluded that these statistically insignificant changes are within the range of long-term decadal variations. At the same time, Batima et al. (2005) documented that changes in precipitation had a localized character; for example, from 1971 to 2001 precipitation decreased by 30 to 90 mm on the northeastern slopes of the Khangai Mountains and western slopes of the Khentii Mountains and increased by 2 to 60 mm in the Altai Mountains and on the

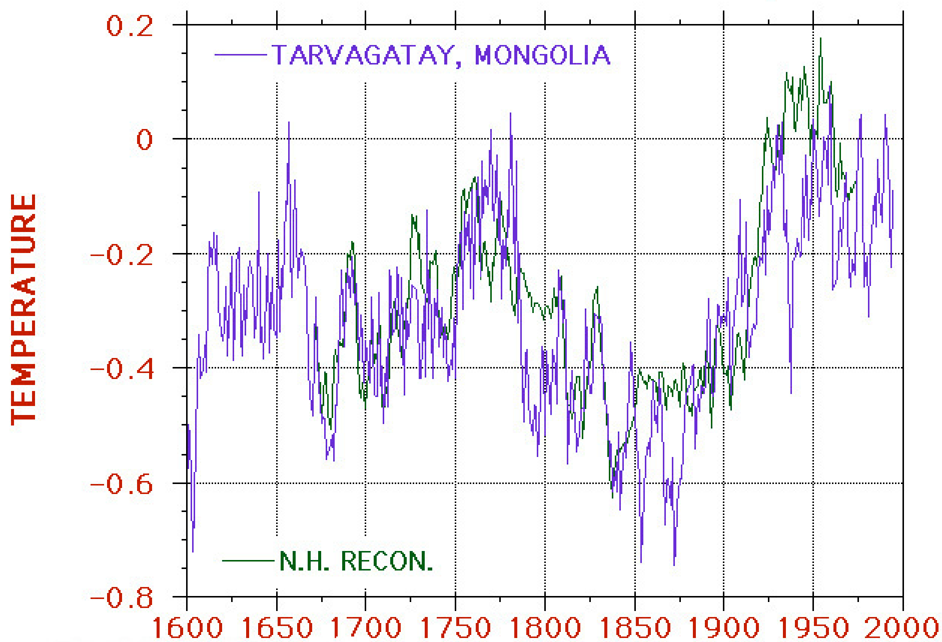

FIGURE 3. Temperature reconstructions from 1600 to 2000 for the Northern Hemisphere (green line) and Mongolia (blue line). From Jacoby et al. (1996).

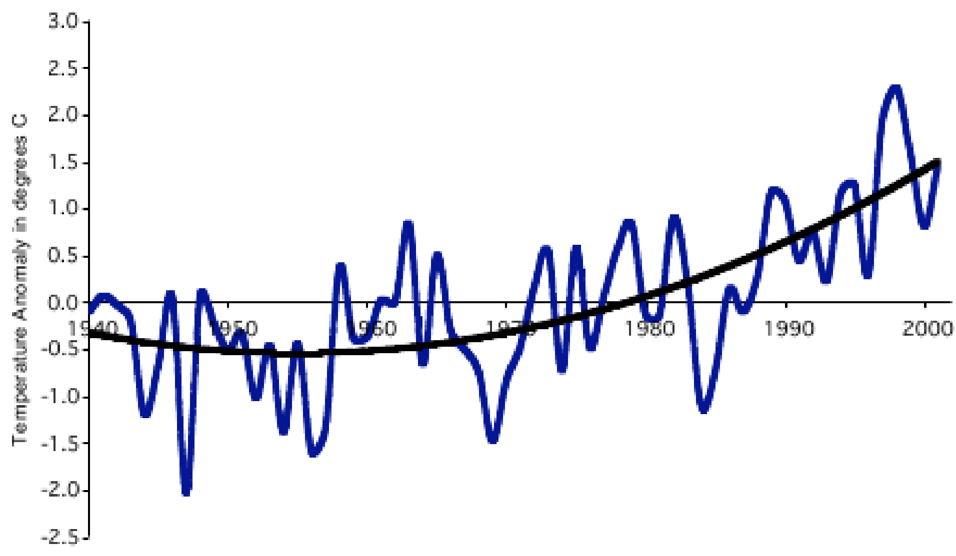

FIGURE 4. Temperature trend from 1940 to 2001 in Mongolia. The blue line is normalized anomalies of air temperature. The black line is a second order polynomial. From Batima et al. (2005).

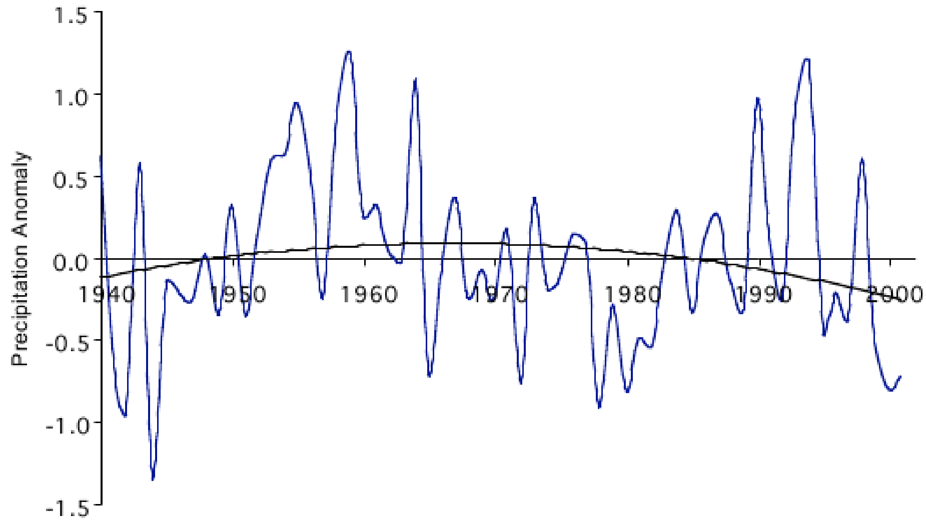

FIGURE 5. Normalized anomalies of mean annual precipitation from 1941 to 2001 in Mongolia. The blue line is normalized anomalies of precipitation. The black line is a second order polynomial. From Batima et al. (2005).

western slopes of the Khangai Mountains. Furthermore, this climate record showed that the first significant snowfall of autumn tends now to occur earlier, while the last snowfall that occurs at the end of spring or the beginning of summer tends to last longer; at the same time the extent of snow cover was unchanged (Batima et al., 2005; Batima, 2006).

Depending on the scenario (SRES A2 and SRES B2), existing climate change models showed a temperature rise of 2 to 8 °C above 2000 temperatures until 2099 for Mongolia, both in summer and winter (Batima et al., 2004). Batima (2006) summarized climate change projections from several models under SREA A2 and B2 scenarios for 33-yr time slices, centered in the 2020s, 2050s, and 2080s, each relative to the climatological baseline period 1961 to 1990; the models suggest a future winter warming of 0.9 to 8.7 °C and a summer warming of 1.3 to 8.6 °C; a precipitation change by −3 to 11% in summer, and by 13 to 119% in winter; a snow cover decrease by 27 to 51%; and an evapotranspiration increase by 13 to 91%. However, general precipitation is relatively low, so that such changes reflect relatively small changes in absolute precipitation (Batima et al., 2004).

For the Great Lakes Basin in western Mongolia, Gomboluudev (2003) calculated the temperature and precipitation for 2020, 2050, and 2080 using two different models (ECHAM4 by Röckner et al., 1999; HadCM2 by Gordon et al., 2000) based on the IS92a scenario of the Intergovernmental Panel on Climate Change (IPCC, 1992) (Table 3). The projected temperature increases are between 2 °C in the short-term and up to 7 °C in the long-term future and are in good accordance with the countrywide estimates (Batima et al., 2004). The HadCM2 model projects a precipitation increase, while precipitation tends to decrease using the ECHAM4 model.

TABLE 3
Changes in temperature and precipitation for the Great Lakes Basin, western Mongolia, calculated from two General Circulation Models (GCMs) based on the IS92a scenario (Intergovernmental Panel on Climate Change [IPCC], 1992). Modified from Gomboluudev (2003).

Year	Temperature (°C)		Precipitation (mm)	
	HadCM2	ECHAM4	HadCM2	ECHAM4
		Annual		
2020	1.9	2.4	23.6	1.7
2050	3.2	4.4	57.1	0.3
2080	4.6	6.6	87.7	−5.7
		Summer		
2020	2.0	2.5	3.9	−0.1
2050	3.2	4.8	7.3	−15.1
2080	4.7	7.0	11.6	−21.8
		Winter		
2020	1.7	2.3	6.0	3.9
2050	3.1	4.7	14.4	11.0
2080	4.7	7.0	26.7	19.3

Khangai Mountains

The only—although today inactive—glacierized area outside the Mongolian Altai (see below) is in the Khangai Mountains, which are in the central part of western Mongolia and extend for roughly 600 km from east to west (Fig. 1). Otgon-Tenger (between 3905 m and 4031 m a.s.l., depending on the source) is the highest peak of the range and the only one that is covered by permanent snow and firn or (stagnant) ice. Baast (1998) measured a glacierized area of 0.27 km^2, without making it clear (unfortunately) if this was based on data from the 1940s or 1985.

Richter et al. (1961) calculated a recent equilibrium line altitude (ELA) of 4000 m a.s.l. in these mountains, while Lehmkuhl and Lang (2001) described two small ice fields reaching down to 3200 m a.s.l. and estimated the recent ELA to be 3700 m a.s.l.

Climate data beginning in 1960 collected in Muren, approximately 150 km north of Egiin Davaa, showed that temperatures generally increased in the Khangai Mountains with an interannual variability of 2 °C; after 2000 both mean annual temperature and summer (June to August) temperature decreased (Stratton, 2007). Batima et al. (2005) found that annual precipitation decreased by 30 to 90 mm from 1941 to 2001. Since the mid-1990s, below-average flows were observed for the rivers draining from the Khangai Mountains into the Great Lakes Basin (Batima et al., 2004).

Mongolian Altai

Besides the few inactive, small ice fields in the western Khangai Mountains described above, the Mongolian Altai (also “Ektag Altai” = “White-peaky Altai”; Fig. 1; Table 1) is the only glacierized region in Mongolia. The Altai extends for roughly 1300 km from the northwest Mongolian-Russian border to the southeast along the Mongolian-Chinese border before turning east and terminating within the Gobi Desert. Khuiten Peak (4374 m a.s.l.) in the Tavan Bogd Range in the far west is the highest peak in Mongolia.

Based on analysis of climate data from nearby weather stations, Khrutsky and Golubeva (2008) noted that in the mountains the general wind patterns are complicated by local air currents, particularly by westerly anticyclonic winds from Kazakhstan and Middle Asia, which can result in abrupt increases of air temperature. They further showed that northern slopes have, relatively, the highest moisture content resulting in more extensive glacierization, and they also concluded that avalanches play only a very minor role in the accumulation of snow on the glaciers. Baast (1998) noted that the general climate conditions in which the Mongolian Altai glaciers exist are probably the strongest of the continental type in the world: the mean annual temperature is below −8 °C; winter temperatures are −20 to −30 °C, and summer temperatures are up to 20 °C; the mean annual precipitation is up to 700 mm. About 70% of the annual precipitation occurs in summer from June to August (Kadota and Davaa, 2007). Direct weather measurements on Mongolian glaciers are rare. Davaa et al. (2008) installed an automated weather station (Aanderaa) at 3600 m a.s.l. at the edge of a flat-top glacier in the Tsambagarav Range (#16 in Fig. 2; Fig. 6) and measured global radiation, air and soil surface temperatures, air humidity, and wind speed and direction between July 2004 and August 2005. They documented an extreme continental climate with daily average air temperatures that did not exceed 10 °C. The calculated ablation rates were relatively low: 54 cm in 2004 and 89 cm in 2005. Schotterer et al. (1997) presented data from ice-core drilling at an elevation of 4000 m at the Tsast Uul ice cap west of Tsambagarav in June 1991: the glacier-ice temperature at 5 m below the surface was −18 °C, and the mean annual accumulation rate was 25 cm water equivalent (w.e.).

Glaciers occur on the highest peaks above the main leveling surface in the central part of various mountain systems within the Mongolian Altai; besides plateau glaciers and cirque glaciers, many isolated ice patches exist (Klinge et al., 2003). At present, it is uncertain how many glaciers exist there and how much area they cover. In the scientific literature, for individual years between the 1940s and (probably) 2000, the number of glaciers/glacierized locations varied between 120 and 731, and the ice-covered area varied between 328 and 659 km^2 (Table 1). The following is a summary of data for glaciers in the Mongolian Altai from these various glacier surveys.

Based on data from 1947 to 1950 and 1972, Dashdeleg et al. (1983) and Dashdeleg (1990) put the total number of glaciers at 187 and 186, respectively, covering a total area of 540 km^2. For 1948/1950, Lehmkuhl (1998) determined the glacier area covered more than 300 km^2. For the 1940s or 1985 (not clear from the publication), Baast (1998) identified 262 glaciers, of which 60% were smaller than 1 km^2, covering an area of 659 km^2 and estimated a glacier thickness of 5 to 185 m, with an average of 30 m. Based on material from the 1940s, 1980s, and 1990s, Klinge (2001) published one of the most extensive glacier mapping studies for the

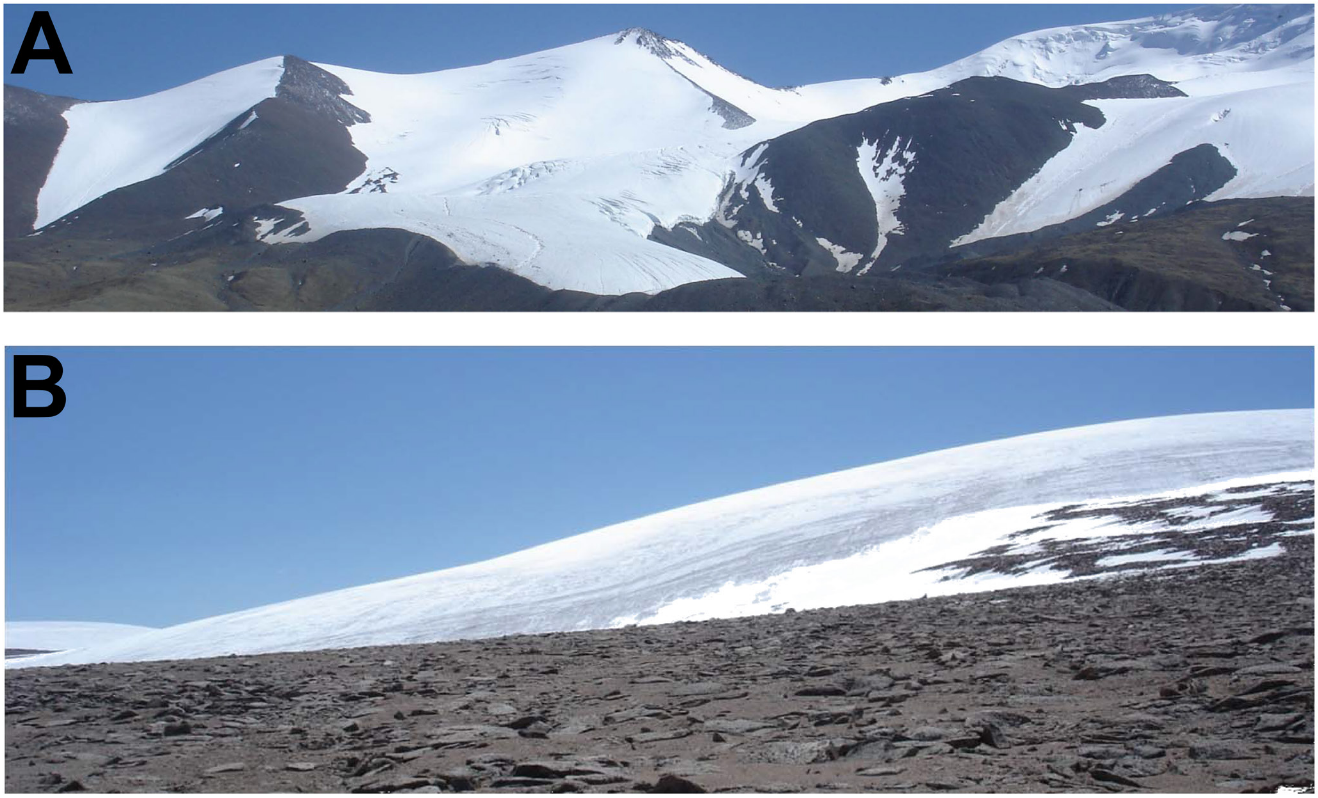

FIGURE 6. Ground photographs of two glaciers in the Tsambagarav Range, Mongolia: (A) Northern Slope Glacier; and (B) Flat Top Glacier. From Davaa and Kadota (2009).

Mongolian Altai and identified 731 glaciers and glacierized locations covering 655 km^2 in the 1990s; although the author's higher total "glacier" number does not agree with the one presented by Baast (1998), the total glacierized area matches almost exactly. For 1971/1972, Selivanov (1972) counted 120 glaciers between 0.5 and 20 km in length and measured a glacier area of 328 km^2. For 1999 to 2002, Ohata et al. (2009) and Yabouki and Ohata (2009) counted around 580 and 578 glaciers, respectively, with both surveys covering 423 km^2, which is roughly 24% of the Mongolian Altai. Enkhtaivan (2006)—without giving the reference year—counted around 250 glaciers and calculated a glacier area of 514 km^2. She also listed the following main glacier aggregations: Katunsky Ridge including Sapozhnikova, Great Berelsky, Gebler, and Rodzevich Glaciers; North-Chuysky Ridge including Great Maashei, Left Aktru, and Right Aktru Glaciers; South-Chuysky Ridge including Sofiisky and Great Taldurinsky Glaciers; and Tabyn-Bogdo-Ola Massif. In the new GLIMS glacier inventory for Mongolia, Kamp and Pan (in prep.) present the following information based on the analysis of Landsat imagery: in 1989–1991, 691 glaciers covered 541 km^2; in 1998–2000, 716 glaciers covered 429 km^2; and in 2010–2011, 670 glaciers covered 372 km^2.

Walter and Breckle (1994) classified 70 of the glaciers in the Mongolian Altai as being large—unfortunately, these authors did not define "large." The 11-km-long Potanin Glacier, the largest glacier in Mongolia, is found in the Tavan Bogd Range and has a surface area of 43 km^2 (Kadota and Davaa, 2007) (#15 in Fig. 2; Figs. 7 and 8).

The total number of glaciers can be divided into three different types: 75% mountain-slope glaciers, 21% valley glaciers, and 4% flat-top glaciers (Batima et al., 2004). Baast (1998) noted that the mountain glaciers are of the deep-freeze cold type and form at elevations from 2800 to 4374 m a.s.l. According to Klinge (2001) and Klinge et al. (2003), the generally decreasing precipitation from west to east results in a 600 m rise of the snowline from 3200 m a.s.l. in the northwestern Altai to more than 3800 m a.s.l. in the southeastern part.

In the alpine zone of the Mongolian Altai, climate data from several weather stations showed that precipitation, particularly in winter, decreased for the last several decades, while temperatures increased by 1.1 to 1.7 °C (Khrutsky and Golubeva, 2008). Khrutsky and Golubeva (2008) explained that summer was characterized by an enhancement of cyclogenesis processes with the highest frequency of occurrence of cyclones in July, making it the month with maximum precipitation, largely as snow. They concluded that climate warming with decreased winter precipitation had caused a general recession of the glacierized area since the middle of the 20th century, although phases of local glacier stagnation were recorded. However, this general trend of negative glacier mass balances has continued into the 21st century.

Klinge (2001) compared topographic maps from the 1940s, aerial photographs from the 1980s, and field observations from 1997 and 1998; he concluded that, in general, the glacierized area in the Mongolian Altai has decreased. Baast (1998) put the loss in glacial area at 6.4% and the loss in glacial ice volume at 4.6% from the 1940s until 1985. However, Ohata et al. (2009) gave a much higher number of 30% ice-area loss from the 1950s until 2000. Also Kadota and Davaa (2004, 2007) measured a general loss in area of 91 glaciers in several locations since the 1940s; however, they also noticed that the general recession varied considerably between individual glaciers and between regions, and that many of the glaciers had been stagnant since the early 1960s or late 1980s. Kamp and Pan (in prep.) found the following decrease in glacial area: −21% from 1990 to 2000, −13% from 2000 to 2010, and −31% from 1990 to 2010.

TURGEN-KHARKHIRAA MOUNTAINS

The Turgen-Kharkhiraa Mountains (Figs. 1 and 9; #20 in Fig. 2; Table 1) in the northern part of the Mongolian Altai represent two neighboring mountain systems that formed during the Variscan (Hercynian) orogeny (late Paleozoic Era): Turgen Nuruu (with a summit elevation between 3954 and 3978 m a.s.l. depending on the source) and Kharkhiraa Uul (with a summit elevation between 4037 and 4040 m a.s.l. depending on the source) (Lehmkuhl, 1999; Khrutsky and Golubeva, 2008). They extend over approximately 20 km in a northwestern direction from Lake Khara-Us Nuur to the Mongun-Taiga mountain group. In the west the mountains border the Achit Nuur–Ureg Nuur systems of hollows; in the east, the Great Lakes Basin. During a period of intense tectonic uplift that continued throughout the Quaternary, the mountains were shaped mainly by glacial and fluvial erosion (Khrutsky and Golubeva, 2008). The general morphology of the entire mountain system results in relatively high ablation rates on southern and western slopes, and relatively low ablation rates on northern and eastern slopes.

Weather stations do not exist within the Turgen-Kharkhiraa Mountains; thus, climate data series are not available. However, Khrutsky and Golubeva (2008) estimated that above an elevation of 2500 m a.s.l. the mean annual solid precipitation is 400 to 500 mm. Using climate data from weather stations in the surroundings of the mountains, Böhner (2006) interpolated temperature data at an elevation of 3825 m a.s.l. in the summit region: the mean annual

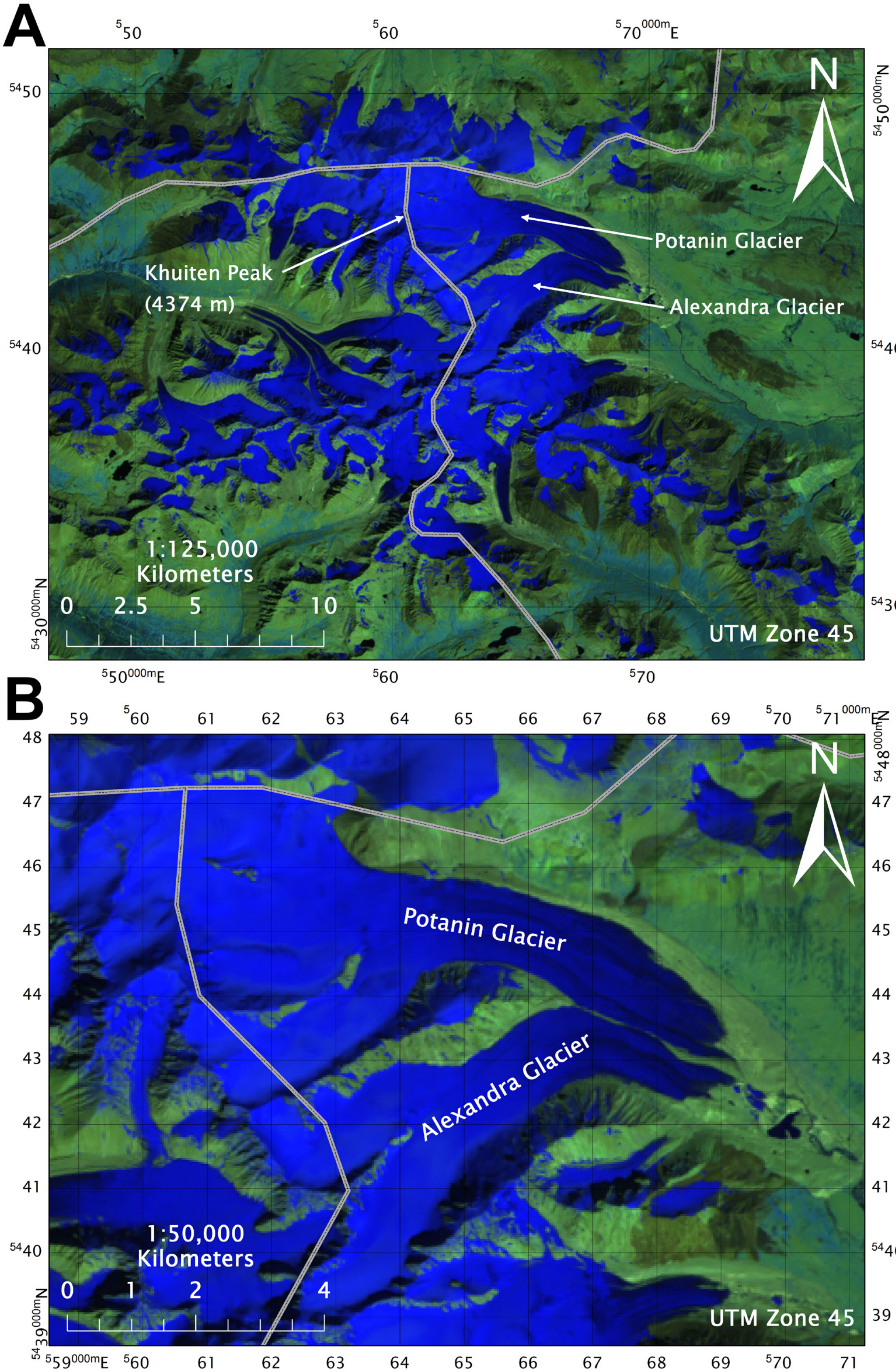

FIGURE 7. (A) Landsat 5 image of the Tavan Bogd Range, Mongolian Altai Mountains; and (B) enlargement of Landsat 5 image centered on the Potanin Glacier. In the false-color composite image (bands 4, 5, 7), glaciers are dark blue. Dotted line represents international borders (LT51430262010232IKR00, 20 August 2010).

FIGURE 8. Ground photograph of the Potanin Glacier (right) and Alexandra Glacier (left), Tavan Bogd Range, Mongolian Altai Mountains. Khuiten Peak, at 4374 m a.s.l. the highest peak in Mongolia, is in the center in the background. From Davaa and Kadota (2009).

temperature is −8 °C, and the mean monthly temperature ranges between −23 °C in January and 5 °C in July (Table 2).

The most detailed study is from Jansen (2010), who used climate data from 1952 to 1995 collected at the weather station in Ulaangom (Fig. 1) to model climate parameters for the Turgen-Kharkhiraa Mountains (Table 2) and concluded that, in winter, inversions are common with temperature increases of up to 2 K 100 m^{-1}; hence, the Turgen-Kharkhiraa Mountains represent a "heat island" compared to the basin. The following data from Jansen (2010) characterize the climate of the Turgen-Kharkhiraa Mountains. The mean annual precipitation at the ELA (3511 m a.s.l.) was 601 mm, ranging from 8 mm in January and February to 116 mm in July. The mean annual temperature at the ELA was −7.2 °C, ranging from −24.0 °C in January to 6.5 °C in July. The mean annual temperature at the recent glacier-margin altitude (here: GMA; 3196 m a.s.l.) was −6.8 °C, ranging from −25.0 °C in January to 8.0 °C in July. The mean annual total insolation at the GMA was 190.8 kWh m^{-2}, ranging from 50 kWh m^{-2} in December to 266 kWh m^{-2} in June. The mean annual total insolation at the ELA was 199.3 kWh m^{-2}, ranging from 52 kWh m^{-2} in December to 284 kWh m^{-2} in June. The mean annual wind speed at the GMA was 6.0 m s^{-1}, ranging from 4.8 m s^{-1} in August to 7.3 m s^{-1} in April. The mean annual wind speed at the ELA was 7.0 m s^{-1}, ranging from 5.6 m s^{-1} in August to 8.5 m s^{-1} in April.

Probably because of location and ease of access, the Quaternary glaciations and modern glaciers in the Turgen-Kharkhiraa Mountains are relatively well studied. One of the most detailed such studies is from Khrutsky and Golubeva (2008), who stated that these mountains represent a significant center of glacierization in the Altai Mountains that is not exceeded in area by any other glacierized basin (e.g., Tsast-Ula, Munkh Khairkhan, and Delyun Ranges).

The first Western descriptions of glaciers in the Turgen-Kharkhiraa Mountains were given by Potanin (1914), Carruthers (1911, 1912, 1914a, 1914b), and Price (1968). During a Russian expedition from 1876 to 1879, Potanin mapped the eastern slopes of the mountains. Great Britain's Carruthers and Price were part of a Royal Geographical Society expedition to Mongolia in 1910. The explorers produced a detailed topographic map and also documented the areal extent of glaciers with photographs. In his Unknown Mongolia, expedition leader Carruthers (1914a, pp. 276–277) described the range as the expedition approached it from the north 100 years ago:

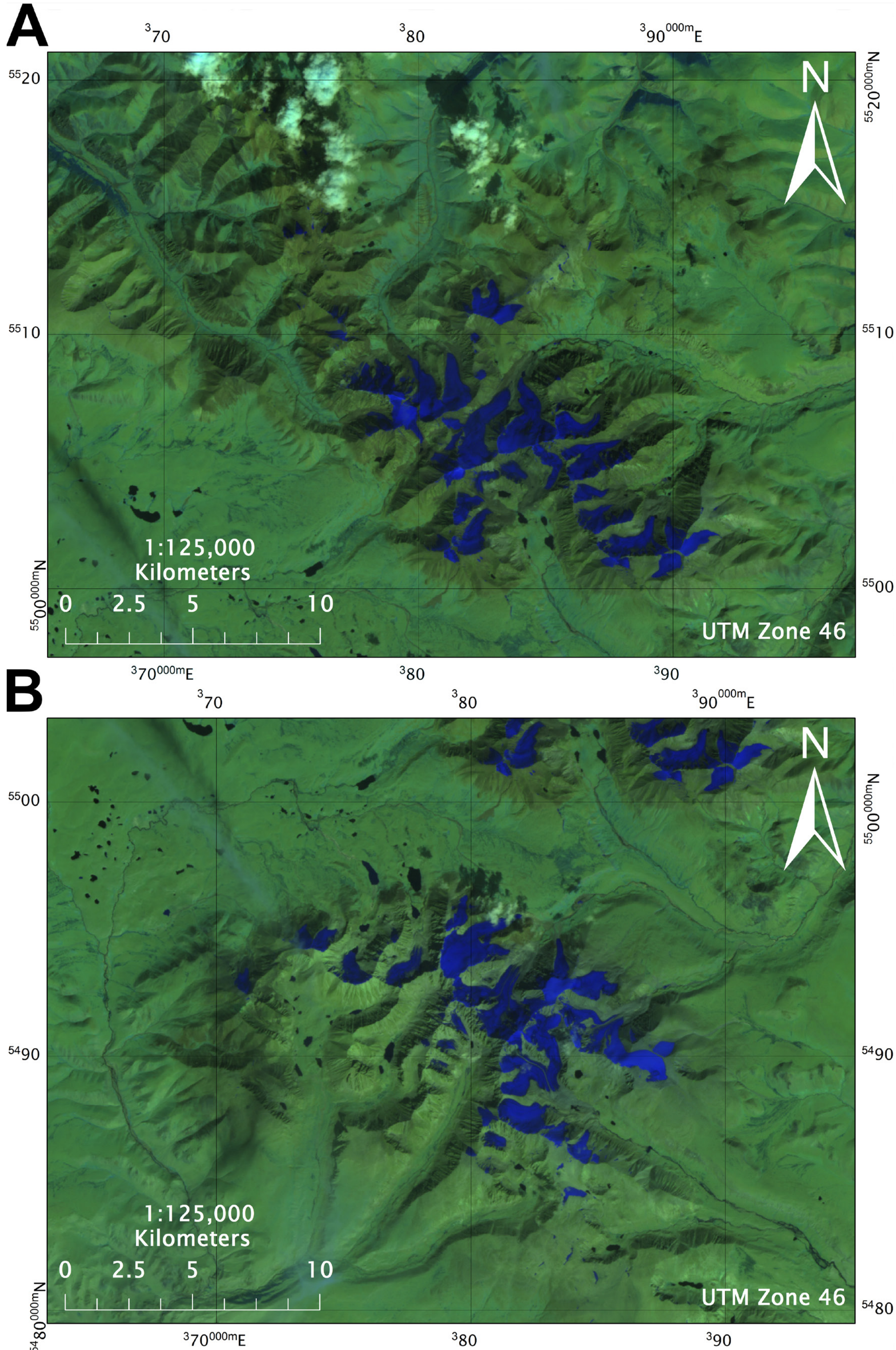

FIGURE 9. Landsat 5 image of the Turgen-Kharkhiraa Mountains, Mongolian Altai Mountains: (A) Turgen Range; and (B) Kharkhiraa Range. In the false-color composite image (bands 4, 5, 7), glaciers are dark blue (LT51420252010241IKR00, 29 August 2010).

> With superb grandeur the snow pinnacles rise above the forested valleys and grassy plateaux. From every point of the compass, for many days' journey away, one can see the principal peak, a cone of ice, which rises to over 13,000 ft. in altitude. […] As a snow-capped mountain of alpine character, the Turgen stands solitary, rising sharply above the steppes and the desert-ranges which surround it on all sides.

In one of his other publications from this expedition, Carruthers (1914b, p. 383) also described the general precipitation conditions as particularly remarkable:

> We were on the range in mid-August, the period of the highest snow-line. […] It should be understood, however, that the precipitation on these particular mountains is phenomenal, and cannot be taken as typical of Northern Mongolia in general. […] The snowfall is great, mist and cloud envelop the ranges during the summer, and thus the snow-fields and glaciers are preserved.

In the literature the proposed number of glaciers and glacierized area in the Turgen-Kharkhiraa Mountains are as follows (Table 1). For example, for 1948/1950, Lehmkuhl (1998, 1999) counted 58 glaciers covering an area of 103.5 km^2 and noted that most of the glaciers are in the area surrounding the highest peaks. However, also for 1948/1950, Lehmkuhl (2012) identified 96 glaciers covering an area of 100.7 km^2. For 1969, Khrutsky and Golubeva (2008) put the number of glaciers at 71 and the glacier area at 95.6 km^2. Kamp and Pan (in prep.) report that 114 glaciers covered 111.9 km^2 in 1989. Varying numbers were presented for 1991, although analyses used the same source material: Lehmkuhl (1999) presented 92.3 km^2 of glacier area; Klinge (2001) counted 90 glaciers/glacierized areas and measured a glacier area of 79 km^2; Jansen (2010) identified 69 glaciers/glacierized areas covering 70.3 km^2; and Lehmkuhl (2012) mapped 79 glaciers and 69.7 km^2 of glacier area. Davaa and Basaandorj (2005) reported a glacierized area of 108.4 km^2 in 1992. Kamp and Pan (in prep.) show that 83 glaciers covered 85.3 km^2 in 2001. For 2002, Khrutsky and Golubeva (2008) identified 67 glaciers covering an area of 63 km^2. For 2010, Kamp et al. (2013) put the glacierized area at 61.8 km^2 and Kamp and Pan (in prep.) report that 76 glaciers covered 63.4 km^2. These fluctuating numbers—even for the same year of investigation—from the existing literature only confirm that extreme caution must be used when interpreting and applying results from glacier mapping and monitoring analyses.

For 1991, Lehmkuhl (1998) reported that the ELA was at 3520 m a.s.l. and in the Turgen Range (#19 in Fig. 2), small valley glaciers up to 7 km long terminated at 2800 m a.s.l. on northern slopes and were often debris covered in their ablation zones, while on southern slopes mainly ice fields and hanging glaciers occurred; in the southern part of Kharkhiraa Range (#6 in Fig. 2), small plateau glaciers existed. Khrutsky and Golubeva (2008) calculated a GMA of 3290 m a.s.l. and an ELA of 3490 m a.s.l. for the Turgen Range; in the Kharkhiraa Range it was 3340 m and 3500 m a.s.l., respectively (Table 4). Most of the glaciers in the two mountain ranges were of valley, "near-slope," and "hanging" type, and were located in elevated flat or smoothed dome-shaped watersheds. While no complex-valley glaciers were recorded in the Turgen Range, cirque glaciers were more common in the Kharkhiraa Range; in both ranges the largest were valley glaciers. Furthermore, Khrutsky and Golubeva (2008) reported that in the Turgen Range 39 glaciers covered an area of 33.7 km^2, of which 25 glaciers (64%), or 25.6

TABLE 4
Characteristics of glaciers in the Turgen-Kharkhiraa Mountains in the northern Altai of Mongolia for 1969, 1992, and 2002. The decision for the identification of the three investigated years was based on availability of data from topographic maps and satellite imagery. Modified from Khrutsky and Golubeva (2008). Glacier coefficient = ratio of the accumulation area to the ablation area of a glacier.

Year	Aspect	Number of glaciers	Weighted mean indices: Area (km^2)	Length (km)	Changes in length (m a^{-1})	Glacier margin altitude (m)	Snow line altitude (m)	Glacier coefficient
				Turgen				
1969	Northern	15	1.45	2.11	n/a	3180	3460	—
1992		15	1.33	1.71	−17.4	3195		1.04
2002		15	1.01	1.60	−4.8	3240		—
1969	Eastern	10	1.47	1.86	n/a	3260	3497	—
1992		10	1.16	1.46	−17.6	3276		0.90
2002		10	1.02	1.40	−2.6	3290		—
1969	Southern and Western	14	0.97	1.57	n/a	3285	3510	—
1992		14	0.56	1.23	−14.8	3310		0.60
2002		14	0.53	1.04	−7.8	3340		—
				Kharkhiraa				
1969	Northern	16	2.10	1.97	n/a	3200	3490	—
1992		16	1.60	1.83	−6.1	3230		0.68
2002		16	1.32	1.47	−15.6	3270		—
1969	Eastern	8	0.90	1.40	n/a	3240	3500	—
1992		8	0.84	1.07	−14.3	3320		1.20
2002		7	0.78	1.00	−21.3	3370		—
1969	Southern and Western	8	0.64	1.30	n/a	3280	3515	—
1992		5	0.23	0.69	−26.5	3350		0.40
2002		5	0.16	0.50	−8.2	3385		—

km^2 (76%) of the glacierized area, were located on northern and eastern slopes, and 14 glaciers (36%), or 8.1 km^2 (24%) of the glacierized area were located on southern and western slopes.

Khrutsky and Golubeva (2008) also presented data for glacier-ice volumes and ablation rates at the ELA for 2002 (Table 5): in the Turgen Range the ice volume was 1.51 km^3 and the ablation rate was 3.47 m a^{-1}; in the Kharkhiraa Range it was 1.07 km^3 and 3.65 m a^{-1}. Most of the ice (50%) was stored in valley glaciers, followed by “near-slope” glaciers (23%), complex-valley glaciers (14%), cirque and cirque-valley glaciers (7%), and “hanging” glaciers (6%).

Another detailed study on climate and glaciers was presented by Jansen (2010), who classified 77% of all glaciers in the Turgen-Kharkhiraa Mountains as valley glaciers (82% in the Turgen Range, 71% in the Kharkhiraa Range); 60% of all glaciers were oriented towards northern directions and 18% towards southern directions (55% and 26% in the Turgen Range, 62% and 11% in the Kharkhiraa Range). Jansen (2010) explained that this preferred glacier occurrence for northern aspects is a result of lower insolation and advective precipitation at the Tien Shan front. Based on climate parameters that were modeled from weather station data from Ulaangom from 1952 to 1995 (see above), Jansen (2010) presented the following modeled glacier and snow characteristics (Tables 6 and 7). In the Turgen Range the GMA was 3196 m a.s.l., and the ELA was 3511 m a.s.l.; in the Kharkhiraa Range it was 3254 m and 3521 m a.s.l., respectively. The mean angle of all glaciers was 23° (24° in the Turgen Range, 22° in the

TABLE 5
Glacierized area, ice volume, annual melt runoff, and their changes from 1969 to 2002 in the Turgen-Kharkhiraa Mountains in the northern Altai of Mongolia. The decision for the identification of the three investigated time periods (1969 to 1992, 1992 to 2002, and 1969 to 2002) was based on availability of data from topographic maps and satellite imagery rather than on statistical breakpoints. Modified and extended from Khrutsky and Golubeva (2008).

	Glacierized area		Ice volume		Annual melt runoff	
Year and span	km^2	percent	km^3	percent	km^3	percent
Turgen						
1969	46.8	n/a	2.62	n/a	0.16	n/a
1992	38.6	n/a	1.78	n/a	0.14	n/a
2002	33.7	n/a	1.51	n/a	0.12	n/a
1969–1992 (23)	−8.2	−17.5	−0.84	−32.0	−0.02	−12.5
1992–2002 (10)	−4.9	−12.7	−0.27	−15.2	−0.02	−14.3
1969–2002 (33)	−13.1	−28.0	−1.11	−42.4	−0.04	−25.0
Kharkhiraa						
1969	48.8	n/a	2.14	n/a	0.18	n/a
1992	36.6	n/a	1.54	n/a	0.12	n/a
2002	29.3	n/a	1.07	n/a	0.09	n/a
1969–1992 (23)	−12.2	−25.0	−0.60	−28.1	−0.06	−33.3
1992–2002 (10)	−7.3	−20.0	−0.47	−30.5	−0.03	−25.0
1969–2002 (33)	−19.5	−40.0	−1.07	−50.0	−0.09	−50.0
Turgen-Kharkhiraa						
1969	95.6	n/a	4.76	n/a	0.34	n/a
1992	75.2	n/a	3.32	n/a	0.26	n/a
2002	63.0	n/a	2.58	n/a	0.21	n/a
1969–1992 (23)	−20.4	−21.3	−1.44	−30.3	−0.08	−23.5
1992–2002 (10)	−12.2	−16.2	−0.74	−22.3	−0.05	−19.2
1969–2002 (33)	−32.6	−34.1	−2.18	−45.8	−0.13	−38.2

Kharkhiraa Range); however, cirque glaciers in the Kharkhiraa Range included one glacier with an angle of 32°. The mean annual snow accumulation was 195 mm at the GMA, 272 mm at the ELA, and 431 mm at the summit altitude (4040 m a.s.l.). The two snowy seasons were May and September to December, while almost no snow fell from June to August, with the exception of elevations above 3900 m a.s.l. The mean snow ablation was 287 mm at the GMA, 272 mm at the ELA, and 243 mm at the summit altitude. Higher ablation rates occurred from May to August, and to some degree September. The mass balance was −92 mm at the GMA, and 189 mm at the summit altitude. Negative mass-balance budgets occurred between May and August at the GMA, between June and August at the ELA, and in July at the summit altitude. When using a moderate snow density of 150 kg m^{-3}, the mean monthly snowmelt at the ELA was between 68 mm water equivalent (w.e.) in September and 140 mm w.e. in July.

The first notes on changes of glaciers in the Turgen-Kharkiraa Mountains were from Carruthers (1911), who reported that all of the documented glaciers were in a stage of retreat. Lehmkuhl (1998) estimated a general glacier retreat of 200 to 500 m from 1948 to 1991. Kadota and Davaa (2004, 2007) measured a loss in area from 1968 to 1988 (−19% in the Turgen Range, −28% in the Kharkhiraa Range), followed by stagnation until 2000. They explained this trend with climate data from Ulaangom northeast of the Turgen-Kharkhiraa Mountains: conditions

TABLE 6
Modeled mean monthly and annual snow data from 1952 to 1995 in the Turgen-Kharkhiraa Mountains (TKM), northern Altai of Mongolia. Modified from Jansen (2010).

	Elevation (m)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Snow accumulation (mm)														
Recent ice margin	3196*	7.2	7.3	13.5	13.7	25.9	0	0	0	46.7	22.4	38.6	20.0	195.3
Equilibrium line altitude	3511	7.9	8.1	14.9	15.1	78.9	0	0	0	57.0	24.9	42.9	22.0	271.7
Highest summit	4040	9.1	9.3	17.2	17.5	98.8	53.4	6.6	49.2	65.5	29.1	50.2	25.5	431.4
Snow ablation (mm)														
Recent ice margin	3196*	3.0	4.6	10.4	14.1	40.4	56.2	60.1	52.1	29.4	8.5	4.9	3.2	286.9
Equilibrium line altitude	3511	3.8	5.3	11.7	15.0	36.9	51.8	54.8	47.5	26.0	9.3	5.8	4.1	272.0
Highest summit	4040	5.3	6.6	13.9	16.7	31.2	44.4	45.9	39.6	15.3	10.8	7.4	5.7	242.8
Mass budget (mm)														
Recent ice margin	3196*	4.2	2.7	3.1	−0.4	−14.5	−56.2	−60.1	−52.1	17.3	13.9	33.7	16.8	−91.6
Equilibrium line altitude	3511	4.1	3.8	3.2	0.1	42.0	−51.8	−54.8	−47.5	31.0	15.6	37.1	17.9	−0.7
Highest summit	4040	3.8	2.7	3.3	0.8	67.6	9.0	−39.3	9.6	50.2	18.3	42.8	19.8	188.6
Snow melt (mm w.e.) #														
Equilibrium line altitude	3511	n/a	n/a	n/a	n/a	83	124	140	127	68	n/a	n/a	n/a	n/a

* The original elevation in Jansen (2010) was 3200 m. The difference of only 4 m between the two elevations was neglected in the study at hand.
# w.e. = water equivalent; based upon snow density of 150 kg m^{-3}.

were warm and dry in the 1970s but changed to cool and wet until the mid-1990s, slowing down or stopping the recession. Davaa and Basandorj (2005) supported and continued these studies and compared the areal extent of the glaciers in 2000 with those in 2002; they found that after a long phase of stagnation until 2000, the glacier areas decreased in the following two years: 0.9 km^2 (3%) in the Turgen Range and 4.8 km^2 (13%) in the Kharkhiraa Range.

In contrast, Khrutsky and Golubeva (2008) did not mention a phase of stagnation in the Turgen-Kharkhiraa Mountains since the late 1980s. For the time period 1969–2002, the authors measured a reduction in glacier area of 34% (32.6 km^2; 1 km^2 a^{-1}) and a general glacier-terminus recession of 80 to 190 m throughout those mountains; in the Turgen Range the loss in glacier area was 28% (13.1 km^2; 0.1 km^2 a^{-1}), and in the Kharkhiraa Range it was 40% (19.5 km^2; 0.1 km^2 a^{-1}) (Tables 1 and 8). Khrutsky and Golubeva (2008) also showed that the glaciers retreated at an annual average of 423 m (12.8 m a^{-1}) in the Turgen Range and 475 m (14.3 m a^{-1}) in the Kharkhiraa Range; the annual retreat was 11–15 m at "hanging" and cirque glaciers and as high as 18 m at valley glaciers. They further noted that 4 of the 32 glaciers that existed in 1969 had totally disappeared by 2002—three cirque glaciers and one "near-slope" glacier. For the Turgen-Kharkiraa Mountains, Kamp and Pan (in prep.) report a reduction in glacierized area from 1989 to 2001 by 24%, from 2001 to 2010 by 26%, and for the entire time period 1989–2010 by 43%.

Some of the camera stations, where photographs were taken by the 1910 Royal Geographical Society Expedition under the leadership of Douglas A. Carruthers, were reoccupied during a U.S.–Mongolian anniversary expedition in 2010, and the results showed a recession of valley glaciers. Kamp et al. (2013) compared the 1910 and 2010 photographs with a

TABLE 7
Modeled mean monthly snowmelt in the Turgen Mountains, northern Altai of Mongolia (in mm water equivalent (w.e.) during the "rainy season" at the equilibrium line altitude (ELA) of 3511 m). Modified from Jansen (2010).

Snow Density	May	Jun	Jul	Aug	Sep
100 kg m^{-3}	55	83	93	85	46
150 kg m^{-3}	83	124	140	127	68
200 kg m^{-3}	110	165	186	169	91

1970/1971 Soviet topographic map based on 1968 aerial photography and with Landsat imagery from 1992 and 2010, and they quantified the recession: West Turgen Glacier receded by 403 m from 1910 to 1968 (approximately 7 m a^{-1}), by 87 m from 1968 to 1992 (approximately 3.6 m a^{-1}), and by 110 m from 1992 to 2010 (approximately 6 m a^{-1}); in total, it receded by around 600 m during the 100 years from 1910 to 2010 (Fig. 10). Kamp et al. (2013) also documented a surface lowering of around 70 m at West Turgen Glacier from 1910 to 2010 (Fig. 11). In contrast to these changes at many valley glaciers, the plateau glacier on Turgen Peak and other glacierized areas above an elevation of 3500 m a.s.l. appeared to be more or less unchanged (Fig. 12).

Based on the numbers from Khrutsky and Golubeva (2008), some corrections and new calculations are presented in the following description of the loss in glacier area from 1969 to 2002 related to glacier type (Table 8): (i) the highest relative loss in glacier area occurred at "hanging" glaciers (58%), followed by cirque-valley glaciers (47%), "near-slope" glaciers (46%), complex-valley glaciers (31%), cirque glaciers (27%), and valley glaciers (20%); and (ii) the highest absolute loss in glacier area occurred at "near-slope" glaciers (11.4 km^2), followed by valley glaciers (7.3 km^2), "hanging" glaciers (6.7 km^2), complex-valley glaciers (4.9 km^2), cirque-valley glaciers (1.5 km^2), and cirque glaciers (0.8 km^2). In general, these recession rates were similar in both the Turgen Range and the Kharkhiraa Range, with the exception of cirque and cirque-valley glaciers. In the Turgen Range the loss in glacier area was less than 10% for both types; in the Kharkhiraa Range it was much higher (41% and 82%, respectively).

While most studies present data only on changes in glacier area, Khrutsky and Golubeva (2008) also calculated ice loss from melt runoff based on a simplified model for each river basin; the model calculates the melt runoff (W) by multiplying the mean summer ablation (A) at alimentation line with the glacierized area (S) (Table 5). They showed that the Turgen-Kharkhiraa Mountains lost almost half (46%) of their ice mass from 1969 to 2002; the loss was greater in the Kharkhiraa Range (50%) than in the Turgen Range (42%). As a result of such high loss, the annual melt runoff decreased by 38% in the entire range in these 33 years; in the Kharkhiraa Range the decrease was twice as high as in the Turgen Range (50% and 25%, respectively). The highest contribution to this melt runoff came from large valley glaciers.

Besides this general recession in the Turgen-Kharkhiraa Mountains, Khrutsky and Golubeva (2008) reported also on some glaciers that were advancing. For example, their Glacier No. 9 in the Turgen Range advanced by 270 m from 1969 to 2002, which was explained by the glacier's specific location at high elevation (terminus at 3800 m a.s.l.) and having a favorable ratio (6.4) of accumulation area to ablation area.

TABLE 8

Glacier number, glacierized area, and changes by glacier type from 1969 to 2002 in the Turgen-Kharkhiraa Mountains in the northern Altai of Mongolia. The decision for the identification of the three investigated time periods (1969 to 1992, 1992 to 2002, and 1969 to 2002) was based on availability of data from topographic maps and satellite imagery rather than on statistical breakpoints. The most important numbers are shown in gray shading. Revised, extended, and partly corrected from Khrutsky and Golubeva (2008).

Year and span	Complex-valley glacier			Valley glacier			Near-slope glacier			Hanging glacier			Cirque glacier			Cirque-valley glacier			All glaciers		
	No.	km^2	Percent	No.	km^2	Percent	No.	km^2	Percent	No.	km^2	Percent	No.	km^2	Percent	No.	km^2	Percent	No.	km^2	Percent
Turgen																					
1969	0	0	n/a	12	24.2	n/a	8	11.4	n/a	15	8.4	n/a	2	1.3	n/a	2	1.5	n/a	39	46.8	n/a
1992	0	0	n/a	12	21.8	n/a	8	8.8	n/a	15	5.3	n/a	2	1.2	n/a	2	1.5	n/a	39	38.6	n/a
2002	0	0	n/a	12	20.3	n/a	8	7.0	n/a	15	3.8	n/a	2	1.2	n/a	2	1.4	n/a	39	33.7	n/a
1969–1992 (23)	±0	±0	±0	±0	−2.4	−9.9	±0	−2.6	−22.8	±0	−3.1	−36.9	±0	−0.1	−7.7	±0	±0	±0	±0	−8.2	−17.5
1992–2002 (10)	±0	±0	±0	±0	−1.5	−6.9	±0	−1.8	−20.5	±0	−1.5	−28.3	±0	±0	±0	±0	−0.1	−6.7	±0	−4.9	−12.7
1969–2002 (33)	±0	±0	±0	±0	−3.9	−16.1	±0	−4.4	−38.6	±0	−4.6	−54.8	±0	−0.1	−9.9	±0	−0.1	−6.7	±0	−13.1	−28.0
Kharkhiraa																					
1969	3	15.7	n/a	5	12.9	n/a	10	13.6	n/a	7	3.2	n/a	6	1.7	n/a	1	1.7	n/a	32	48.8	n/a
1992	3	11.3	n/a	5	12.3	n/a	9	9.6	n/a	7	1.9	n/a	4	1.2	n/a	1	0.3	n/a	29	36.6	n/a
2002	3	10.8	n/a	5	9.5	n/a	9	6.6	n/a	6	1.1	n/a	4	1.0	n/a	1	0.3	n/a	28	29.3	n/a
1969–1992 (23)	±0	−4.4	−28.0	±0	−0.6	−4.7	−1	−4.0	−29.4	±0	−1.3	−40.6	−2	−0.5	−29.4	±0	−1.4	−82.4	−3	−12.2	−25.0
1992–2002 (10)	±0	−0.5	−4.4	±0	−2.8	−22.8	±0	−3.0	−31.3	−1	−0.8	−42.1	±0	−0.2	−16.7	±0	±0	±0	−1	−7.3	−19.9w
1969–2002 (33)	±0	−4.9	−31.2	±0	−3.4	−26.4	−1	−7.0	−51.5	−1	−2.1	−65.6	−2	−0.7	−41.2	±0	−1.4	−82.4	−4	−19.5	−40.0
Turgen-Kharkhiraa																					
1969	3	15.7	n/a	17	37.1	n/a	18	25.0	n/a	22	11.6	n/a	8	3.0	n/a	3	3.2	n/a	71	95.6	n/a
1992	3	11.3	n/a	17	34.1	n/a	17	18.4	n/a	22	7.2	n/a	6	2.4	n/a	3	1.8	n/a	68	75.2	n/a
2002	3	10.8	n/a	17	29.8	n/a	17	13.6	n/a	21	4.9	n/a	6	2.2	n/a	3	1.7	n/a	67	63.0	n/a
1969–1992 (23)	±0	−4.4	−28.0	±0	−3.0	−8.1	−1	−6.6	−26.4	±0	−4.4	−37.9	−2	−0.6	−20.0	±0	−1.4	−43.8	−3	−20.4	−21.3
1992–2002 (10)	±0	−0.5	−4.4	±0	−4.3	−12.6	±0	−4.8	−26.1	−1	−2.3	−31.9	±0	−0.2	−8.3	±0	−0.1	-5.6	−1	−12.2	−16.2
1969–2002 (33)	±0	−4.9	−31.1	±0	−7.3	−19.7	−1	−11.4	−45.6	−1	−6.7	−57.8	−2	−0.8	−26.7	±0	−1.5	−46.9	−4	−32.6	−34.1

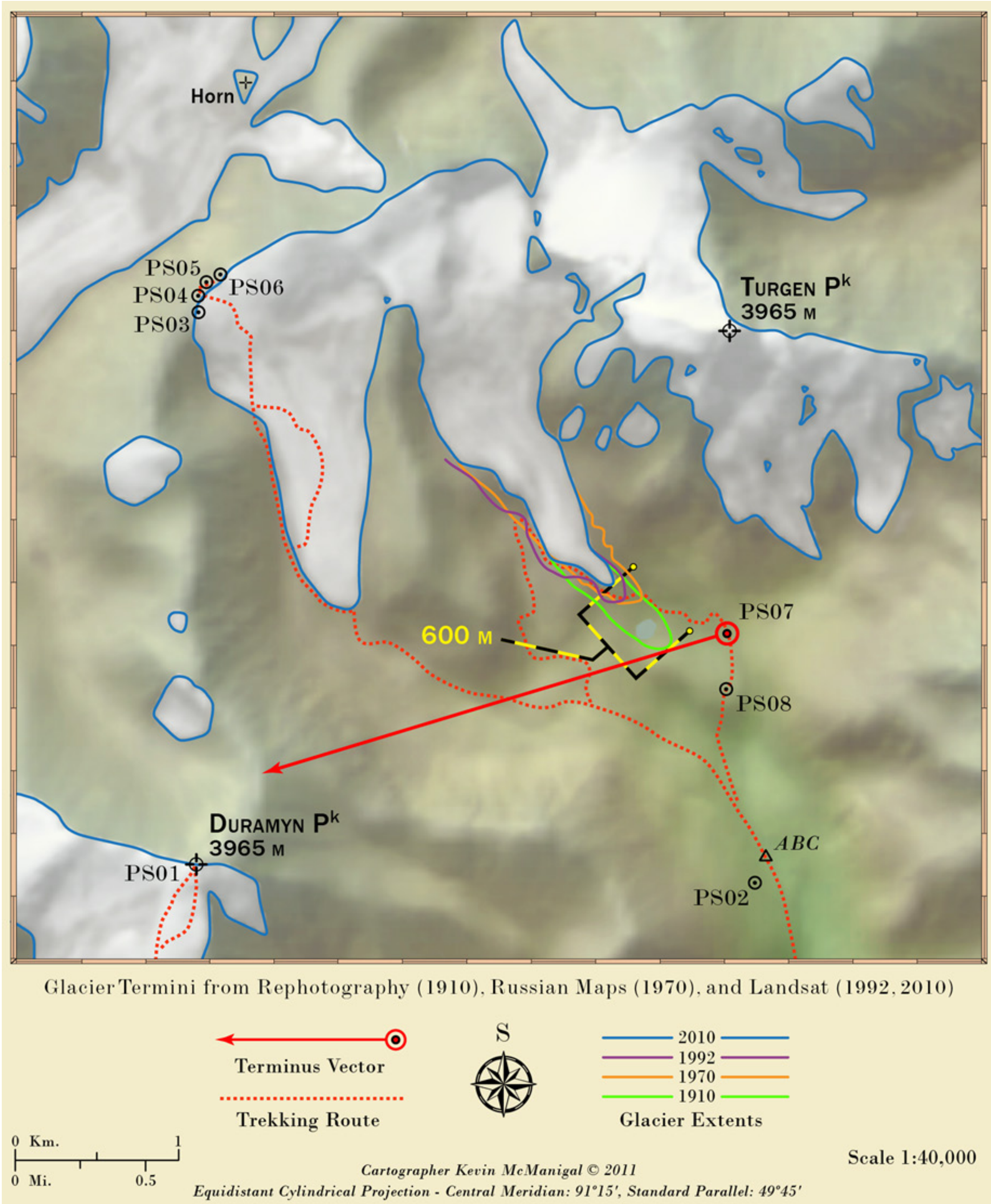

FIGURE 10. Recession of the terminus of the West Turgen Glacier, Turgen Range, between 1910 and 2010, mapped from repeat ground photographs taken in August 1910 by the Royal Geographical Society Expedition to the Turgen Mountains and in July 2010 by the U.S.-Mongolian Anniversary Expedition; 1:100,000-scale topographic maps from 1970/1971 compiled by the former Soviet Union from vertical aerial photographs taken in 1968; Landsat 4 image (p141r025_4dt19920625_z46_20 and p141r026_4dt19920625_z46_20, 25 June 1992); and Landsat 5 image (L5142025_02520100829, 29 August 2010). The glacier receded by 403 m from 1910 to 1970, by 87 m from 1970 to 1992, and by 110 m from 1992 to 2010. From Kamp et al. (2013).

FIGURE 11. Ground photograph from 19 July 2010 of West Turgen Glacier (in the foreground) and East Turgen Glacier (in the background), Turgen Range, Mongolian Altai Mountains. A comparison with the August 1910 photograph from the Royal Geographic Society (RGS) Expedition to the Turgen Mountains of Mongolia under the leadership of Douglas Carruthers revealed that in the confluence of the two glaciers, the ice down-wasted by approximately 70 m during the intervening 100 years. From Kamp et al. (2013).

TAVAN BOGD MOUNTAINS

For Tavan Bogd (Fig. 1; #15 in Fig. 2), Kadota and Davaa (2004, 2007) noticed a loss in glacier area of 10% from 1945 to 1988 followed by stagnation until 2000. Krumwiede et al. (in press) report a decrease in glacier area from 213 to 204 km^2 (4%) from 1989 to 2009; the 13 largest glaciers had individual losses of between 4.3 and 14.1%. Kamp and Pan (in prep.) report the following numbers: 126 glaciers covered 115.3 km^2 in 1989; 97 glaciers covered 95.9 km^2 in 1998; and 110 glaciers covered 95.0 km^2 in 2011. In contrast to the concluded stagnation between 1988 and 2000 presented by Kadota and Davaa (2004, 2007) (see above), Kamp and Pan (in prep.) calculate a loss of glacierized area by 17% between 1989 and 1998 followed by a stagnation until 2011 (loss of only 1%).

Potanin Glacier (Figs. 7 and 8) is probably one of the best-studied glaciers in Mongolia. Dashdeleg et al. (1983) gave its length as 12 km and its area as 54 km^2; however, for which year is uncertain. Baast (1998) measured an area of 47 km^2 (for 1985?); and Kadota and Davaa (2007) determined a length of only 11 km and an area of 43 km^2 for 2000. Kadota and Davaa (2007) noted no significant change in glacier area between 1988 and 2000, and Konya et al.

FIGURE 12. Ground photograph of Turgen Peak and the end moraine of West Turgen Glacier to the left. In this 2010 photograph, the summit ice cap looks unchanged compared to 1910, but the small glacier descending from the cirque on the right has retreated, along with a reduction of ice in the center frame seracs. The debris-covered ice in the center of the moraine has also completely ablated (from Kamp et al., 2013).

(2008) measured a “current” negative mass balance, although the year(s) of the measurement(s) is (are) unknown. In contrast, for the budget year 2007 to 2008, Ohata et al. (2009) calculated a positive mass balance of 1.4 m. Krumwiede et al. (in press) find that Potanin Glacier lost 1.13 km^2 (4.3%) in area and receded by 516 m, a mean rate of 25.8 m a^{-1} from 1989 to 2009; over the same period Alexandra Glacier lost 1.20 km^2 (8.1%) and receded at a mean rate of 32.7 m a^{-1} (653 m in total).

Batima et al. (2004) noted that the glaciers of Tavan Bogd contribute more than 50% of the annual flow of Khovd River, and calculated that a temperature rise of 3 °C at constant precipitation until 2099 would lead to changes in discharge between −18% (ECHAM4) and +21% (HadCM2) based on IS92a and SRES scenario estimates of the Intergovernmental Panel on Climate Change (IPCC, 1992, 2000). When applying the Water Global Assessment and Prognosis (GAP) model (Alacamo et al., 2003; Döll et al., 2003), which in its version 2.1 cannot simulate glacier dynamics, Batima et al. (2004) calculated an even higher decrease in discharge of up to 25% for the lower Khovd River by 2025. Furthermore, the models showed that discharge of the Khovd River increases in April and May, while significant reductions occur in June, July, and August. Nevertheless, Batima et al. (2004) concluded that, although these numbers document high uncertainties in some climate model results and glacier dynamics are not even included, they provide a first indication of the general range of possible flow alterations due to climate change. In the future, models that include such glacier scenarios might predict different changes in discharge.

MUNKH KHAIRKHAN MOUNTAINS

Klinge (2001) showed that the glacier area of the Munkh Khairkhan Mountains (Figs. 1, 13–15; #9 in Fig. 2) in the central Mongolian Altai was 25.2 km^2 in the 1980s/1990s (Table 1) and reported that mostly individual plateau glaciers, like the one at the summit of Munkh Khairkhan (4204 m a.s.l.), and snowfields were common, while cirque glaciers were rare, and only three valley glaciers existed.

During the last decades, glaciers in the Munkh Khairkhan Mountains exhibited a general trend of recession. Krumwiede et al. (in press) show that from 1990 to 2006, the glacier area decreased by 28%, from 39 to 28 km^2 (Fig. 15; Table 1), and almost all of the glaciers receded by 20–80 m at a rate of 1.3–5 m a^{-1}; only the Khar Tsunkh Glacier increased in area by 6%. However, Krumwiede et al. (in press) point out that the recession must have occurred somewhere between 1990 and 2000, because the glaciers remained in a phase of stagnation for the entire next decade from 2000 to 2010. Kamp and Pan (in prep.) show that 108 glaciers covered 44.0 km^2 in 1991; 54 glaciers covered 31.0 km^2 in 2001; and 49 glaciers covered 27.4 km^2 in 2011; the loss of glacierized area was 30% between 1991 and 2001, 12% between 2001 and 2011, and 38% between 1991 and 2011.

OTHER MOUNTAINS

For the Tsambagarav Range (Figs. 1 and 16; #16 in Fig. 2), Kadota and Davaa (2004, 2007) measured a loss in glacier area of 29% from 1948 to 1963 followed by stagnation until 2000. Davaa and Basandorj (2005) supported these conclusions and found that after a longer phase of stagnation until 2000, the glacierized area decreased between 2000 and 2002 by another

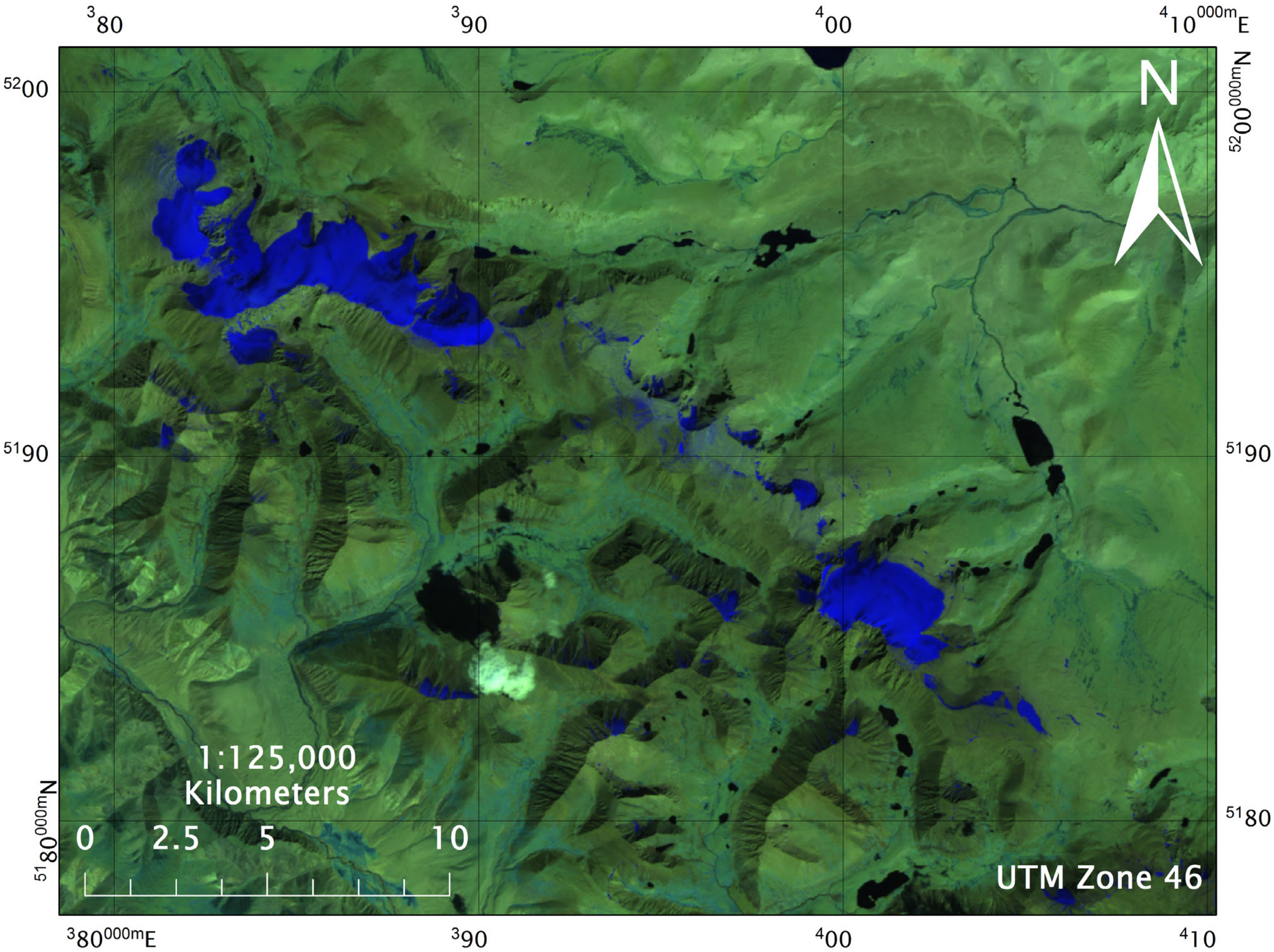

FIGURE 13. Landsat 5 image of the Munkh Khairkhan Mountains, Mongolian Altai Mountains. In the false-color composite (bands 4, 5, 7), glaciers are dark blue (LT51410272010234IKR00, 22 August 2010).

3.3 km^2 (4%). Kamp and Pan (in prep.) report that 30 glaciers covered 86.6 km2 in 1991; 30 glaciers covered 76.6 km^2 in 1998; and 27 glaciers covered 69.3 km^2 in 2011; between 1991 and 1998 the loss in glacierized area was 12%, between 1998 and 2011 it was 10%, and between 1991 and 2011 it was 20%.

In the Huh Serh Range (Figs. 1, 17, and 18), Dundon and Ganbold (2009) measured a summit elevation of the ice cap above Rhyolite Valley at 3980 m a.s.l., which is about 35 m lower than recorded on Russian topographic maps from 1963. Ladig (2009) listed the recent glacierized area as only 2.2 km^2 in 2007 and 2.1 km^2 in 2008. Temperature data from Khovd and Duluun showed no major change from 1937 to 2009, while precipitation data from Deluun showed a negative trend in mean average precipitation from 1993 to 2009 (Ladig, 2009).

For the Khukh Serkhyn Range, Bader et al. (2008) showed the glacierized area decreased from 7 km^2 in 1961 to 4 km^2 in 2008, which represents an order of magnitude increase in mean loss rate of glacier area since 1963, compared to the mean loss rate since the Last Glacial Maximum (LGM) (Ladig, 2009).

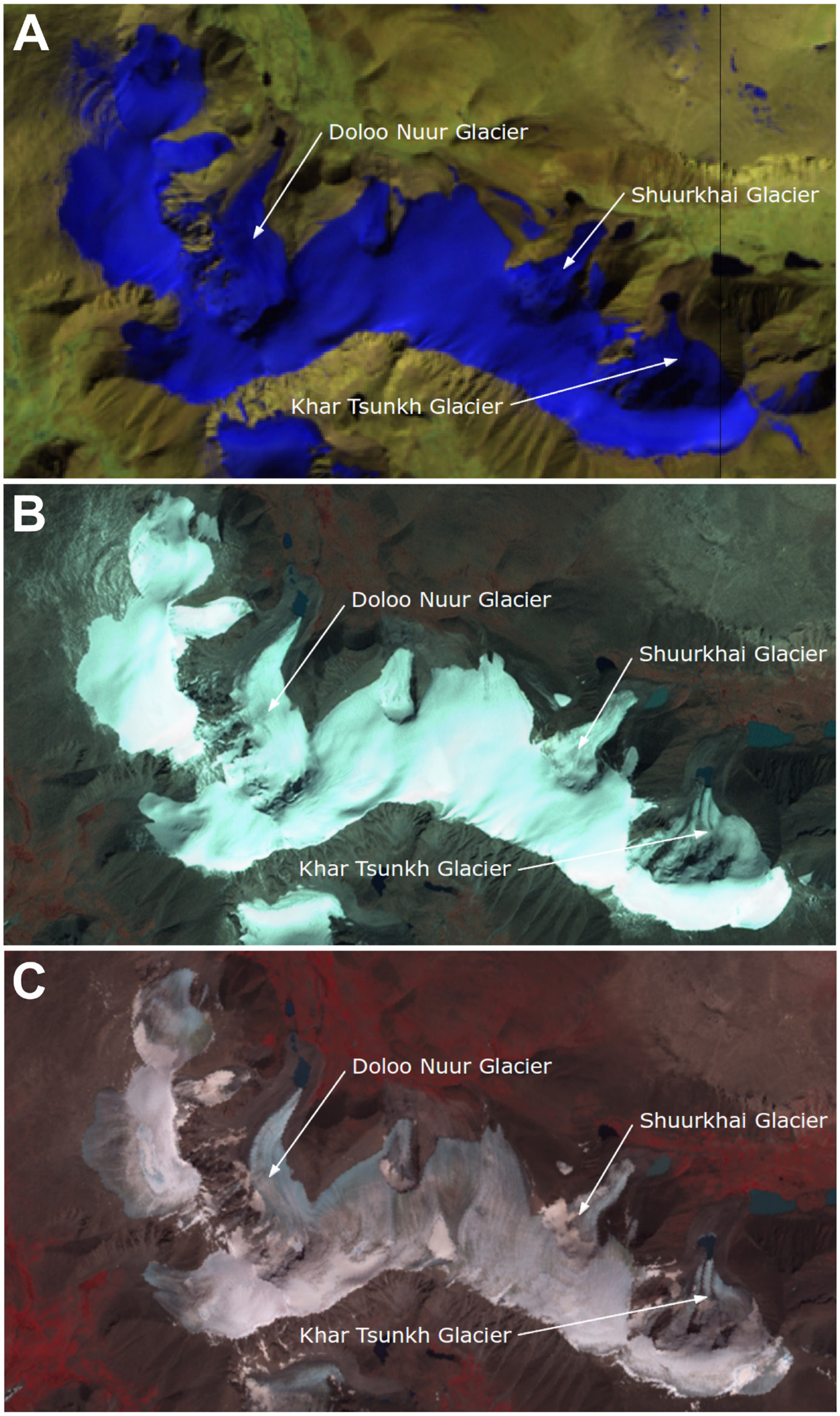

FIGURE 14. Glacierization of the main range of the Munkh Khairkhan Mountains, Mongolia: (A) Landsat 5 false-color composite (bands 4, 5, 7) (ETP141R27_5T19900916, 16 September 1990); (B) Landsat 7 false-color composite (bands 2, 3, 4) (LE71400272000240SGS00, 27 August 2000); (C) ASTER color-composite (bands 1, 2, 3) (AST_L1B _00308032006050008_20090420191731_1296, 3 August 2006) (from Krumwiede et al., in press).

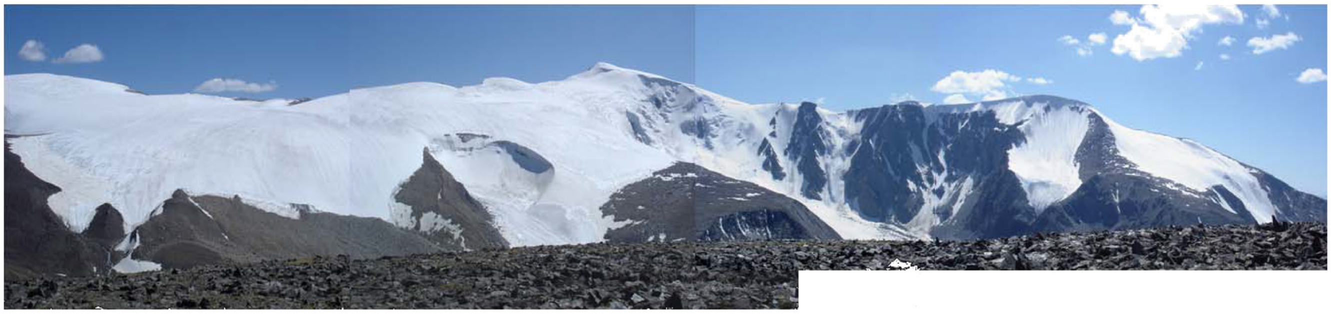

FIGURE 15. Ground photograph of plateau and cirque glaciers in the Munkh Khairkhan Mountains, Mongolian Altai Mountains. Munkh Khairkhan Peak is in the center of the photograph (from Davaa and Kadota, 2009).

Conclusions

The exact number of glaciers and the extent of the glacierized area in Mongolia are still uncertain, although the first complete glacier inventory generated for the GLIMS project is available. This international glacier mapping and monitoring initiative identified and delineated the glaciers using the latest satellite- and DEM-based methodologies and the newest geographic information system (GIS) technologies. It is believed that 670 glaciers covered an area of 372 km^2 in 2010 in the Mongolian Altai (Kamp and Pan, in prep.). Nevertheless, in the literature, the number of glaciers ranges between 187 and 731 and the area of glaciers ranges between 300 and 659 km^2 for the time window between the 1940s and 2010.

With the exception of only one glacierized area in the Khangai Mountains in central Mongolia, all glaciers are located in the Altai Mountains of western Mongolia. At 11 km in length, Potanin Glacier in the Tavan Bogd Range is Mongolia's longest and probably also one of the best-studied glaciers.

The recent general trend of negative mass balance in Mongolia's glaciers will probably continue in the 21st century, because air temperatures are likely to increase. The Institute of Meteorology and Hydrology [Mongolia] (2003) predicted a temperature increase of 4.5 K between 2000 and 2100. Batima et al. (2005) noted that the generally increasing temperatures in Mongolia will have impacts especially in the mountains. Based on modeling, Davaa et al. (2008) predicted that air temperatures at 3050 m a.s.l. will increase by 1.0 °C from 2010 to 2039, 2.9 °C from 2040 to 2069, and 5.8 °C from 2070 to 2099. The increase in air temperatures will probably lead to a higher frequency of negative mass balance in Mongolia's glaciers and continue the trend of glacier recession. For the Khukh Serkhyn Mountains, Bader et al. (2008) predicted that if the present rate of loss continues, these glaciers will disappear by about 2075.

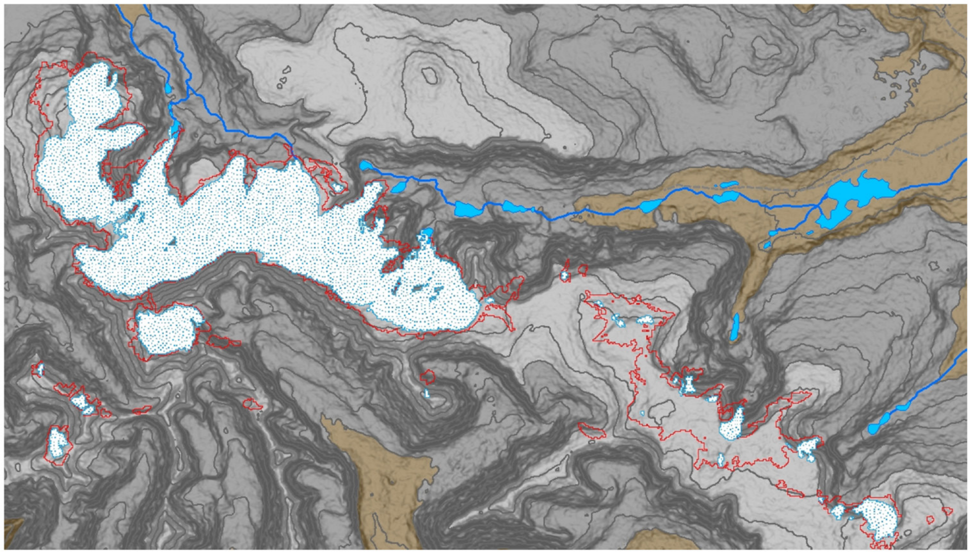

FIGURE 16. Areal changes in glaciers in the Munkh Khairkhan Mountains, Mongolian Altai Mountains, from 1990 (red outline) to 2006 (white with blue dots) mapped from Landsat 5 images (ETP141R27_5T19900916, 16 September 1990; LT51400272006232IKR00, 20 August 2006) (from Krumwiede et al., in press).

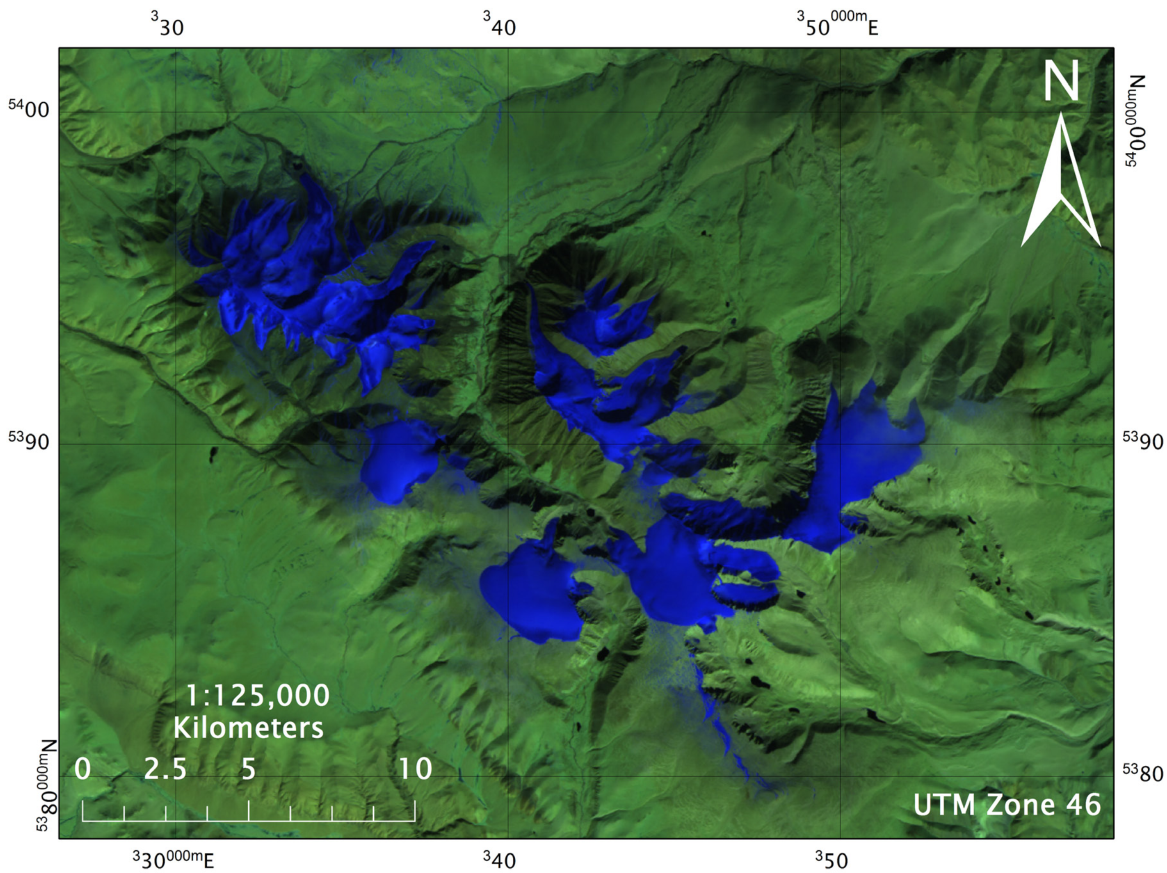

FIGURE 17. Landsat 5 image of the Tsambagarav Range, Mongolian Altai Mountains. In the false-color composite image (bands 4, 5, 7) glaciers appear dark blue (LT51410262006271IKR00, 28 September 2006).

FIGURE 18. Ground photograph of erosional remnant in the valley in front of three cirque glaciers in the Huh Serh Range, Mongolian Altai Mountains (from Ladig, 2009).

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