

Changing of the Altai glacier system since the mid-twentieth century and its response to the climate warming in future

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Статья принята к печати 18 марта 2012 г.

Алтай, изменение климата, каталог ледников, ледниковые системы.
Altai, glacier system, glacier inventory, climate change.

Characteristics of the Altai glacier system are analyzed on the data from Chinese and Former Soviet Union glacier inventories. Two glacier data sets, recent remote sensing data and the glacier inventories data were compared. It has been found that 208 glaciers disappeared and the glacial area decreased by 12%. Functional models of the glacier system variations have been developed using the equation of relationship between an annual glacier ablation and a mean summer temperature; the glacier system structure and behavior of the equilibrium line altitudes at the steady state were taken into account as well. The models were used to study response of the glacial runoff to a climatic change. The model results show that, under the climate warming scenario of 0.05 °C/year, only 3% Altai glaciers in China and 9% in Russia will remain by the end of this century.

Introduction

The Altai mountain system is located in the centre of Euroasia at boundaries of China, Kazakhstan, Russia and Mongolia. It extends from east to west for longer than 2000 km. As a whole, the Altai consists of a series of individual mountains, and its highest peak, Belukha, with altitude of about 4506 m, is located at the intersection of Russian and Kazakhstan boundaries. Owing to its relatively high elevation the Altai is a large glacierized region in middle latitudes [1, 5, 14].

A glacier system is understood as a system consisting of certain number of individual glaciers, located in the same region and, thus, influenced by similar climate conditions, so they should be organized according to similar interior laws. It can be divided and sub-divided according to their certain physical characteristics, mountain ranges, watershed boundaries etc. [13]. As it follows from the glacier inventories in Russian [2, 3], the total area of the Altai glaciers located on the territory of Former Soviet Union is 910 km², and the total glacial area of the Mongolian Altai (including China and Outer Mongolia of nowadays) is 840 km². Therefore, the total glacial area in the Altai is 1750 km² with their volume of about 84 km³. In this paper, the Altai glaciers are considered as the large glacier system sub-divided into the Russian Altai glacier system, its total area of 880 km², in the North and the Chinese Altai glacier system, its total area of 280 km², in the South. Structures, change of characteristics of the Altai glacier system are analyzed, and its future changes due to the climate warning are predicted by means of the above functional model.

Structural characteristics of the glacier system

Quantitative structure of the glacier system. The glacier inventories of Russia [2, 3] and China [11] were reassembled in the view of the glacier system. Volume of ice was calculated by the empirical formula deduced from relationship between different types of glacier volumes and average thicknesses [6]. The statistical result shows that the Altai glacier system consists of 1441 glaciers with area of about 1160 km² and volume of about 59 km³ (Table 1).

Dimensional structure of the glacier system. Dimensional structure of the glacier system was determined according to the size rate standard of the World Glacier Monitoring Service based on the reassembled glacier database of a region under consideration. We organized the glaciers from the smallest size to the largest one in area, number and volume with respect to a glacier system and then calculated its cumulative percentage. When the cumulative percentage reached 50%, the glacier sizes in the glacier system were defined as medium size in area ($S_{med}(S)$), number ($S_{med}(N)$) and volume ($S_{med}(V)$), respectively. The medium sizes of the Altai glacier system are presented in Table 2 and Fig. 1. The median sizes of $S_{med}(N)$, $S_{med}(S)$, $S_{med}(V)$ are 0,3; 2 and 3, 4, respectively. They are relatively smaller than those in southern Tibet and the river Tarim Basin [20, 22]. The median sizes of glacier system of the rivers Katun and Biya headstream were the largest ones. Since the median size in area ($S_{med}(S)$) is more informative than the average value of

Table 1. Quantitative characteristics of the Altai glaciers in different watersheds*

Watershed	N		S		V		\bar{L}	\bar{S}	\bar{D}
	number	%	area, km ²	%	volume, km ³	%	km	km ²	m
<i>Russian Altay</i>									
Irtysh	201	13.95	102.20	8.81	5.6026	9.47	1.2	0.51	55
Katun	777	53.92	742.40	64.03	37.927	64.10	1.3	0.96	51
Biya	24	1.67	8.10	0.70	0.323	0.55	0.7	0.34	40
Others	36	2.50	27.80	2.40	1.307	2.21	1.2	0.77	47
Total	1 039	72.03	880.50	75.94	45.1596	76.32	1.0	0.85	52
<i>Chinese Altay</i>									
Irtysh	390	27.06	275.12	23.73	13.8376	23.39	1.1	0.71	50
Inner basin	13	0.90	3.91	0.34	0.174	0.29	0.8	0.30	45
Total	402	27.97	278.98	24.06	14.0116	23.68	1.0	0.69	57
<i>All studied area</i>									
Total	1 441	100.00	1159.53	100.00	59.1712	100.00	1.2	0.80	49

*N is quantity of the glaciers, S is the glacier area. V is the glacier volume; \bar{L} is the mean length of glaciers; \bar{S} is the mean area of glaciers; \bar{D} is the mean thickness of glaciers.

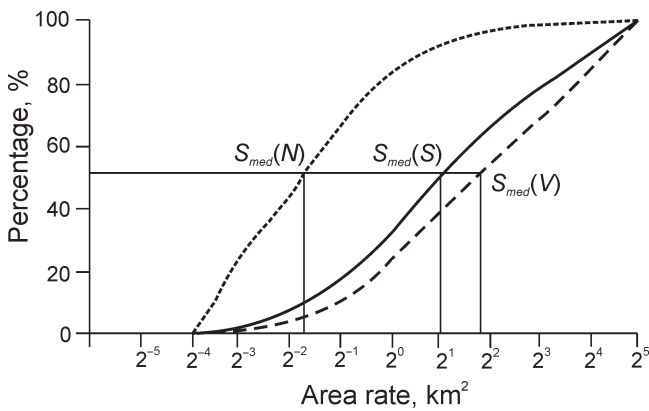


Fig. 1. Cumulative percentage curve of number (N), area (S), and volume (V) of the glacier system versus different glacier size rates in Altai

Рис. 1. Кумулятивные кривые процентного соотношения количества (N), площади (S) и объёма (V) ледников разных размеров в ледниковой системе Алтая

glacier area (\bar{S}) [10], the $S_{med}(S)$ was used as a calculating parameter to run the functional model of the glacier system response to climate warning instead of mean area value of glacier system.

Altitude structure of the glacier system. Two approaches were applied to obtain the altitude structure characteristics of the glacier system. One was direct averaging of the characteristic elevations of individual glaciers in a glacier system, such as a median, highest and lowest elevation, etc. The other approach was interpreting of information about distribution of glacier area against the glacier elevation in a glacier system. Empirical formula was developed to calculate distribution of glacier area

Table 2. The median size of glaciers in river basins of Altai

Watershed	$S_{med}(N)$	$S_{med}(S)$	$S_{med}(V)$	\bar{S}
<i>Irtysh Russian</i>				
Buhtama	0.2	1.4	2.9	0.6
Kenjelic	0.5	0.9	0.8	0.74
Headstream of Irtysh	0.2	0.5	0.7	0.39
Kurjum	0.1	0.2	0.2	0.19
Uba	0.2	0.2	0.2	0.16
<i>Irtysh China</i>				
Haba	0.2	0.93	1.42	0.53
Burgin	0.25	2.28	2.66	0.82
Harertysh	0.11	0.12	0.12	0.11
Source of Irtysh	0.12	0.23	0.25	0.18
<i>Irtysh Katun</i>				
Total	0.21	1.71	4.4	0.66
Argut	0.3	1.69	2.6	0.84
Kapjai	0.6	1.1	1.1	0.79
Sobehie	0.3	1	1	0.13
Kuragana	0.3	0.8	0.8	0.46
Headstream of Katun	0.8	4.1	4.1	2.5
Biya	0.6	4.3	4.8	1.49
Total	0.35	2.1	3	0.96
Other watershed	0.6	1.8	1.9	1.08
The entire Altai:				
Total	0.3	2	3.4	0.8

against the elevation [4], and it was successively applied for glacier systems of Tien Shan [15], Southern Tibet [21], Tarim River Basin [19]. This formula is also workable for the Altai glacier system. The altitude struc-

Table 3. Characteristics of the glacier altitude structure in Altai, m*

Watershed	H_{maxs}	H_{med}	H_{mes}	\bar{H}_{med}	\bar{H}_{max}	\bar{H}_{min}	$\Delta\bar{H}$
Irtysh	3000	3150	3122	2979	3191	2767	424
Katun	3099	3150	3129	3053	3332	2774	558
Other watersheds	3203	3350	3281	3179	3360	2998	362
Whole investigated area	3101	3150	3172	3027	3278	2776	502

* H_{maxs} , H_{med} and H_{mes} are the maximum elevation, median elevation and elevations weighted by area obtained from calculated distribution of glacier area with elevation by empirical formula provided by Kuzmichonok (1996) respectively; \bar{H}_{med} , \bar{H}_{max} and \bar{H}_{min} are the averages of the median elevation, highest elevation and lowest elevation of individual glaciers in the glacier system, respectively; $\Delta\bar{H}$ is a difference between \bar{H}_{max} and \bar{H}_{min} .

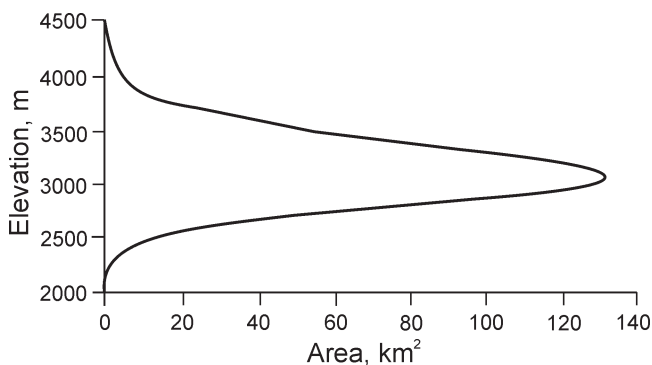


Fig. 2. Distribution of glacier area with height in the Altai Mountains

Рис. 2. Распределение площади ледников на Алтае по высоте

ture obtained from results of calculation is shown in Fig. 2 and Table 3 which indicate that the maximum area elevation (H_{max}) is 3100 m, and approximately 50% of glacier area is concentrated within the range 2950–3250 m. Differences between the average highest elevation (\bar{H}_{max}) and the average lowest elevation (\bar{H}_{min}) of two largest watersheds (the Irtys and Katun rivers) are 424 and 558 m, respectively.

Altitude of equilibrium line of the glacier system. In the glacier catalogues of China and USSR, the equilibrium line altitude (ELA) of glaciers in Altai was measured by method of Hess (ELA_H). However, only 34% of relatively large glaciers are included into these inventories. To get the ELA of each glacier, the relationship between ELA_H and H_{me} (the mean elevation of a glacier, which is the average value between maximum and minimum elevations of this glacier) was analyzed in the Altai glacier system, and the following empirical formula was developed:

$$ELA_H = 0.6723H_{me} + 939.01; n = 490; R^2 = 0.8. \quad (1)$$

Comparison between ELA calculated by formula (1) and ELA_H shows the average error equal to -37 m. Therefore, we used formula (1) to calculate the ELA of all glaciers. The average ELA of the Altai glacier system is 2983 m, which is close to the value 3000 m measured by Hess.

To investigate laws of distribution of the equilibrium line altitudes, we constructed a map of the ELA distribution. We used for that the Kriging interpolation method [9], the calculated ELA values and the geographic coordinates of glaciers. One can see that equilibrium line altitude ascends from North to South following increasing of the solar radiation, on one hand, and it descends from East to West as precipitation decreases, on the other hand (Fig. 3, a). The lowest ELA of glaciers passes on the West (2500 m) and the North (2700 m) of the Altai where the precipitation is relatively high abundant, while the highest ELA runs on the East and the South of inner arid basin (3200 m). As a whole, the ELA demonstrates a tendency to increase from outer mountains to inner ones, and the closed curves of higher ELA values indicate the center of Altai.

The recent changes of glaciers

Russian Altai. Since 1950s, the Russian glaciologists measured lengths and areas of the Altai glaciers at different times, and they found that the glaciers were retreating in the course of time. Certainly, different glaciers have different rates of retreat [6–8, 16]. In 1998, the glacier area of Russian Altai was investigated based on images received from the Russian resources satellite Resurs-3 [6]. It was found that during the period 1952–1998 the glacier areas and volumes reduced by approximately 7.1 and 10%, respectively, and the average retreat rates of the areas and volumes amounted 0.0015 and 0.00216 per a year, respectively. In addition, the number of these glaciers evidently decreased, as many small glaciers disappeared and some larger glaciers were broken into smaller ones. Totally, 78 glaciers disappeared during this period. Other results obtained for glaciers in North and South Chuya Ridges show that for the period 1952–2004 126 glaciers with their area exceeding 0.5 km² reduced by about 19.7% with the rate of retreating 0.0037 per a year [7, 16]. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imageries were used to obtain data on the glacier surface areas for 2004. Data from the World Glacier Inventory (WGI) dating to 1952 and aerial photographs made in 1952 were used to estimate changes in

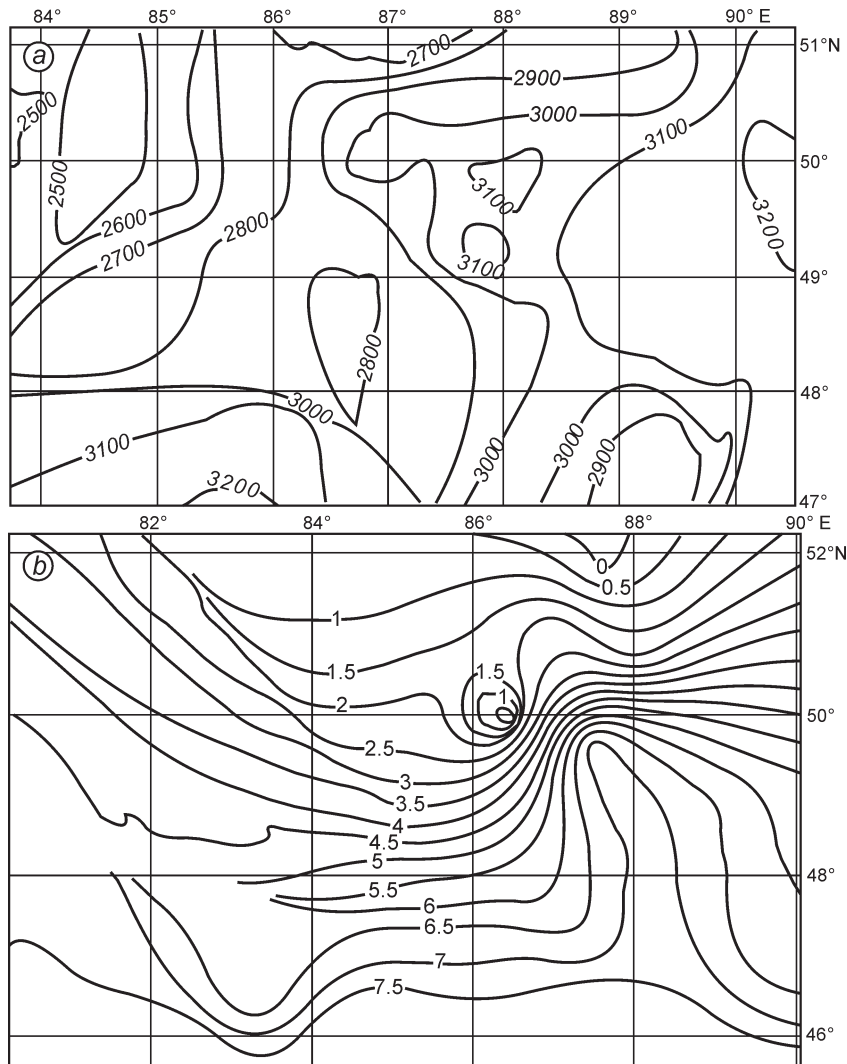


Fig. 3. Maps of distribution of the equilibrium line altitudes (ELA) for the Altai glacier system (a) and mean summer temperatures in Altai at the altitude 3000 m (b)

Рис. 3. Поля высоты границы питания ледников (a) летней температуры на фиксированной высоте 3000 м (b) в ледниковой системе Алтая

sizes of glaciers. 256 glaciers with their total area of 253 km² were identified for studying area in 2004. Glaciers with area smaller 0.5 km² were not included into consideration because of potentially large errors in evaluation of their areas of 1952. Verification of the WGI data by the re-mapping of 21 test glaciers performed on the basis of original aerial photographs of 1952 together with the WGI data set made possible to find average difference of 5.5% between the original and re-mapped patterns. This means the 3% overestimation of glacier retreat when the WGI data are used.

The summarized surface area of the test glaciers decreased between 1952 and 2004 by 15.4% according to the WGI, and this figure is 12.2% when the re-mapped values of 1952 are used. The discrepancy is within the typical accuracy of glacier mapping. Glaciers of different sizes have lost approximately the same total area, however small glaciers (< 2 km²) have lost much greater areas. On average, the small glaciers have lost 28% of their area but changes in their surface area exhibit a wide range of vari-

ability from 2 to 68%. No strong differences between proportional area losses by glaciers were found with an exception of east- and west-facing glaciers. The last ones have lost 43% (the east-facing, and the highest loss) and 12% (the west-facing, the lowest loss) of their areas since 1952. The largest absolute decrease in surface area is characteristic for the valley glaciers. The largest relative loss is characteristic for cirque-valley glaciers whose tongues retreated rapidly while their parts remaining in cirques experienced smaller changes. The cirque glaciers lost smaller part of their surface areas.

Chinese Altai. The length and area of several glaciers were surveyed for the glaciers inventory in the Chinese Altai in 1959–1980 [11]. To get the latest glacier changes in the Chinese Altai, two vector data sets on the glacier area were used, i.e. we compared data on the glacier outlines vector in 1959 obtained from topography maps of the scale 1:100 000 and similar data of 2000 obtained from Landsat ETM+ images with the pixel resolution of 15 m. All vector data were converted into a common format

Table 4. Change in glacier areas from 1959 to 2000 in the Altai Mountains, China

Watershed	Number		Vanished	Area, km ²		Area changes, %	Area annual reduce, %
	1959 r.	2000 r.		1959 r.	2000 r.		
Irtysh:							
Haba	35	34	1	18.6	12.47	32.95	0.80
Burgin	302	202	100	247.55	173.41	29.94	0.73
Kelan	1	0	1	0.26	0	100	2.50
Harertish	11	3	8	1.19	0.34	71.43	1.74
Head of Irtysh	41	29	12	7.52	4.03	46.41	1.13
The inner basin:							
Upstream of Bergen	6	3	3	2.69	0.9	66.54	1.62
Qinguli	7	2	5	1.22	0.5	59.01	1.44
Total	403	273	130	279.03	191.65	31.31	0.76

defined in Arc/Info grid with Gauss-Kruger projection and Krasovsky 1940 spheroid. Thus, changes in the glacier area of the Chinese Altai during the period 1959–2000 were calculated (Table 4).

Area of the Halace Glacier in the Burgin watershed decreased from 31.03 km² in 1960 down to 28.86 km² in 2000. The retreat percentage amounted 4.21% during the past 40 years. 100 glaciers disappeared and about 30% glacier area was lost in the Buljing watershed. In the Haba River basin, one glacier disappeared and 33% of the glacier area was lost. As regards the Chinese Altai glacier system, in 1959–2000 130 glaciers disappeared here and 87.38 km² of the glacier area was lost with the average decrease rates of 0.0076 per a year, which is ~4.9 times larger than that of the Russian Altai glaciers for the same time. The average decrease rates in Altai is also the largest ones as compared to other glaciers in China. It means that glaciers in the Chinese Altai intensely melted during the past 40 years.

On the whole, 208 glaciers disappeared in the Altai glacier system, and 144.27 km² of the glacier area was lost with the annual retreat rate of 0.003.

Climate and glacier changes in Altai

The Altai glaciers melted rapidly during the past 40 years that was closely related to the global temperature rise. Note, that rates of the temperature rise in Russian Altai and Chinese Altai are different. According to meteorological data of Russian Altai published by World Meteorological Organization (http://www.wmo.int/pages/index_en.html) the temperature rose by 1.4 °C with average rate of warming ~0.014 °C/year, while in Northern Xinjiang and the average rate of the temperature rise during 1951–1999 was 0.05 °C/year recently. Since middle of 1980s, researchers indicated that in the northwest China climate experienced a transition from the warm-dry into the warm-wet type with the rainfall increasing [17]. However, as the glaciers in inner region of China

belong to the summer-supply type, the relatively large part of liquid rainfall played a certain role in alimentation of the glaciers during the warm summer seasons. Therefore, the rapid retreat rate of glaciers here was mainly resulted from the temperature rapid rising. Thus, the larger rate of the glaciers retreat in the Chinese Altai comparing to that in the Russian Altai was possibly caused by relatively higher rate of the temperature rise in the Chinese Altai.

Modeling of the glacier system responses to climate warming. In this paper, we used the functional model of a glacier system response to climate warming for modeling reaction of the Altai glacier system. It was verified to be reliable and widely applicable in glacial regions of China [19, 21, 22]. Principles and methods of this model were presented in details in several papers [20, 21]. That is why only the main parameters of the model are introduced and the modeling results are shown and discussed in this part.

The basic data and parameters. Main parameters of the Altai glacier systems were taken from inventories of the Chinese Altai and the Russian Altai to investigate a response of glacier system to climate warming by means of the above functional model. Additional data of the Chinese Altai and the Russian Altai were obtained from aerial photographs taken in 1959 and 1952, and the year of 1955 was arbitrarily adopted as initial year to run the model. Mean summer temperatures at the level of equilibrium line altitude (ELA₀) of glacier systems were retrieved from the temperature field at the altitude of 3000 m (see Fig. 3, b) that was calculated using vertical temperature gradient 0.6 °C/100 m and the ground meteorological data in the Altai Mountains. Additionally, difference of 0.5 °C between glaciated and non-glaciated areas was simultaneously taken into account. The temperature of ELA will undoubtedly fall as ELA₀ increases, and in order to calculate the value of ELA₀ lifting under conditions of climate warming, we use the

Table 5. Parameters of glacier systems in Altai Mountains used for prediction*

Glacier system	T_0	S_0 , km ²	V_0 , km ³	$S_{med0}(S)$, km ²	\bar{ELA}_0 , m	AAR ₀	t_{s0} , °C	a_0 , m	W_0 , km ³
Chinese Altai	403	279.03	14.011 5	1.98	2 989	0.698	3.93	2.259	0.63
Russian Altai	1 038	880.50	46.220 3	2.00	2 973	0.783	1.84	1.402	1.23
All studied area	1 441	1 159.53	60.231 8	2.00	2 983	0.724	3.37	2.001	2.32

* T_0 is the initial year 1955 for the model running; S_0 and V_0 are glacier area and volume in the initial year; \bar{ELA}_0 is the equilibrium line altitude in the initial year; $S_{med0}(S)$ is the median size of initial year; AAR₀: Accumulation area ratio; t_{s0} is the mean summer temperature at the ELA₀ in the initial year; a_0 is depth of annual ablation in the initial year, which can be calculated by the formula of Krenke; W_0 is the annual glacial runoff in the initial year, which equals $a_0 S_0 / 1000$.

altitude structure of the glacier system for calculating the accumulative area rate (AAR₀). AAR₀ can be used as an indicator of climate conditions in a certain glaciated region. It is relatively less affected by climatic fluctuations. So, when glacier retreating begins with the terminus, ELA₀ moves up and the temperature simultaneously falls. Statistic results show existence of polynomial relationship between rising of ELA₀ and shortening of glacier area [20, 21]. The parameters used to run the functional model are listed in Table 5.

Predicted results of glacier change

In IPCC, 2007 it is declared that the climate will be warming on our planet during this century, though with greater uncertainties [12]. We make some assumptions about climatic scenarios with possible rates of temperature rise of 0.01 °C/year, 0.03 °C/year and 0.05 °C/year in the future. Corresponding changes of the glacier runoff (W/W_0), the glacier area (S/S_0) and the glacier volume (V/V_0) of the Altai glacier system are shown in Fig. 4.

As we know, when the temperature continuously rises, at first a glacier runoff increases due to increase of glacier ablation. But, when it reaches maximum value, it will fall down because of the lost of too large glacier area. So, on the basis of the glacier runoff process, the three signal runoff specific years of a glacier system can be identified (Table 6). The first specific year, T_1 , is the year when the runoff of a glacier system reaches its maximum runoff magnitude caused by climate warming. It will require 20–30 years (i.e., at about 1980s) to reach the specific year of T_1 . During a peak period of T_1 , the glacier runoff changing rate (W/W_0) would range from 1.0231 to 1.0872 in the Chinese Altai glacier system, from 1,0341 to 1,171 in the Russian Altai glacier system, and from 1.08 to 1.092 in the whole Altai glacier system under different climatic scenarios followed by less than 10% glacier area lost and 10–60 m of ELA rising value.

The second specific year, T_2 , is the year when the runoff of a glacier system returns to its original runoff level. Under different climatic scenarios, it should take about 48–50 years (i.e., at the beginning of this century) to restore its original runoff level and 4–22% of glacier area will be lost being accompanied with 50–220 m rising

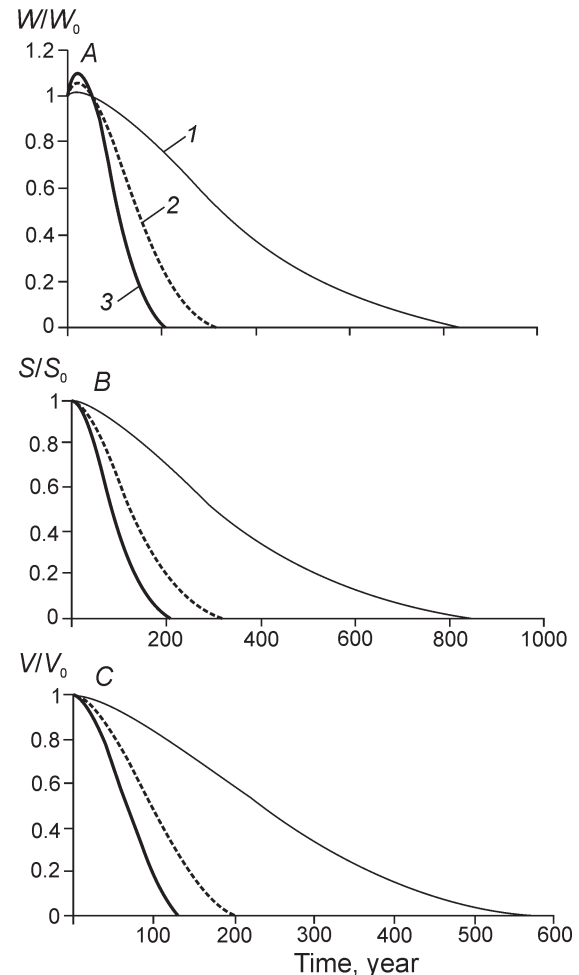


Fig. 4. Model responses of the Altai glacier system for different climatic scenarios.

Temperature rising rates, °C/year: 1 – 0.01; 2 – 0.03; 3 – 0.05; A – runoff; B – glacier area; C – glacier volume

Рис. 4. Результаты моделирования отклика ледниковой системы Алтая для разных климатических сценариев.

Повышение температуры, °C/год: 1 – 0,01; 2 – 0,03; 3 – 0,05; A – сток; B – площадь; C – объём

of ELA during this time. However, the specific year of T_2 of the Russian Altai glacier system (70–83 years) is obviously longer than T_2 of the Chinese Altai glacier system (46–54 years). The third specific year, T_3 is the year when

Table 6. Predicted results of the glacier runoff rate of changes (W/W_0), the glacier area rate of decreasing (S/S_0), the rising value of ELA₀ (ΔELA) and its corresponding temperature decreasing value (Δt) in specific year of the Altai glacier systems

Warming rate, °C/year	T_1				T_2				T_3		
	year	W/W_0	S/S_0	ΔELA	year	W/W_0	S/S_0	ΔELA	year	ΔELA	Δt
<i>Chinese Altai</i>											
0.01	21	1.0231	0.99	11	54	1	0.95	55	675	1112	-6.07
0.03	19	1.0547	0.9629	33	47	1	0.8282	132	272	1016	-6.06
0.05	18	1.0872	0.9528	56	46	1	0.6798	202	171	1015	-6.05
<i>Russian Altai</i>											
0.01	32	1.0341	0.9785	20	83	1	0.9166	164	835	1265	-7.50
0.03	31	1.1024	0.9392	64	70	1	0.7719	172	321	1263	-7.57
0.05	30	1.1710	0.9049	77	77	1	0.5456	259	204	1268	-7.58
<i>Altai Mountains</i>											
0.01	20	1.0180	0.9897	13	50	1	0.9591	49	861	1262	-7.58
0.03	19	1.0549	0.9691	37	49	1	0.8671	143	314	1260	-7.54
0.05	18	1.0929	0.9485	61	48	1	0.776	220	205	1258	-7.52

the runoff of glacier system becomes exhausted and glaciers disappear. If the climate is continuously warming at the rate of 0.01 °C/year, the life-span of the Chinese Altai is 675 years and the Russian Altai is 835 years. However, if the climate is continuously warming at the rate of 0.05 °C/year, the life-span of the Chinese Altai is only 171 years while of the Russian Altai is only 207 years. At the end of this century, only 3% of the glacier area in the Chinese Altai and 9% of the glacier area in the Russian Altai would possibly remain as compared with the glacier area in the middle of the last century under extremely warming rate of 0.05 °C/year.

Discussion and conclusion

When modeling response of the Altai glacier systems to climate warming, only the temperature rise is considered in this paper, however the temperature rising is possibly accompanied with the precipitation increasing in North-West of China in this century. Usually, the precipitation increase plays positive roles in a glacier system responding to climate change, i.e., slows down the area retreating rate, accelerates the runoff increasing rate and depresses magnitude of ELA rising. It was reported that 10% of the precipitation increasing can slow down the glacier area reducing rate of about 4% under the climatic warming rate of 0.01 °C/year in Northern Xinjiang glacier system [18].

The data on glacier variations obtained from satellite and alpine meteorological data make it possible to verify the functional model simulating results. In the Chinese Altai glacier system, remote sensing investigation indicated that 31% of the glacier area decreased during the second half of the last century which was largely consistent with that of the model results under temperature

rising rate of ~0.05 °C/year (the temperature rising rate was actually ~0.05 °C/year in North Xinjiang during the second half of the last century [17]). In the Russian Altai glacier system, the glacier area decreased less during the same time that agrees well with the model results under the temperature rising rate of 0.01–0.02 °C/year (the temperature rate was actually 0.014 °C/year). Therefore, we can assume that overall results of the functional model simulating are reliable.

In conclusion, both average area (0.8 km²) and the median size (2 km²) of the Altai glacier system are relatively smaller as compared with other mountain glacier systems in high Asia. During the past decades, glaciers in the Altai Mountains were rapidly retreating. The difference in the retreating rate was possibly caused by different temperature rising rates on both sides. The glaciers in the Altai Mountains are rather sensitive to climate changes, therefore recent glacier retreating is a result of temperature rising. The Russian Altai glacier system is characterized by relatively smaller decreasing rate of the glacier area and has longer life span responding to climate warming than those of the Chinese Altai glacier system. By the end of this century, only 3% of glacier area in the Chinese Altai and 9% of glacier area in the Russian Altai will possibly remain as compared with the glacier area in the middle of the last century under the extremely warming rate of 0.05 °C/year. The glacier runoff reached its maximum value in 1980s, and was fading during this century that undoubtedly had significant impacts upon ecological environment of the Altai Mountains.

Acknowledgements. This research was supported by Natural Science Foundation of China (NSFN: 40870143) and Russian Foundation for Basic Research (RFBR: 11-05-91159-NSFN_a).

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Изменение ледниковой системы Алтая с середины XX столетия и возможная реакция на потепление климата в будущем

Исследуется ледниковая система Алтая, расположенная на границах России, Казахстана, Монголии и Китая. Общая площадь оледенения Алтая по данным Мирового каталога ледников равна 1750 км², из них 880 км² находятся в России и 280 км² в Китае. Характеристики ледниковой системы проанализированы на базе данных из Каталогов ледников СССР и Китая. Средняя площадь ледника равна 0,8 км², а его медианная площадь по размерам, площади и объёму составляет соответственно 0,3, 2 и 3,4 км². Высота границы питания возрастает с запада на восток и от периферии к центру горной страны вслед за уменьшением величины осадков. Средняя высота границы питания равна 3000 м; максимальная площадь оледенения характерна для высоты 3100 м. Данные каталогов ледников СССР и Китая отражают состояние ледников на середину XX в., использованы также материалы космической съёмки, относящиеся к началу XXI в. Сравнение этих данных показало, что 208 ледников растаяли, а площадь оледенения в целом сократилась на 12%.

Для исследования изменчивости ледниковой системы была разработана модель, в основу которой положена известная формула зависимости величины аккумуляции/абляции от средней летней температуры воздуха на высоте границы питания. На базе этой модели исследовалась реакция ледникового стока на климатические изменения. В процессе моделирования учитывали эффект роста высоты границы питания в случае увеличения температуры и количества осадков при потеплении климата. Модельные расчёты показали, что при потеплении на 0,05 °C/год к концу столетия сохранится всего 9% оледенения Русского Алтая и 3% оледенения Китайского Алтая. Согласно результатам моделирования, ледниковый сток достигал своего максимума в 1970–80-х годах, а затем сокращался. Такой вариант развития гляциоклиматических процессов, несомненно, повлияет на состояние экологических систем Горного Алтая.