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THE GLACIER COMPLEXES OF THE MOUNTAIN MASSIFS OF THE NORTH-WEST OF INNER ASIA AND THEIR DYNAMICS

ABSTRACT. The subject of this paper is the glaciation of the mountain massifs Mongun-Taiga, Tavan-Boghd-Ola, Turgeni-Nuru, and Harhira-Nuru. The glaciation is represented mostly by small forms that sometimes form a single complex of dome-shaped peaks. According to the authors, the modern glaciated area of the mountain massifs is 21.2 km^2 (Tavan-Boghd-Ola), 20.3 km^2 (Mongun-Taiga), 42 km^2 (Turgeni-Nuru), and 33.1 km^2 (Harhira-Nuru).

The area of the glaciers has been shrinking since the mid 1960's. In 1995–2008, the rate of reduction of the glaciers' area has grown considerably: valley glaciers were rapidly degrading and splitting; accumulation of morainic material in the lower parts of the glaciers accelerated. Small glaciers transformed into snowfields and rock glaciers. There has been also a degradation of the highest parts of the glaciers and the collapse of the glacial complexes with a single zone of accumulation into isolated from each other glaciers. Reduced snow cover area has led to a rise in the firn line and the disintegration of a common accumulation area of the glacial complex. In the of the Mongun-Taiga massif, in 1995–2008, the firn line rose by 200–300 m. The reduction of the glaciers significantly lagged behind the change in the position of the accumulation area boundary. In the past two years, there has been a significant recovery of the glaciers that could eventually lead to their slower degradation or stabilization of the glaciers in the study area.

KEY WORDS: mountain glaciers, the North-East of Inner Asia, dynamics of the glacier complexes, development of the glacier systems.

INTRODUCTION

The North-West of Inner Asia is a territory occupied by the Altai and Sayan ridges of the Arctic Ocean basin, by the mountains that belong to the Mongol Altai and the Tannu-Ola ridges of the inner drainage basin, and by the intermountain depressions separating them. Much of this area is outside of Russia. A characteristic feature of the natural environment of the North-West of

Inner Asia is the presence of relatively isolated mountain massifs that are the centers of modern glaciation.

Mountain glaciers of the North-West of Inner Asia has been a subject of studies of the geographers of St. Petersburg State University for several decades. The first researcher of the glaciation of Western Tuva since 1964 was President of the Russian Geographical Society, Professor Yu. P. Seliverstov (1929–2002). The study of the glaciers includes monitoring of their current state in order to obtain information about the area, length, morphology, and the altitudinal glaciological levels, delineation and surveying of glaciers' edges, and meteorological and balance observations. The main glaciological work is associated with the massifs Mongun-Taiga, Tavan-Boghd-Ola, Turgeni-Nuru, and Harhira-Nuru (Fig. 1).

The glaciers of these massifs exist in arid and sharp continental climatic conditions. Annual rainfall in the highlands is 250–400 mm with about 35–50% in the summer. The glaciers exist due to low temperatures (at an altitude of 3200 m, the average summer temperatures range from 2° to 4°C) and high concentration of snow on the downwind north-eastern slopes. The coefficient of snowdrift and avalanche sediment concentration on glaciers is between 2 and 3 with 6 to 8 at the cirque glaciers. These values are close to the ratio of the glaciers of the Severnaya Zemlya archipelago. Low energy of the glaciation of the North-West of Inner Asia determines its response to significant changes in the mass balance.

MODERN GLACIATION OF THE TAVAN-BOGHD-OLA MASSIF

The Tavan-Boghd-Ola massif is located in the heart of Altai near the junction of Russian and Mongolian Altai and the system of Sayan-Tabyn-Ola. The highest point of the massif is Mount Nairamdal (altitude 4374 m). Mount Tavan-Boghd-Ola (4082 m), the dominant peak in the north of the massif, is confined to the ridge that separates Russia, China, and Mongolia. Other peaks do not exceed 4000 m, even though the height of the mountain passes is higher than 3500 m. At the same time, the foot of the massif is at a high elevation; for example, the Kalgutinsky basin in the north has a height of 2225–2250 m. This explains the relatively low, for such high mountains, vertical and horizontal relief roughness. The largest glaciers of the massif are on the southern slopes; the northern slopes have also significant glaciation in the basin of the Argamdzhi river (Fig. 2).

The first information on the glaciation of the massif was obtained by V.V. Sapozhnikov [1949] who studied the massif in 1897 and 1905–1909. In the first half of the XX century, the glaciers of the massif have been studied by B.V. and M.V. Tronov [1924] who included them in the first catalog of the Altai glaciers. Later, the glaciers of the massif were studied by V.S. Revyakin and R.M. Mukhametov [1993], N.N. Mikhailov [2002], A.G. Redkin [1994], and A.N. Rudoy [Rudoy et al., 2002]. However, before the beginning of the XXI century, there was no detailed description of the glaciers of the northern slope of the massif. At the beginning of the first decade of the XXI century, we have obtained data that allowed us to create maps, descriptions, and catalogs of the modern glaciers of the massif [Seliverstov et al., 2003]. Further studies in the second half of this decade allowed us to update the earlier results.

According to our latest data (for 2011), the glaciation of the northern slope of the Tavan-Boghd-Ola massif has 12 glaciers with the total area of 22.4 km^2 (Table 1). The glaciers form two complexes: (1) the glaciers that originate in a trapezoidal peak (3565.3 m) and a pyramidal peak (3901.3 m); and (2) the glaciers of the basin of the central and western tributaries of the Argamdzhi-2 river. In addition, on the western and eastern outskirts of the massif, where the mountains edging the glaciers fall down by 200–300 m, there are

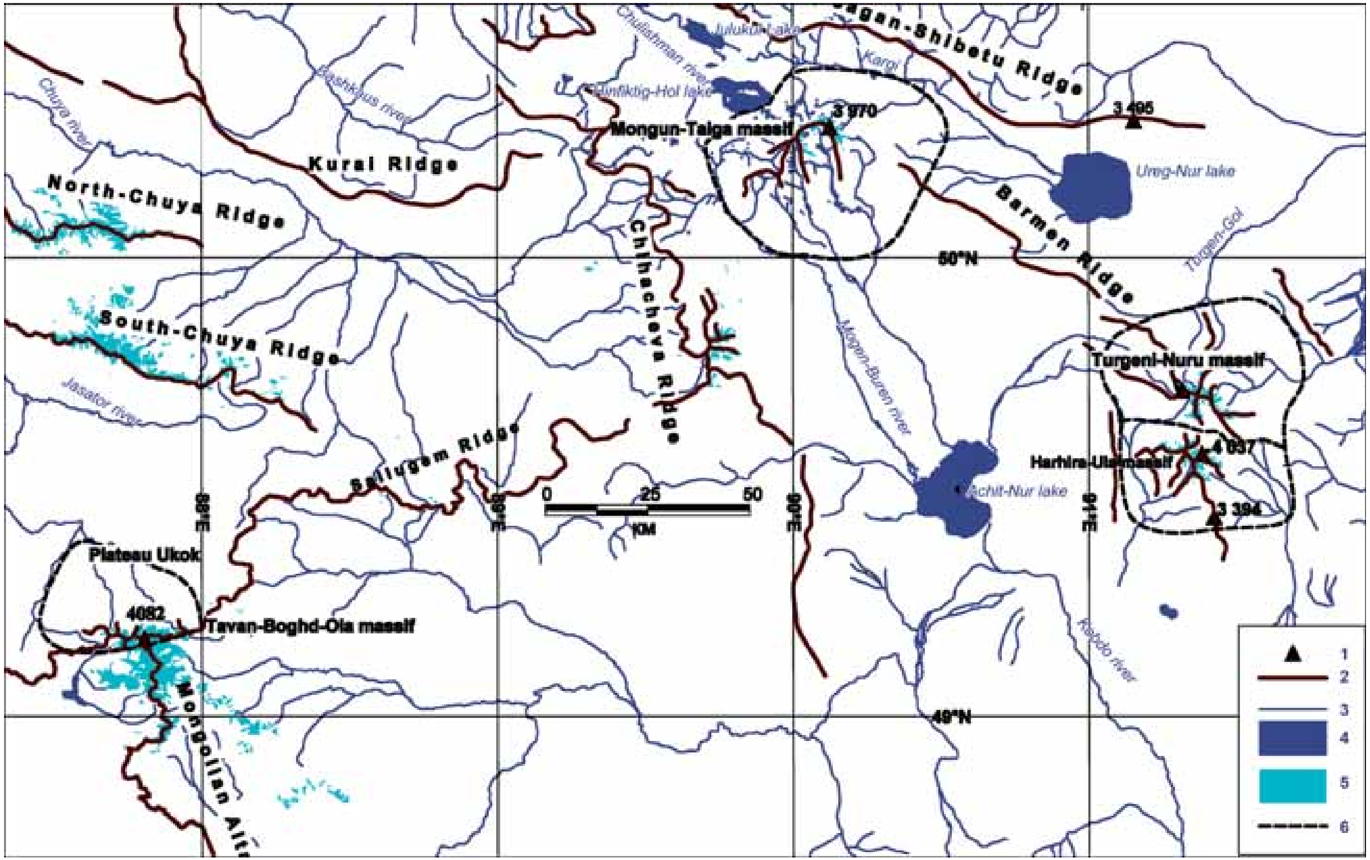

Fig. 1. Main sites of the glaciological work in the North-West of Inner Asia:

1 – mountain peaks, 2 – mountain massifs, 3 – rivers, 4 – lakes, 5 – glaciers, 6 – boundaries of the mountain massifs

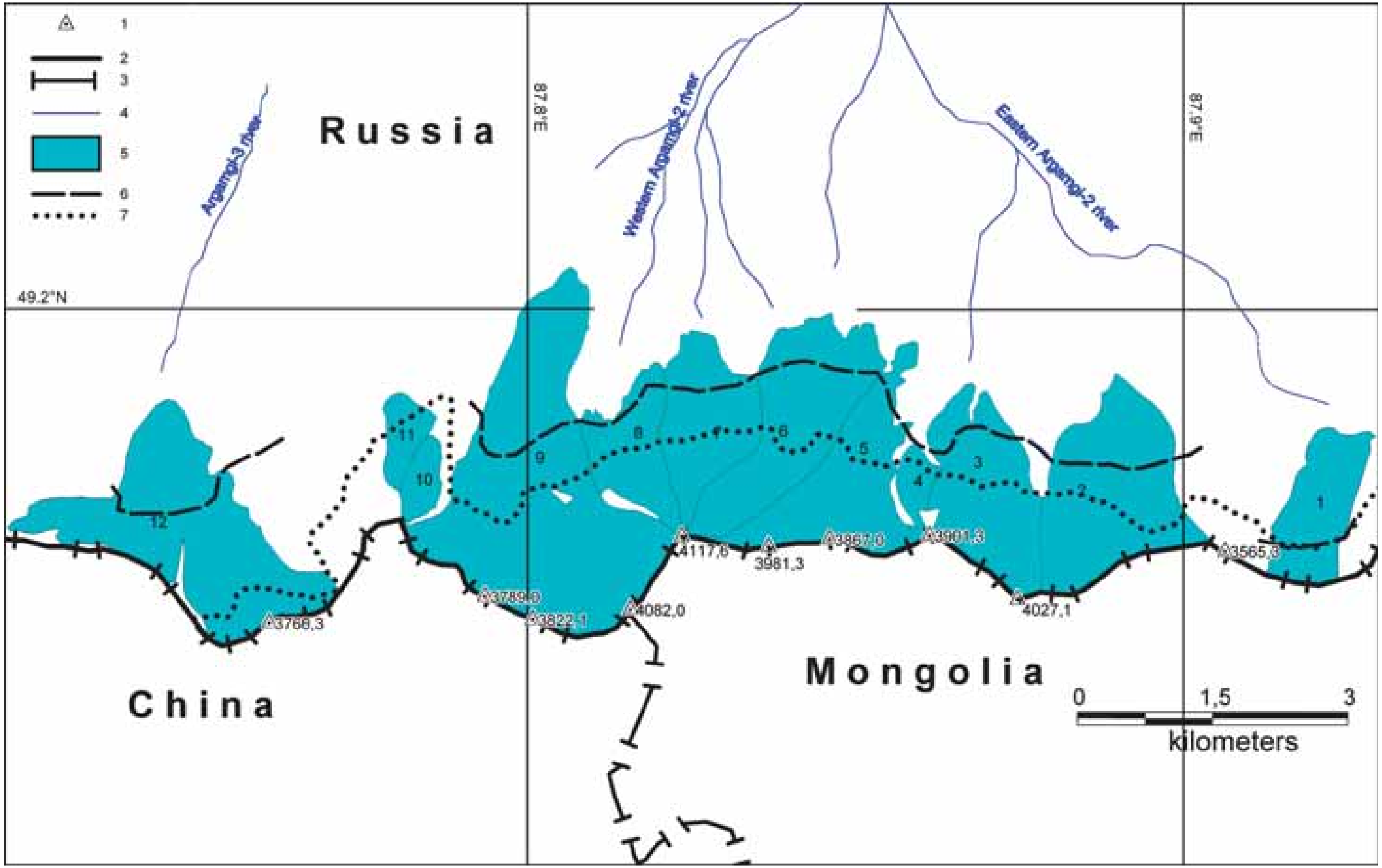

Fig. 2. The scheme of the glaciation of the northern slope of the Tavan-Boghd-Ola massif:

1 – peaks and their elevations; 2 – mountain ranges; 3 – the state border; 4 – rivers, 5 – glaciers and their numbers; 6 – firn line; and 7 – 3500 m elevation contour

Table 1. Features of the glaciers on the northern slope of the Tavan-Boghd-Ola massif

№	Morphological type	S	Sa	L	H1	H2	Hf	A1	A2
1	Slope	1.23	0.92	1875	3610	3275	3495–3515	NNE	NNW
2	Slope	2.00	0.83	2648	3990	3140	3380–3400	NNE	N
3	Transition to slope	1.60	0.34	1975	4000	3100	3280–3340	NNE	N
4	Hanging	0.29	–	1096	3901	3400	3420	N	N
5	Transition to slope	1.96	0.14	3646	4117	3030	–	N	NNE
6	Slope	2.31	0.58	3110	4117	3120	3275–3350	NNE	N
7	Slope	1.51	0.38	2244	4117	3100	3350	N	N
8	Slope	1.09	0.15	1970	4117	3230	2990–3,300	NW	NNW
9	Valley	5.48	0.96	4630	4117	3055	3,235–3,410	NW	NNE
10	Hanging	0.31	–	391	3925	3520	–	NE	E
11	Hanging	0.37	–	713	3925	3370	–	NW	NE
12	Valley	3.57	0.98	2944	3760	2880	3,025–3,285	N	NNW
14	Cirque	0.48	0.00	1040	3400	3080	–	NE	NE
Total		22.39							

Notes: S – glacier area (км^2); Sa – area of the glacier ablation zone (км^2); L – glacier length (m); H1 – highest elevation point (m); H2 – lowest elevation point (m); Hf – elevation of the firn line (м); A1 – exposition of the accumulation zone; A2 – exposition of the ablation zone. The glaciers' numbers correspond to the numbers in Fig. 2.

three glaciers not associated with these complexes.

Analysis of the data for the glaciers of the northern slope of the Tavan-Boghd-Ola massif shows that two of the valley glaciers are the largest and the longest within the massif; their share of the area is about 40%. Two other major glaciers are in the transitional stage from the valley to the slope type. The slope and hanging glaciers prevail in numbers, though their share in the total glaciation area is about the same as the share of the valley glaciers. Almost all of the slope glaciers have a complex structure associated with the morphological non-uniformity in the longitudinal profile, as well as with the multilevel structure and the formation of multiple tongues at the lower boundary of each of the glaciers.

MODERN GLACIATION OF THE MONGUN-TAIGA MASSIF

The Mongun-Taiga massif is located south-east of the junction of the Russian Altai mountain massifs, Mongolian Altai, and the Sayan-Tannuola system. The massif is located to the south of the watershed of the Arctic Ocean and the inland drainage basin, in particular, the Great Lakes basin. The homonymous major peak has an absolute elevation of 3970.5 m and the coordinates 50°16′30″N and 90°8′E. The massif stretches from the southwest to northeast, rising from 3100–3300 m on the western periphery to 3300–3680 m on the watershed of the rivers Orta-Shegetey and Tolayty; to 3500–3970 m on the watershed of the rivers Mugur, Tolayty, and Shara-Horagay; and decreasing to 3000–3200 m further to the east. The existence of the glaciers in the massif was first noted by

Table 2. Features of the glaciation of the Mongun-Taiga massif

№	Name	Morphological type	S	L	A1	H1	H2
1		Slope	0.25	600	N	3440	3100
2	Right Balyktyg	Cirque-valley	0.60	1100	N	3440	2990
3	Eastern Balyktyg	Cirque	0.43	1130	N	3280	2960
4	Western Mugur	Cirque	0.33	930	NE	3550	3060
5	Left Mugur	Cirque-valley	0.93	1730	NE	3660	3060
6	Left Mugur	Cirque-valley	0.10	840	NE	3220	2950
7	Left Mugur	Slope	0.03	600	N	3070	3350
8		Slope	0.57	2010	N	3830	2970
9		Slope	0.62	1770	N	3830	3015
10		Slope	0.29	920	NE	3720	3070
11		Slope	0.13	1270	NE	3720	2970
12	Rught Mugur	Valley	0.82	2480	NE	3830	2895
13	Eastern Mugur	Valley	3.84	3860	NE	3970	2935
14	Sekivestrov	Valley	2.78	3320	E	3803	3135
15		Slope	0.18	590	NE	3615	3355
16		Slope	1.09	1640	SW	3803	3570
17		Hanging	0.27	660	SW	3803	3665
18		Hanging	1.35	1930	SW	3970	3280
19		Hanging	0.09	570	SW	3970	3825
20		Hanging	0.77	1330	W	3970	3450
21		Hanging	0.45	1100	W	3970	3440
22	Tolayty	Valley	0.63	1680	S	3480	3090
23		Cirque-valley	0.87	1700	NE	3660	2950
24		Cirque	0.19	750	NE	3300	2915
25		Cirque-valley	1.03	1370	SW	3260	2915
26		Cirque-hanging	0.38	1060	NE	3300	2910
27		Cirque	0.31	900	N	3300	3010
28		Hanging	0.05	520	N	3650	3250
29		Hanging	0.09	530	N	3650	3050
30		Hanging	0.13	540	N	3090	3650
31		Hanging	0.05	380	N	3310	3650
32		Flat-top	0.62	550	S	3680	3575
		Total	20.27				

Note: For the legend, see Table 1.

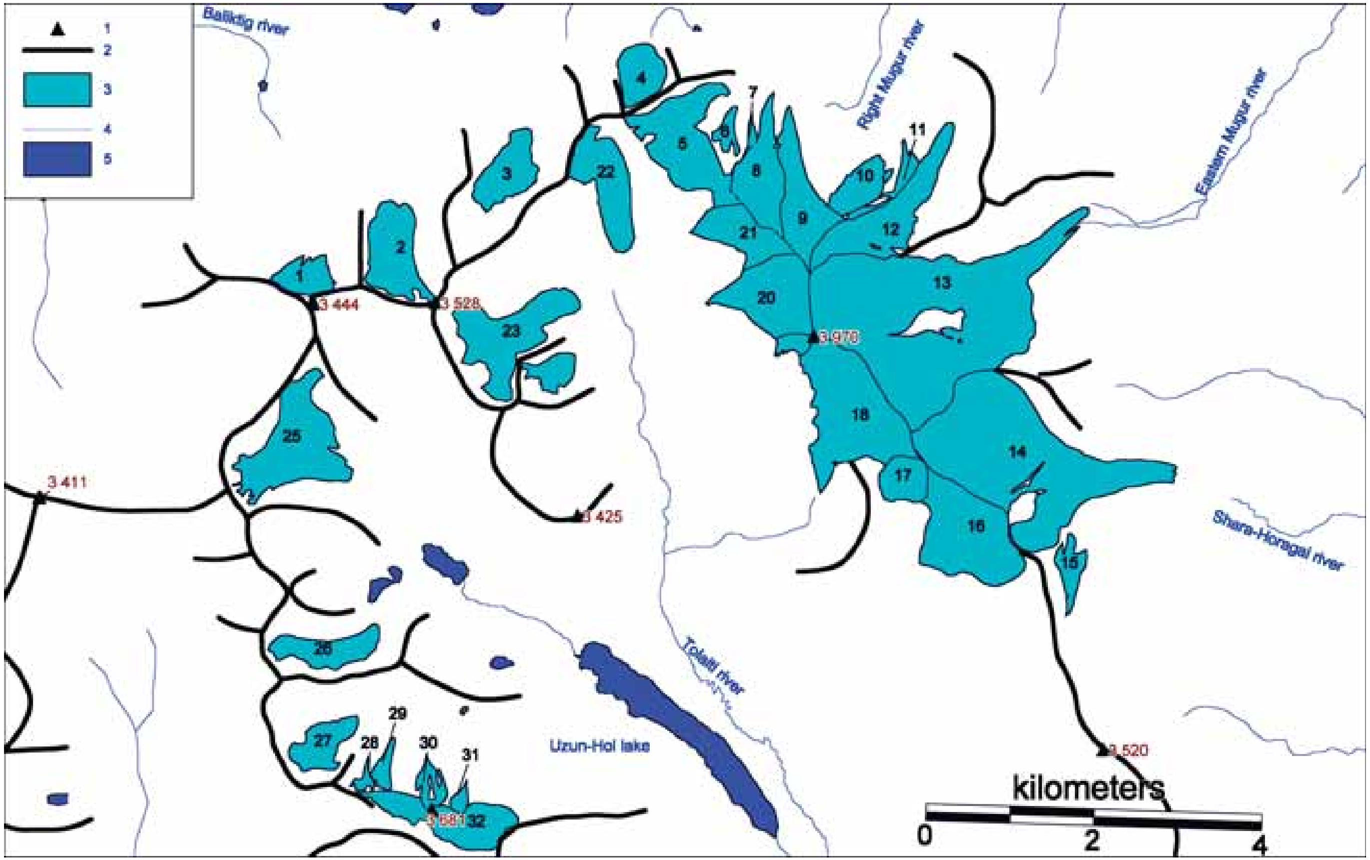

Fig. 3. The scheme of the glaciation of the Mongun-Taiga range:

1 – peaks, 2 – ridges and watersheds, 3 – modern glaciers, 4 – rivers, 5 – lakes

V.V. Sapozhnikov in 1909 [Sapozhnikov, 1949]; the first general description of the glaciation was made by Yu.P. Seliverstov in 1965 [Seliverstov, 1972]; it was later refined and updated by V.S. Revyakin and R.M. Mukhametov [1986]. In 1988–2008, the glaciation was studied by the faculty members of the Faculty of Geography, St. Petersburg State University. The results of the work were compiled into detailed charts and catalogs of the glaciers that have been updated several times since [Seliverstov et al., 1997].

According to our data for 2010, the glaciation consisted of 32 glaciers with the total area of 20.27 km^2 (Table 2). Small glaciers with an average area of 0.7 km2 prevail. More than 80% of the glaciers have the area of less than 1 km^2, but the larger glaciers (including the four valley) comprise approximately 50% of the total glacier area of the massif. The largest glaciers of the massif, i.e., East Mugur and Seliverstov, are the multilevel glaciers formed by several streams of ice from the two tiers of circuses and kars (3250–3350 m and 3600–3700 m) that merge and form the glaciers' tongues. The northeastern exposure prevails (about 40% of the glaciation). In the central part of the massif, the glaciers form a complex around the main peak (Fig. 3); the other smaller complex is located in the southwest of the massif around a plateau-like site with the highest point of 3681 m. Other glaciers are not connected with each other.

MODERN GLACIATION OF THE TURGENI-NURU AND HARHIRA-NURU MASSIFS

The first descriptions of the Turgeni-Nuru glaciers was done by G.N. Potanin (1879 expedition) and D. Carruthers and I.P. Rachkovsky. In the middle of the XX century, Polish scientists E. Rutkowski and B. Slovanski [1966 *a*, *b*; 1970] created a map of the massif's ancient glaciation. In the 1991–1992, filed studies were conducted by the faculty members of the Faculty of Geography, St. Petersburg State University. In the last decade, remote sensing methods have been employed widely. Thus, there were reconstruction of the glaciation dynamics by V.S. Khrutskyi and E.I. Golubeva [2008] made on the basis of the satellite images Landsat 5 and 7 (1992, 2002) and a topographic map of 1 : 200 000 scale (1969). Unfortunately, the data presented in that paper are not supported by field observations and are disputable, since the area of the glaciers is strongly distorted and too high for the 1969 and 1992 glaciers. The information on changes of the length of the glaciers is even less believable (especially a 270-meter expansion of one of the glaciers in 33 years, contrary to our field data).

The orographic massif Turgeni-Nuru is the southern extension of the medium-altitude mountain massif Barmen that stretches from the massif Mongun-Taiga located 90 km to the northwest. The massif Turgeni-Nuru (its part with altitudes over 3 km) stretches about 50 km from northwest to southeast and 20 km from southwest to northeast. The highest point of the massif is Turgen (3965 m). The modern glaciation is concentrated in the southern part of the massif, where the peaks exceed 3500 m (Fig. 4). The northern part of the massif and the peak Turgen-Ola (3386 m) are not glaciated. The massif is divided by radiating river valleys; the northern and eastern parts of the massif belong to the Ubsu-Nur lake basin; the western and southern parts belong to the Achit-Nur lake and the river Kobdo basins. In the south, the Turgeni-Nuru massif is connected with the Harhira-Nuru massif; they are separated by a 2974 m elevation mountain pass. The massif has a horseshoe shape open to the southeast. The dominant mountain peak (4037 m) is located in the east of the massif.

According to our assessment, there are 39 glaciers within the Turgeni-Nuru massif totaling 42 km^2 (Table 3). Twelve glaciers have the length of more than 2 km. The main glaciation is located on the northern

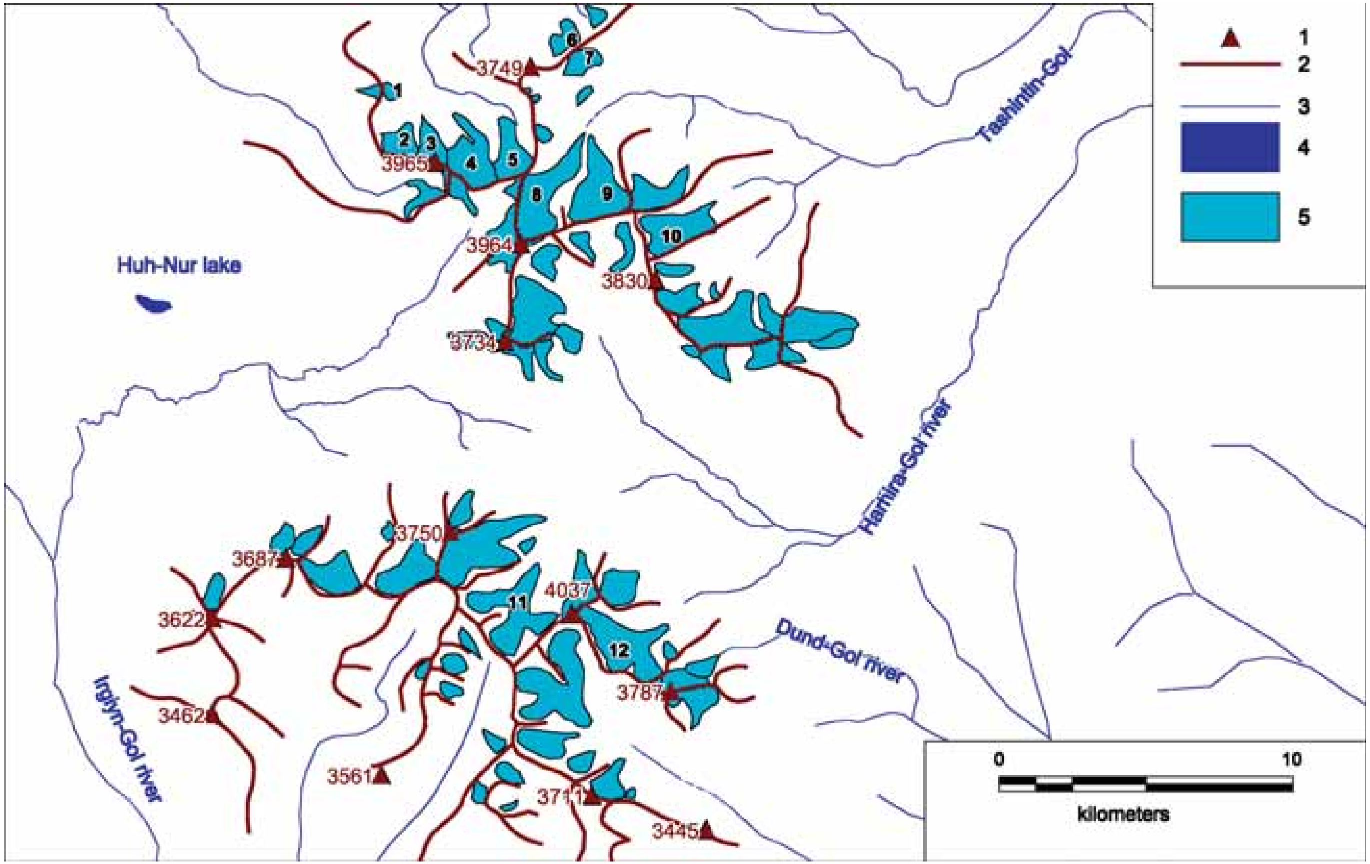

Fig. 4. The scheme of the Turgeni-Nuru and Harhira-Nuru massifs.

The glaciers of the Turgeni-Nuru massif: 1 – Baga-Barun-Degly; 2 – Barun-Hoyt-Degly; 3 – Barun-Urd-Degly; 4 – Tsagaan-Degly; 5 – Dzun-Tsagaan-Degly; 6 – Ara-Duramyn; 7 – Ubur-Duramyn; 8 – Tom-Turgen; 9 – Nareen-Turgen; 10 – Small Baga. The glaciers of the Harhira-Nuru massif: 11 – Barun-Harhira; 12 – Dzun-Harhira

Table. 3. General features of the Turgeni-Nuru massif.

Direction of slope	Number of glaciers		Area			Weight-average elevation of the low glacier's point
	absolute	% of total	км^2	% of total	average	
N	7	18	15.7	37	2.2	3000
NE	8	21	12.6	30	1.6	3067
E	5	13	2.6	6	0.5	3235
SE	5	13	2.6	6	0.5	3256
S	4	10	3.0	7	0.7	3377
SW	2	5	1.2	3	0.6	3462
W	2	5	0.4	1	0.2	3336
NW	6	15	4.0	9	0.7	3185

and northeastern slopes, where the glaciers descend 300–400 m lower than in the south.

The glaciation of Harihira-Nuru is similar to the glaciation of Turgeni-Nuru in size and the basic features. According to the results of our field and remote sensing studies, there are 29 glaciers in the massif with the total area of 33.1 km^2.

The glacier Barun-Yarhira is the most extensively studied; it is located below the main summit of the massif (4037 m) and the Dzun-Harhira, 4 km further to the east. The Barun-Harhira is situated in a large circus of the northeastern exposure with a diameter of about 3 km and the depth of 500–600 m. The length of the glacier is 3.5 km, its tongue reaches a height of 3000 m at its lowest point. The Dzun-Harhira located in a deep through valley. This glacier is 3 km long with its lowest point at an altitude of 3000 m. The morphology is typical of the valley glaciers of the Turgeni-Nuru and Harhira-Nuru massifs and its dynamics depends on the accumulation of avalanche material.

THE DYNAMICS OF THE GLACIATION

Direct observations provide an opportunity to assess changes in the glaciation of the region in the last 40–50 years and identify the main trends in its modern dynamics.

Significant changes in the total number and the area of the glaciers are observed within the Mongun-Taiga massif. The time interval since the last glacial stabilization in the late 1960's (recorded by direct observations and aerial photographs) to 2010 can be divided into two completed periods (1965–1995 and 1995–2008) and a new period that began recently or a new phase of transition to a new period of stabilization of the glaciation (2009–2011).

From 1965 to 1995, the glaciers of the massif have lost 13% of the area, mainly due to the medium-size slope glaciers (–38%) and the cirque-valley glaciers that broke into smaller forms of glaciation. The small glaciers changed as well; six of them disappeared completely (hanging and cirque-hanging), but this was offset by the fragmentation of the larger glaciers. The large valley glaciers lost only 5% of the area.

The second period (1995–2008) was the time of especially rapid degradation of the glaciers; their area decreased by 19% (more than 1% per year). During this period, the following processes took place there:

1. The progressive reduction of the total glacier area.

2. The reduction of the number of the valley glaciers.

3. High rates of degradation of the valley glaciers.

4. The breakage of the relatively large glaciers into the smaller ones.

5. The growing share of the hanging glaciers due to their isolation from the larger forms of the glaciers and the upward retreat of glaciers.

6. The increase in the rate of accumulation of morainic material of the gravitational origin in the lower parts due to a significant decrease in the slope snow-cover.

7. The disappearance of small forms of the glaciation or their transformation into the snowfields and rock glaciers.

8. The decrease of the area of the highest sites of the glaciers and the breakage of the glacier complexes with a common accumulation zone into the glaciers isolated from each other.

An important feature of this period is not only a reduction or transformation of the small glaciers into the snowfields and rock glaciers (18 small glaciers have disappeared; hanging and cirque-hanging glaciers lost 38% and 65% of the area, respectively), but also the increased rate of the degradation of the larger valley glaciers (–21 % of area). The valley glacier Left Mugur split into three smaller ones; the Seliverstov glacier lost half of its tongue and also a large area in the accumulation zone. The glaciers Eatern Mugur and Right Mugur split into several ice streams separated by central moraines.

One of the main features of the dynamics of the glaciers of the Mongun-Taiga massif in 1995–2008 is the deglaciation not only within the glacier tongues, but also within the accumulation zone (Fig. 5). The main maximum of the altitudinal distribution of the glaciation degradation is associated with the interval of 3350–3400 m, which corresponds to the average altitude of the firn line in 1995. In addition, the glaciers have greatly decreased at the elevations of 3450–3600 m within the former zone of accumulation. It should be noted that the level of 3600 meters is the elevation of the climatic snow boundary in 1995; above

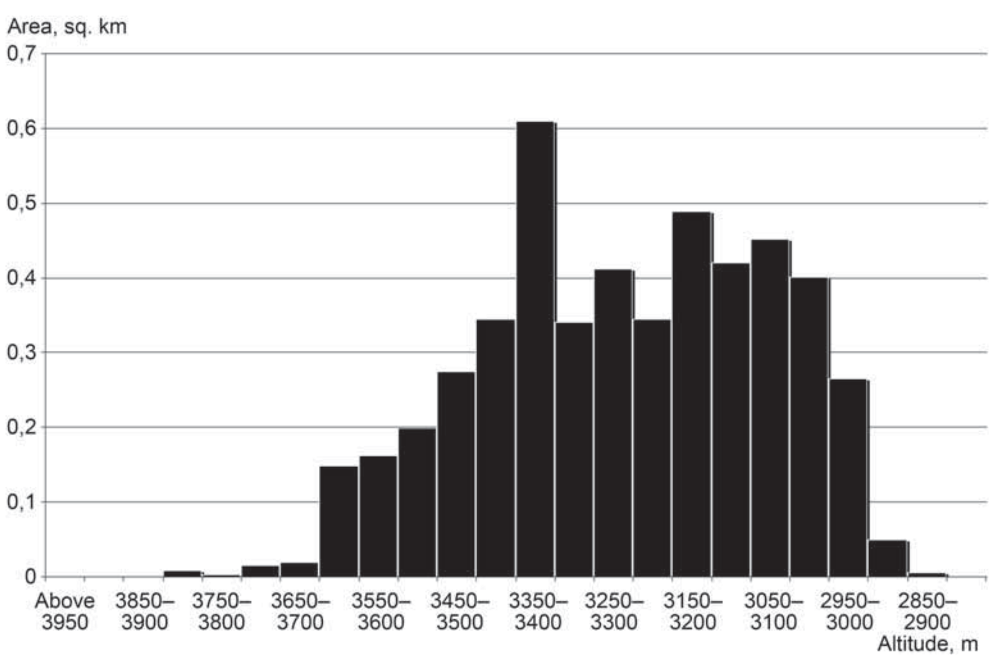

Fig. 5. The altitudinal distribution of the deglaciation of the Mongun-Taiga massif in 1995–2008

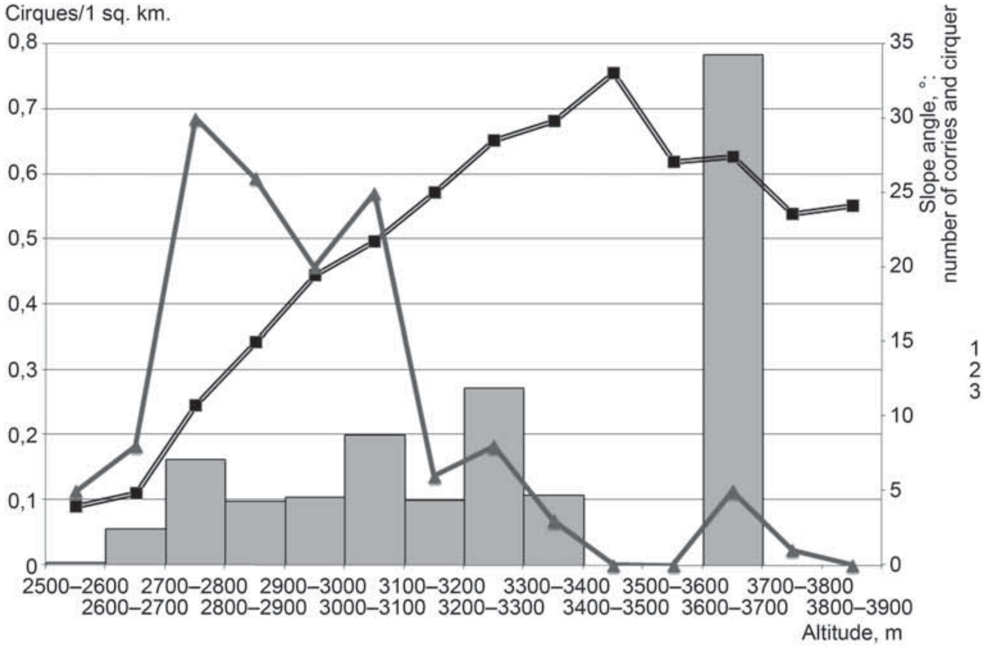

Fig. 6. The altitudinal distribution of geomorphologic characteristics of the Mongun-Taiga massif:

1 – occurrence (number per 1 km2 of a given altitudinal interval, along the left axis) of the cirques; 2 – the average slope grade (along the right axis); 3 – the total number of kars and cirques within an altitudinal interval (along the right axis)

this elevation, the glaciation in 1995–2008 decreased very little.

There are several reasons for the degradation of the glaciers at high altitudes. The first reason is mainly extremely dry and clear conditions in 1995–2008. The fact that there was no significant reduction of the glaciation above the level of the climatic snow line proves that warming was not significant, but dry and low snow conditions have led to the loss of the thickness and of large areas of the glaciers that are below the climatic snow line. A small amount of solid precipitation and high evaporation lead to decrease of the snow-firn fields' area and to the exposure of rocks between the flows of ice. Another reason is the stepped relief of the massif, i.e., the alternation of steep, almost vertical slopes and sub-horizontal surfaces. This feature of the terrain is amplified by cirques and kars (Fig. 6) that form four tiers, three of them within the development of the modern glaciation. This results in a difference in the thickness of ice and snow and the concentration and accumulation of solid precipitation between the lower parts of the circus, kars, their steep slopes, and rock bars. In the past few years, the zone of accumulation of the largest glaciers have lost their unity and became divided into several spots of firn located one above the other, while the sections between them have often exposed rocks.

One result of the stepped relief of the Mongun-Taiga massif is the alternation of periods of disappearance of the small slope and hanging glaciers and periods of disintegration of the large valley and cirque-valley glaciers. According to our reconstructions, the previous period of rapid degradation of the valley glaciers took place in 1850–1925 when the 2700–2800 m level of circuses lost connection with the glaciation; on the contrary, in 1925–1995, mainly small relief forms of the glaciation responded to climatic changes. The period of 1995–2008, in case of further climatic change towards unfavorable, for glaciation, conditions, could

Fig. 7. The deglaciation (km2) of the Mongun-Taiga massif on the slopes of different exposures in 1995–2008

be a transitional stage to the phase when the valley glaciers begin retreating rapidly.

It should be noted that in the past 40 years, there was primarily degradation of the low-lying glaciers on the northern and northeastern slopes (Fig. 7).

The rate of warming of the last quarter century in the study area was one of the maximal not only in Altai. Despite the change in this trend, the summer temperatures remain relatively high. This has led to the fact that in 2002–2008, the snow line was absent in most of the glaciers. Particularly dry and snow-free conditions occurred in 2006–2007 and 2007–2008.

In the massif Mongun-Taiga in 1995–2008, the firn line rose by 200–300 m, reaching the average level of 3600 m. The snow-firn fields have survived only in a few glaciers of the massif; the common zone of accumulation of the glacial complexes of the main peak of the massif transitioned into a group of isolated firn spots, sometimes one above the other, and separated by steep portions of the slopes. Thus, the level of 3600 m does not correspond to some continuous firn line, and is the height above which over 50% of the massif area is covered by firn. Reduced snow cover in the past few decades correlates with the degradation of perennial snow patches. According to our reconstruction and observations from the mid – 1960s to 2008, the altitudinal belt of the snow patches of the Mongun-Taiga massif has shifted 300–400 m upwards; the number of the perennial snow patches has decreased by a factor of four; and the total area has decreased by 15 times.

We should clarify that we consider the firn line as the boundary of glaciers' accumulation area. According to our observations, in the mountain massifs of the North-West of Inner Asia, the equilibrium line and the firn line coincide due to low accumulation of superimposed ice, which does not form in all glaciers and does not appear every year. In some years, superimposed ice appears on the largest glaciers and differences in the firn line and the equilibrium line may reach 20–30 m. On average, the difference between these levels is negligible, especially in the last few years. On the contrary, in the first decade of the XXI century, there was not enough cold accumulation in the glaciers for not only the formation of superimposed ice, but also for the preservation of the integrity of the glaciers themselves which were cut by numerous streams to a depth of 10 meters, even breaking sometimes completely parts of the glaciers from the main glacial body.

Our calculations (using Kurovskyi method) show that the degradation of the glaciers, which occurred from 1995 to 2008, could be caused by the rise of the firn line by only 36 m. The changes taking place in the snow-firn zone of the glaciers, in this period, outpaced their actual degradation.

In the past three years, there has been a significant increase in snow accumulation at high elevations of the massif compared with the period 1995–2008. Our snow survey conducted prior to the period of melting at 3200–3970 m showed that the average thickness of the snow cover is 8–12 cm and remains practically constant independent of the elevation except in the areas where the accumulation may be significant due to avalanches and snowstorm transport. Given that the density of snow in the time of the snow survey was 300–400 kg/m^3, it can be argued that in the high part of the massif, there falls at least 300 mm of solid precipitation alone. This is two-three times greater than the annual precipitation at medium elevations (Mugur-Aksy, 1830 m).

The increase in snow accumulation affected primarily the state of the small slope, near-slope, and cirque glaciers, which, from the beginning of the 1990s, sharply deteriorated and moved into the category of the perennial snow fields or completely debris covered glaciers. Due to the snowstorm transport and avalanche supply, these glacial-nival formations began to recover, i.e., there is an increase of their linear size and thickness. On the surface of the debris covered glaciers, perennial snow patches were formed, which led to the formation of multiple layers in their vertical structure.

The fundamental change in conditions of snow accumulation affected the altitudinal snow line in 2009–2011, that has recovered to the 1994–1995 altitudinal level. For example, its positions in the cirque glacier East Balyktyg (№ 3) and the valley glacier Tolayty are 3050 m and 3150 m, respectively.

The northern slope of the Tavan-Boghd-Ola massif resembles considerably the Mongun-Taiga massif in the behavior of the glaciers. In 1964, the total area of the glaciation was 28.3 km^2 [Catalog..., 1978; Revyakin and Mukhametov, 1993]. In 2002, it was 25.8 km^2 (9% reduction in the area in 38 years) [Seliverstov et al., 2003]. According to our observations for 2002–2009, the area of the glaciers decreased by about 3 km^2 (12% in 7 years). Thus, the glaciers, in those 7 years, lost a larger area than in the previous 38 years.

The reasons for this acceleration of degradation are the same as those causing an increase in the rate of the deglaciation of the Mongun-Taiga massif, mentioned above. Specifically, it is the blockage of the small glaciers and their transformation into a group of the perennial snow fields (the last event took place in two small cirque glaciers on the eastern and western periphery of the massif – see Fig. 2).

Another trend is the exposure of rock and snowsheds and the degradation of the glaciers at high altitudes shown in Fig. 8. Almost 40% of the glaciers' reduction occurred above the average firn line (3310 m as of 2002 [Rudoy et al., 2002]). Most likely, this process is caused by lack of snow in the recent years. The process of disintegration of the ice complex of the northern slope of the massif and its division into separate glaciers has already begun. If the trends in the degradation of the glaciers persist in the next few years, the glaciers № 2, № 3, and № 4 (catalog 2009) will separate from the group

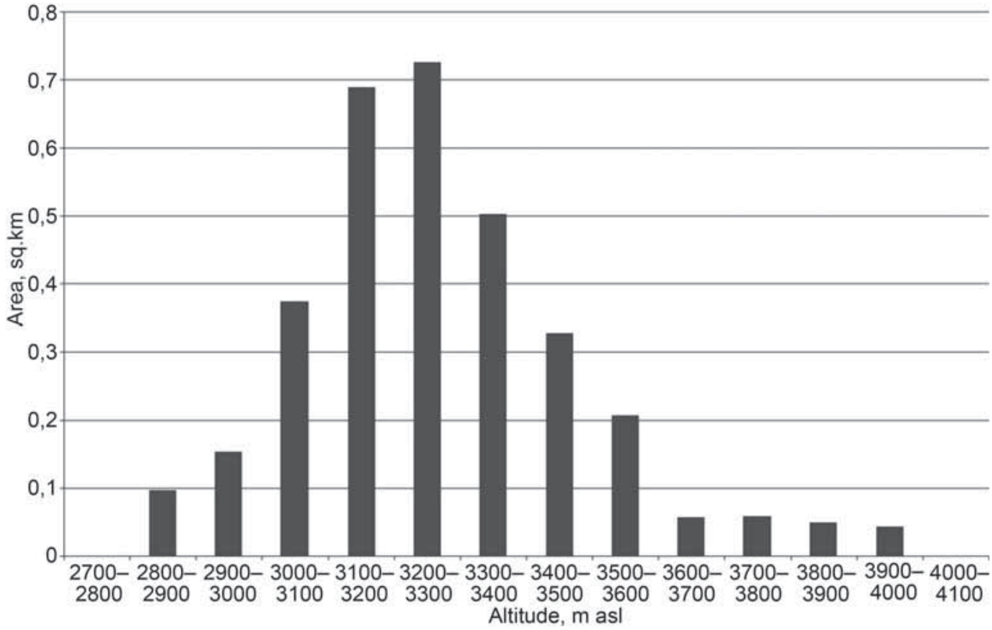

Fig. 8. The altitudinal distribution of the deglaciation of the Tavan-Boghd-Ola massif in 2002–2009

of the glaciers at the 4117.6 m peak (Russkyi Shater), located further to the west.

At the same time, in the Tavan-Boghd-Ola massif, in the past three years, there has been a more favorable glaciation trend, similar to the Mongun-Taiga massif. Thus, in the 2008–2009 balance year, there were numerous summer snowfalls with the establishment of a temporary snow cover to the elevations of 2100–2200 m with the ablation season on the glaciers (only intermittent) of only about a month.

The glaciation of the Turgeni-Nuru massif remains in a more stable condition. According to our estimates for 1992–2002, the loss of the area was only 0.8 km^2 (2%). The reason for such small changes in the glaciers is their high elevation and a relatively large (compared with the glaciers of other massifs) average area that makes the glaciation more inert and resistant to adverse (for glaciers) climatic periods.

Changes in the length of the valley glaciers (the parameter often used for assessment of glacier dynamics) are not representative of the current changes of the glaciation of the mountain massifs of the southeastern Altai. The loss of the area of the valley glaciers, even in cases of small retreat of the glaciers' tongues, may be large due to the deglaciation in the upper parts of the glaciers. Besides, the rates of retreat and changes are different for different glaciers because of their individual morphological features. For example, in the Mongun-Taiga massif, the valley glacier № 13 (East Mugur) and the glacier № 14 (Seliverstov), in 2001–2007, slowed the retreat (Table 4), while the glacier № 5 (Left Mugur), in 1995–2007, retreated 640 m (more than 50 m per year) and two of the glaciers broke away from it. However, in the latter case, there is not so much the retreat of the glacier, as the blockage of its tongue by morainic material with the subsequent separation from the main body of the glacier and the transformation into "dead ice". Changes of climate trends over the past two years have not resulted in significant response of the glaciers; however, there is a general trend to a slower retreat of the glaciers' margins. Thus, the glacier Right Mugur that was retreating 6 m/yr, in 2007–2008, is now retreating at a rate of 4 m/yr. From 1995 to 2007, the Balyktyg glacier's tongue was retreating at

Table. 4. The average rate of the glaciers' retreat (glacial tongues) of the Mongun-Taiga and the Tavan-Boghd-Ola massifs

Mongun-Taiga								
№	Morpho-logical type	Average rate of retreat, m/yr						
		1952–1961	1961–1966	1966–1981	1981–1986	1986–1995	1995–2001	2001–2007
13	Valley	4.2	2.4	6.5	5.0	8.7	4.0	2.25
14	Valley	6.7	5.2	13.4	12.8	19.0	27.5	8.3

Tavan-Boghd-Ola						
№	Morpho-logical type	Average rate of retreat, m/yr				
		1984–2001	2001–2004	2004–2006	2006–2009	Average 2001–2009
2	Slope	–	–	–	–	12.4
6-e	Slope	–	3.3	5.8	0.1	2.9
7	Slope	–	–	–	–	9.8
8-6	Slope	–	–	–	–	2.6
9	Valley	7.9	6.3	15.5	16.6	13
12	Valley	5.2	14.3	5	13.3	11

a rate of 5 m/yr, but during the last two years, its retreat has decreased and is 1 m/yr. The low rates of retreat of the largest valley glaciers of the Mongun-Taiga massif in the past few years are due to an intense blockage of the glaciers' tongues with morainic material, which reduces their melting. Another factor is the glaciers' retreat to the limits of the circuses with more favorable conditions because of a high concentration of snow and greater shadow.

The retreat of the tongues of the valley glaciers of the Tavan-Boghd-Ola massif increased; on the contrary, the tongues of the small glaciers of the same massif retreated very little. Thus, the rates of retreat do not change synchronously with climate change because of the inertia of the large glaciers and their morphological features.

The glaciers behave differently not only within the same mountain massif, but on the same slope, which is true sometimes even for the adjacent glaciers. The first scenario is the acceleration of the blockage of the glaciers' margins, decrease in melting, and separation of the lower parts of the glaciers by water streams. Another scenario is associated with separation of passive firn spots by water streams. The third mechanism is the decrease in the thickness of ice that leads to the exposure of rock bars. Two evolution paths are possible for the small glaciers: the transformation into the rock glaciers or into the perennial snow fields.

CONCLUSION

Based on the latest trends in changes of the glaciation, two ways of development of the glacier systems in the study area are possible. The first path is a return to the warm and dry conditions of 1995–2008. In this case, during the next 10–15 years, the glacier complexes will be broken into isolated glaciers and most valley glaciers will transform into the cirque-valley glaciers. This will result in the increase of the total number of glaciers.

The second path is the transition to more humid conditions similar to the 1990s. In this case, large glaciers, within the nearest several years, will continue to decrease because of their inertia, while small glaciers will stabilize or will be regenerating.

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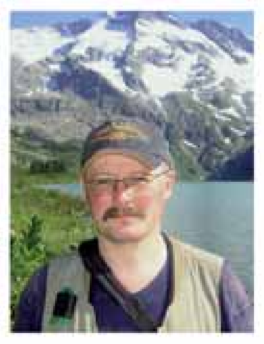

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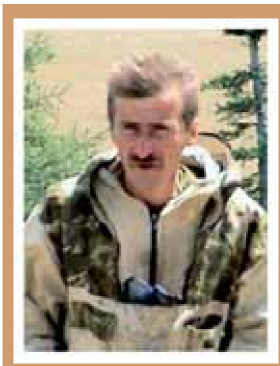

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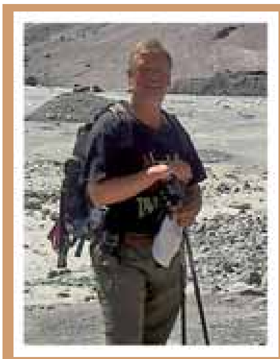

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