Current State of the Altai Glaciers (Russia) and Trends Over the Period of Instrumental Observations 1952–2008

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Abstract Results of research into climate and glacier dynamics in the Altai Mountains (Russia) over the period of instrumental observations (1952–2008) are presented in this article. About 1030 glaciers with a total area of 805 km² and volume of 42.5 km³ have been recorded in the Altai Region. The average summer air temperature in different regions of the Altai has increased during the study period from about 0.2°C (Aktru) to 1.1°C (Akkem). The annual atmospheric precipitation rate has also increased, by 8–10%. Since 1952, the glacier area in different regions of the Altai has decreased by 9–27%, and volume by 12–24%. By 2008, as a result of degradation, the total number of glaciers was 953 with an area of 724 km² and volume of 38 km³.

Keywords Mountain glaciers · Glacier inventory · Glacier retreat · Glacier mass balance · Altai

INTRODUCTION

Determination of the area, volume, length, etc., of glaciers at different times allows us to consider questions connected, on the one hand, with the dynamics of the natural processes of glacier development, and, on the other hand, with processes determining the regime shift and dynamics of glaciers reacting to climate change.

The investigation of the Altai glaciers began in the first half of the nineteenth century when F. V. Gebler in 1835 studied the Altai Mountains and introduced them to the community of geographers as a glacial area. The systematic study of glaciers was started by V. V. Sapozhnikov in the end of the nineteenth century and continued with the expeditions of the Tronov brothers. The first Tronovs' expedition was organized in 1912. In 1925, B. V. Tronov

made the first catalogue of the Altai glaciers (Tronov 1925) in which data on 408 glaciers covering a total area of 590 km² were systematically presented. M. V. Tronov continued the investigations and described 724 glaciers with an area of 600 km² (Tronov 1949).

During the International Geophysical Year (1957–1959) and the International Hydrological Decade (1965–1974), the main focus was on investigations of the main glaciers from permanent research stations that were established in the basins of the Aktru, Multa, and Akkem rivers (Fig. 1). Repeated cataloguing of the Altai glaciers was then carried out (Catalogue of glaciers of the USSR 1978). Currently, such observations continue only at the Aktru Station. A huge amount of material on the Altai glaciers was contributed to the study of regional glaciation in the Atlas of snow and ice resources of the World (World Atlas 1997). As a result, an opportunity occurred to begin the study of internal and external interrelationships with the environment not only for individual glaciers, but for the glacial system as a whole.

The period since 1980 until the present time is characterized by the most detailed and comprehensive data on the characteristics of the Altai glaciers reflecting recent trends of glacier regimes and mass balance. The new data on many glaciers located in various areas of the Altai were published in numerous sources (e.g., FOG 1967–2005; MBB 1991–2009; Narozhniy 2001; Narozhniy and Nikitin 2003; Narozhniy et al. 2002, 2006; Nosenko et al. 2010). These publications include information on: ice reserves in glaciers (120 glaciers), mass balance (5 glaciers), accumulation and distribution of snow (26 glaciers), ablation (8 glaciers), and other characteristics. The structural stratigraphic features and temperature conditions of the active layer of several glaciers were also investigated. These observations and analyses have resulted in the

Fig. 1 Schematic map of the Altai Mountains (a) and observational network within the Aktru Basin (b): 1 cumulative precipitation meters, 2 the Aktru meteorological station, 3 the Upper Aktru seasonal meteorological station, 4 secondary seasonal meteorological

sites, 5 water discharge gauging sites, 6 snow pits, 7 boreholes for ice temperature measurements, 8 ablation stakes, 9 permafrost meters (a device measuring a depth at which an ice surface is located in water filled vertical pipe)

detection of spatial differences of glacial climate, glacier ice formation and glacier flow. As many of the publications are of limited distribution and are in Russian, we make the data widely accessible here by presenting an integration of the permanent observations and research of glacio-hydro-climatic parameters carried out in the mountainous glacierised basin of Aktru since 1957. The annual data on mass balance and dynamics of three Aktru glaciers—Maliy Aktru, Leviy Aktru and Vodopadnyy are also presented and this data contributes to the World Glacier Monitoring Service (WGMS) databank (FOG 1967–2005; MBB 1991–2009).

STUDY AREA

The Altai Mountains represent the highest part of the Altai-Sayan mountain system. They are located between 48–52° N and 84–90° E, and cover an area about of 200 000 km². The region has borders with Mongolia and China in the south and Kazakhstan in the west (Fig. 1a).

The climate of the Altai is determined by three major factors: (1) its location in temperate latitudes of the Northern hemisphere; (2) a dominant direction of water-carrying air mass transport from the Atlantic to the east; (3) the effect of the powerful Asian anticyclone with frosty weather and a cloudless sky in winter-time (an absolute minimum air temperature of –62°C was recorded at the Kosh-Agach meteorological station in 1969). The rate of precipitation decreases from west to east and the glaciers' equilibrium-line altitude increases from 2200 up to 3200 m above sea level in the same west to east direction. Accordingly, the accumulation rate at the glaciers equilibrium-line altitude decreases from 3500 to 500–1000 mm in water equivalent.

In the central part of the area, mountain ridges and massifs reach elevations of 3000–4000 m. Numerous forms of recent glaciation are obvious here. The highest peak is Mount Belukha (4506 m above sea level, the highest point in Siberia), where the largest glaciers in the area, with a size of 12 to 21 km², are located. In the Central Altai (where the Katunsky, North-Chuysky and South-Chuysky Ranges are situated), the Alpine type of glaciation is characteristic, with a prevalence of valley and cirque-valley glaciers with extensive, steep accumulation zones and less steep glacier tongues located at the bases of ancient cirques and trough valleys. The glaciers are non-uniformly distributed over the territory being grouped around the highest mountain peaks and massifs (World Atlas 1997). According to the Catalogue of glaciers, about 1030 glaciers with a total area of 805 km² and volume of 42.5 km³ have been recoded in the Altai region (Catalogue of glaciers of the USSR 1978; Narozhniy and Nikitin 2003).

MATERIALS AND METHODS

To determine the natural and possible climate change-induced dynamics of the Altai glaciers we have chosen a period of 56 years—from 1952 to 2008. The reasons were as follows:

- this period corresponds to the most intensive data gathering by direct field observations and by comparison of cartographical materials from different years;
- interdisciplinary research, including glaciology (mainly studies of mass balance), climatology and hydrology, at fixed points and during field expeditions began in the 1950s;
- large-scale maps (1:25 000, 1:50 000), aerial photographs (1952, 1961, 1975, 1980), and satellite images (1998–2008) for practically all areas of the modern Altai glacial area had been collected by the end of the 2000s.

An integrated analysis of the results obtained during this period gives a wide spectrum of information about quantitative changes of the Altai glaciers for the last 56 years. This information relates to climate change and change of five main parameters of glaciers: (1) glacier tongue location, (2) glacier area, (3) glacier volume, (4) glacier mass balance, and (5) the number and morphological types of glaciers.

Trends in Climate

We estimate changes of climatic parameters over the last decades using observation data from three of the highest mountain meteorological stations of the Altai—Akkem (2050 m above sea level, asl), Aktru (2150 m asl), and Kara-Tyurek (2600 m asl) located in the immediate proximity of a glacial zone. In the basin of Aktru, more detailed observations are carried out at different sites (Fig. 1b).

Change of Glaciers in the Aktru Basin

The most detailed observations and research are conducted at the Aktru research station since 1957. One of the most widely used indicators of the general dynamics of glaciers is the change of their length as a result of the retreat of the glacier tongue front. The glacier front location is being measured annually in the Aktru basin.

We have tried to reconstruct the glacier characteristics of the Aktru basin back to the middle of the nineteenth century. The glacier tongue locations in the Aktru basin at that time are well marked in landforms and confirmed by numerous radiocarbon, dendrochronological, and other types of dating (Galakhov and Nazarov 2008; Solomina 1999). Basic morphometric characteristics for different years are shown in Table 1. These values have been defined using materials

from the Catalogue of glaciers (1978), topographic maps released in 1957, aerial photographs of 1952, photo-theodolite surveys of 1978, and also space images of 2004 and 2008 (ASTER) (Narozhniy 2001; Nosenko et al. 2010).

The mass balance and its components are also being measured annually in the Aktru basin (Fig. 1b).

Change of Glacier Length and Area in the Altai Mountains

We used annual data of glacier length and tongue front retreat in the Aktru basin assessment and less

frequent tongue retreat data on glaciers in other glacierised basins.

Data on the glacier length and area in the Altai Mountains have been derived using new topographic maps constructed with following field surveys in 1998–2008 and large-scale satellite images processed with GIS-technologies. The creation of digital models of glaciers has been carried out on the basis of the Landsat 7 images of August 2008 with 14.5 m resolution. As a program framework we chose the GIS-package Microdem Terrabase-11 (V 6.3). Morphometric characteristic of glaciers have been calculated by means of the module MD-TB Calculate with Shuttle Radar Topography Mission (SRTM) matrix use.

Table 1 Aktru Basin glacier changes between 1850 and 2008

Glacier morphological type and aspect	Year	Glacier front retreat (m)	Annual retreat rate (m/year)	Area (km ²)	Area reduction (km ²)	Volume (km ³)
Maliy Aktru (valley, N)	1850			3.40		0.307
	1911	260	4.3	3.16	0.24	0.276
	1936	90	3.6	3.09	0.07	0.266
	1952	59	3.7	3.05	0.04	0.258
	1999	256	5.4	2.83	0.22	0.245
	2008	146	16.1	2.68	0.15	0.234
Vodopadnyy (plateau, N)	1850			1.16		0.062
	1952	245	2.5	0.84	0.32	0.045
	1999	79	1.7	0.75	0.08	0.041
	2008	46	5.1	0.69	0.06	0.033
Maliy Aktru Cirque (cirque, NW)	1850			0.92		0.080
	1952			0.92		0.066
	1999	150	3.1	0.91	0.01	0.062
	2008	47	5.2	0.90	0.01	0.061
Karatash (hanging, N)	2008	–	–	0.09	–	0.003
Bolshoy Aktru (valley, E)	1850			12.04		1.011
	1936	288	3.3	11.50	0.54	0.893
	1952	72	4.5	11.42	0.08	0.870
Leviy Aktru (valley, SE)	1999	463	9.9	5.95	0.20	0.534
	2008	145	16.0	5.87	0.08	0.524
Praviy Aktru (valley, NE)	1999	301	6.4	5.15	0.12	0.288
	2008	123	13.7	4.65	0.50	0.280
Stazhor (cirque-hanging, N)	1850			0.33		0.017
	1952			0.26	0.07	0.014
	1999			0.24	0.02	0.013
	2008			0.22	0.02	0.011
Uchitel (foothill, N)	1850			0.12		0.0043
	1952	160	1.6	0.08	0.04	0.0027
	1999	70	1.5	0.06	0.02	0.0020
	2008	40	4.4	0.04	0.02	0.0014
Basin in total	1850			18.055		1.4842
	1952			16.655	1.40	1.2591
	1999			15.98	0.68	1.1881
	2008			14.88	1.1	1.155

Change of Glacier Volume in the Central Altai Mountains

Over the period 1983–2004, detailed radar-tracking sounding of glaciers in three main centers of the central Altai glacier area (the Katunsky, North-Chuysky and South-Chuysky Ranges) has been conducted. The basic data set has been obtained between 1996 and 2003. The original portable radar-tracking instrument that measures ice thickness has been applied for this purpose. The device characteristics, technique of measuring and post-processing are described in Narozhniy and Nikitin (2003). The data obtained were used to make a new estimation of ice reserve distribution.

For determination of ice reserves in other time intervals and for other glaciers the dependence of the ice volume on the glacier area was used. The power law relationships for glaciers of four dominant morphological types have been obtained on the basis of radio-sounding data on 120 glaciers of the Altai Region (Narozhniy and Nikitin 2003):

$$V = 0.0444 F^{1.134} \text{ (for 46 valley glaciers),} \quad (1)$$

$$V = 0.0464 F^{1.028} \text{ (for 36 cirque-valley glaciers),} \quad (2)$$

$$V = 0.0487 F^{1.244} \text{ (for 29 cirque and cirque-hanging glaciers), and} \quad (3)$$

$$V = 0.0451 F^{1.128} \text{ (for all 120 glaciers including 9 ice dome glaciers and glaciers of other types).} \quad (4)$$

In these relationships, V is the glacier volume (a dependent variable) and F is the glacier area (an independent variable). The high coefficients of determination that exceed 0.79 have allowed the estimation of not only the total volume of ice in the Altai glaciers, but also the detailed distribution of the glacier area and volume between separate glacial basins and morphological types of glaciers (Table 2).

To detect glacier volume changes over the 56-years period (1952–2008), we have calculated glacier volumes related to 1952. In order to obtain glacier ice volume

estimates for 1952, the above-mentioned statistical dependencies of the volume on the area of a glacier derived for the inventory period of 1996–2003 have been applied assuming that these dependencies are valid for different periods of time.

RESULTS AND DISCUSSION

Trends in Climate

The basic climatic parameters influencing the glacial state are the average summer air temperature and the precipitation rate (in summer, winter, and annual). In Fig. 2, the long-term dynamics of the summer (June–August) air temperature at Kara-Tyurek, Akkem, and Aktru stations is shown. Air temperature has increased during the period 1951–2005 at all the stations (0.6°C Aktru, 0.8°C Kara-Tyurek, and 1.1°C Akkem), but the increase was actually observed only over the last two decades, since 1985. By comparing the long-term dynamics of the atmospheric precipitation at the stations, it is possible to see that their linear trends are also positive both for the annual period and for the summer and winter seasons, but they are less significant than the increases in air temperature. On average, the annual precipitation rates have increased by 8–10%, summer precipitation by 4–5%, and winter precipitation by 10–12%.

Trends in the Number of Glaciers and Areal Extent of Glaciers of the Aktru Basin

Currently, there are eight glaciers in the Aktru basin (Fig. 3). Their basic morphometric characteristics for different years are shown in Table 1.

By the middle of the twentieth century, there were six glaciers in the basin, but as a result of the disintegration of the large complex-valley glacier Bolshoy Aktru into the Leviy and Praviy Aktru glaciers and the separation of a

Table 2 Total glacier area and volume decrease during 1952–2008 in the main mountain ranges of the Altai

Ranges	Area (km ²)		Area reduction		Volume (km ³)		Volume reduction	
	1952	2008	km ²	%	1952	2008	km ³	%
Katunsky	319.05	290.24	28.81	9.1	15.476	13.241	2.235	11.9
South-Chuysky	216.01	195.41	2.60	9.5	12.055	10.786	1.269	12.2
North-Chuysky	166.04	148.66	17.38	10.4	9.695	8.585	1.110	11.5
South Altai and Karaalakhinskiye Mountains	57.0	50.4	6.6	11.5	3.064	2.490	0.574	18.5
Tabin-Bogdo-Ola	31.1	27.4	3.7	11.9	1.703	1.291	0.412	24.2
Saylyugem, Chikhacheva	6.3	5.2	1.1	20.5	0.245	0.161	0.084	33.6
Basin of the Biya River	9.4	6.9	2.5	26.9	0.327	0.218	0.109	33.0
Altai in total	804.9	724.2	80.7	10.2	42.565	37.222	5.793	13.6

Fig. 2 Mean summer air temperature time series at the alpine meteorological stations of the Altai: 1 Kara-Tyurek, 2 Akkem, 3 Aktru

tributary from the Maliy Aktru glacier (it was named Maliy Aktru cirque glacier), the number of glaciers in the Aktru basin has become eight. A process of disintegration began in the end of the 1950s—beginning of the 1960s. The total decrease of the Leviy and Praviy Aktru glacier area from the mid-19th century up to 1952 was about of 0.62 km², and between 1952 and 2008 the Praviy Aktru glacier has decreased by 0.62 km² and Leviy Aktru by 0.28 km² (Table 1). It is important to note that over this period the length of the Leviy Aktru glacier tongue was being reduced 1.5 times faster than the tongue of the Praviy Aktru glacier. This may be explained by both aspect of the glaciers' surfaces and amount of moraine material lying on the lower parts of the glacier tongues. The decrease of the Leviy Aktru glacier area was only 0.01 km², but at the same time the area of the Praviy Aktru has decreased by 0.35 km², or 7.15% of the glacier area.

The glacier of Maliy Aktru is a basic glaciological benchmark in the Aktru basin and all over the Altai Region. Its area was 2.68 km² in 2008, from which 0.07 km² was covered by the right lateral moraine with a thickness of at least 10–60 cm. The open surface of the glacier was separated from the moraine-covered part by an abrupt borderline, i.e., deep lateral cracks and an ice fault from 5 up to 20 m height. Now the moraine-covered part of glacier surface is the most passive: here velocities of ice motion do not exceed 1–2 m/year while velocities of ice flow in the open part of the glacier reach 15–30 m/year. In the mid-nineteenth century, the glacier area was 3.4 or 0.79 km² (23.3%) more than present. The changes have affected not only the glacial tongue but also the glacial accumulation area: in just over the last 30 years (since 1978, the beginning of regular photo-theodolite surveys) the area in the high-altitude zones of 2800–3300 m above sea level has been reduced by 0.14 km², that represents almost one third of the area decrease during

the study period of 1952–2008. This rapid rate of decrease might be because the glacial accumulation area is thin and is connected to rock. The second reason might be a general depression of the glacier surface by 3–8 m.

The most significant changes of glacier area in the Aktru basin have taken place at the plateau glacier of Vodopadnyi (total decrease by 0.46 km², or 35%, from 1850 to 1952) and these decreases occurred all around the glacier. Its area has decreased only by 0.15 km² (10%) since 1952, but the surface has become 3–10 m lower since then (Table 1). Over the last years, the speed of its retreat has gradually slowed down. In 1978, 1986 and 1993 a stationary state of the glacier was observed. Currently, the glacier is moving only slowly (velocities of its surface ice motion are 3–6 m/year only) and it is losing its ability to move at all because it has been reduced in size. Other glaciers of the Aktru basin are related to small forms of glaciers.

The total decrease of the glacier area in the Aktru basin since the mid-nineteenth century is 2.75 km², or 18%. More than half of this decrease has occurred since 1952, though the rate of area degradation of each glacier was very different—from 8–10% up to 35 and even 50% (Table 1; Fig. 4).

The range of glacier length reductions is extremely great (Table 1): it varied from 100 m (Vodopadnyi) up to 550 m (Leviy Aktru) within only the last 56 years (1957–2008). Importantly, for this period the intensity of valley glaciers retreat has increased 1.3–1.8 times in comparison with the period 1850–1952. The annual intensity of retreat fluctuates from 2–3 m/year up to 45–50 m/year.

Trends of Glacier Ice Volume in the Aktru Basin

The large reductions of the area and length of glaciers described above have resulted in a reduction of ice mass.

Fig. 3 Glaciers of the Aktru basin: **a** Maliy Aktru, **b** Praviy and Leviiy Aktru, **c** Vodopadnyi

Fig. 3 continued

Quantitative estimations made on the basis of both the direct echo-sounding of glaciers and use of the dependencies (1)–(4) for different periods of time show that the volumes of ice are being reduced more intensively than the glacier area, except for the Vodopadnyi glacier (Fig. 4). A

half of the volume decrease on the Vodopadnyi glacier is caused by the reduction of its area and another half by its thinning and amplification of surface flatness. For the Maliy Aktru glacier this ratio is 30 to 70%, for the Leviy and Praviy Aktru glaciers it is 20 to 80%, and for all

Fig. 4 Reduction of glacier areas F (solid lines) and volume V (dashed lines) (in percentage of values estimated for 1850): 1 Maliy Aktru, 2 Vodopadnyy, 3 all glaciers

glaciers of the basin the ratio is 25 to 75%. Moreover, looking at the curves in Fig. 4 and taking into account recent trends of climate warming and the effect of glacier morphology change (i.e., glacier thinning and surface flatness), it is possible to assume that relative loss of glacier volume will be more significant than the area. At the same time, the rate of area reduction might be slowed down due to the elevational increase of the lower glacier boundary and large ice thickness near the lower edges of the glaciers.

Trends of Glacier Mass Balance in the Altai Mountains

The long-term trends of glacier mass balance changes for some glaciers and the relationships of these changes to climate fluctuations have been estimated. For the period of instrumental observations of mass balance (1957–2008), the cumulative mass deficit of glaciers ranged on average from 600 to 800 cm in water equivalent. At the same time, the state of each individual glacier differed (even the sign of the mass balance can differ). Nevertheless, deviations from the long-term mean balance value at all of the glaciers coincide, and this determines the average trend of glaciation development in the Altai Mountains for each year.

The amplitude of mass balance decreases from the west to east. Within the inter-annual variability of annual mass balance, some periods of accumulation or loss of ice mass were detected (Fig. 5): in 1967–1973, 1975–1977, and 1983–1990 mass balance was positive, and in 1961–1966,

1978–1982, and 1991–2003 loss of mass occurred. The duration of these periods was 6–9 years. Abnormal positive values of mass balance were observed every 9–12 years and abnormal negative values every 20–22 years. The cumulative deficit of mass balance of the Maliy Aktru glacier (a basic glaciological benchmark and reference glacier of the Altai Mountains) was 730 cm in water equivalent for the period of instrumental observations.

It is possible to determine a similar kind of cyclicity in the components of the fluctuations in glacier mass balance (the total accumulation and ablation) (Fig. 5), although during the last two decades the inter-annual variability of mass balance has changed little, e.g., before the mid-1980s, we could trace visible asynchrony in the inter-annual fluctuations of accumulation and thawing, and after that date there were other trends. The probable cause of such changes in behavior of the glaciers might be the change of the global climatic system.

Climate warming since the early 1980s has been reflected in the regime characteristics of glaciers. As our investigations show, significant increases of annual air temperatures have been observed everywhere in the Altai Mountains. In the highlands, increases of temperature have been recorded in all seasons of the year except for autumn, but the most intensive warming took place in the summer period when the increase of the average air temperature was 0.6–1.1°C over the period 1952–2005 (Fig. 2). Moreover, the warming has affected precipitation—both the total amount and intra-annual distribution. The increase of the annual precipitation is determined by increases in

Fig. 5 Annual variations of **a** total accumulation c_t , **b** annual ablation a_t , and **c** mass balance b_n of the Maliy Aktru glacier between 1962 and 2008. *Solid line* annual variations; *dashed line*: 2–5-years running means

winter and especially in spring (April–May). These increases resulted from a strengthening the zonal circulation processes in the Altai Region. However, they have resulted in increased winter mass balance values.

It is important to note that for the last 15–20 years, the frequency of abnormal values both of annual mass balance and its separate components has been increasing. The amplitude of annual glacier mass balance fluctuations was about 1600 mm, mass balance values ranging from 340 to –1230 mm. The change in total accumulation varied by a factor of almost two (from 700 to 1270 mm) and the ablation varied by more than two times (from 950 to 2020 mm). Within individual years, the structure of the mass balance varies. In some cases it is possible to observe a significant shift of the beginning of the onset of ablation to an earlier date, e.g., May 9th, 1991 or April 13th, 1997 when the average date of the beginning of the ablation process on glaciers is May 15th. As a result, glacier tongues completely lose snow cover much earlier, ice forming processes in the glacier zone of accumulation finish earlier and the contribution of glacial melting to river run-off increases. In such cases, glaciers usually have significant or sometimes catastrophic mass deficits. In other cases, when the melting begins later (e.g., in the first 10 days of June), the frequency of heavy and intensive summer snowfall events increases. These events are generally related to cyclone transport from the Barents and Kara seas, and also to shifting northwest cyclone trajectories and the formation of a high-altitude cyclone above the Altai Mountains. At the end of August or beginning of September, the end of the ablation period occurs. The lower air temperatures of the summer months during these events also promote the decreased rate of melting of glaciers if the temperatures are decreased by about 1–3°C. In such years, the annual mass balance of the glaciers is close to zero or is even positive (Fig. 5).

Change of Glacier Length and Area in the Altai Mountains

Data on change of location of the glacier tongue fronts since 1835 are shown in Fig. 6 for several of the largest and most investigated glaciers of the Altai Mountains. In general, the prevailing trend of glacier retreat is unquestionable, but there is great variability within the whole glacial system or in its individual basins. Moreover, additional data on 98 glaciers of the Altai that have infrequent series of observations (about 3 to 5 measurements over the 1952–2008 period) show that there are no completely stationary glaciers in the study area, except for several small glaciers of 0.1–0.5 km² in area that are cirque, cirque-slope and slope glaciers located at high altitude and oriented to the north or east.

However, over the 56-year period 1952–2008 glaciers have not only been declining. Numerous instrumental observations show that against a general background of decreasing glacier area over the whole period of 1952–2008, periods of a stationary state or even advance of individual glaciers have occurred. In addition, annual observations for the last 25 years of 15 glaciers in the central Altai Mountains (Narozhniy et al. 2002, 2006; FOG 1967–2005) show that the first period of delayed retreat and even advance of glaciers occurred in 1987–1988 (5 of 15 advanced), and that a second period occurred in 1993 when 8 glaciers advanced. The rates of advance were rather insignificant and fluctuated from 2 to 7 m/year. These small advances have been overcompensated by thawing during the following balance year.

The generalized dynamics of all of the observed glaciers over the 56 year period 1952–2008 can be summarized as follows: for the first decade (1952–1961) intensive glacier recession was followed by a rather long period of relatively low rates of glacier retreat until 1980. Subsequently, short-

Fig. 6 Cumulative curves of glacier front variations during the instrumental observation period

term periods of substantial increases in retreat rates occurred until 1987 after which, for the last 20 years (1988–2008), there has been increased variability. Against a background of a general trend of increasing rates of glacier decline, there have been individual years of extremely high rates of glacier retreat (1991, 1992, 1998) and years of extremely low rates of retreat and even of glacier advance in 1988 and 1993.

Annual data analysis of movement of glacier tongue fronts shows that they are not synchronous and differ from -2 to -10 m/year or more in 1 year and vary among separate years by $+7$ to -45 m/year. The greater the glacier area, the wider is the inter-annual amplitude of glacier tongue front fluctuations. Despite overall asynchrony, fluctuations are mostly synchronous for glaciers located on one slope of a mountain range in similar orographic and climatic conditions. Nevertheless, in some cases, even within one basin, glacier behavior might be completely individualistic, e.g., the behavior of the Levisy Aktru glacier in the Aktru basin.

Comparison of glacier areas published in the Catalogue of glaciers (1978), with corrections and additions (Narozhniy and Nikitin 2003; Nosenko et al. 2010), and updating by including the areas obtained in 2008 has shown that for the period of 56 years, the reduction of the glacier-covered area of that part of the Altai Mountains in the Russian Federation only, reached 80.7 km^2 (Table 2). The smallest areas of decline are associated with the glaciers of the central part of the glacier-covered area (9.1 – 10.4%)—on the Katunsky, North-Chuysky and South-Chuysky Ranges. These ranges have the highest altitudes that reach or exceed $4,000$ m and about 80% of the Altai glaciated area is situated here. Along the periphery of the main centre of glacier-covered area, the loss of the glacier area becomes more significant reaching a maximum of 20 – 27% on mountain ranges with small glaciers of 0.1 to 1.5 km^2 in area (the Kuraysky, Chikhacheva Ranges, etc.). Over the 56-years period, the glaciers of the central Altai in total have receded with a rate of $1.175 \text{ km}^2/\text{year}$ (i.e., by 0.17% of their initial area). For the total glaciated area of the Altai Mountains (not just the central area), the recession rate was $1.441 \text{ km}^2/\text{year}$, or 0.18% changing from 0.10 to 0.50% in different years.

Of the total area decrease of 80.7 km^2 since 1952 (Table 2), 57% corresponded to valley glaciers (i.e., complex-valley glaciers, valley glaciers, and cirque-valley glaciers), 37% to slope glaciers (cirque, cirque-hanging, hanging glaciers, etc.), and the remaining 6% to plateau, ice dome and basin type glaciers.

Examining each morphological type of glacier separately, it appears that the greatest losses of area are observed at plateau and ice dome glaciers—an average of 16.1% during the study period (0.35% per year)—with

variations from 8% (0.17% per year) up to 30% (0.65% per year).

Cirque and cirque-hanging glaciers have lost on average 9.4 and 8.8% of their areas, respectively, with variations from 3 up to 20% for individual glaciers. From the east to west part of the mountain region, the area reduction for this morphological group of glaciers increases markedly from 7.5 to 8.5% (for the whole period) on the South-Chuysky Range, up to 10.5% on the Katunsky Range, and reaches a maximum of 12 – 17% in the West-Katunsky centre of glaciation.

Cirque-valley glaciers decreased on average by 7.2% . Valley glaciers experienced the least reduction of area—on average about 4% , with individual variations from 2.5 up to 8% . The complex-valley glacier area was slightly more reduced—by 5.1% . There are only three glaciers of this type in the region (the glaciers of Gebler, Bolshoy and Maliy Berelskiy), which are located on the southern slope of the Katunsky Range. The fronts of their tongues are situated at the lowest altitudes (1980 , 1940 and 2110 m, respectively) of all glacier front tongues throughout the Altai Mountains.

Change of Glacier Volume in the Central Altai Mountains

In the study area, 120 glaciers with a total area of 263.5 km^2 (41.2% of the glacier area) and ice volume of 15.1 km^3 have been measured by direct radio-sounding over the period of 1996 – 2003 . Among the glaciers measured, the valley and cirque-valley glaciers represent 72% of the area and 75.8% of ice volume, cirque and cirque-hanging glaciers 18.7% of the area and 15.1% of the volume, and basin and plateau glaciers contribute the remaining 9.3% of the area and 9.1% of ice volume. According to our estimates, the volume of all the central Altai glaciers obtained by direct radio-sounding and use of statistical relationships (1)–(4) between glacier area and volume is 33.527 km^3 with an average glacier thickness of 51.5 m. The greatest average glacier thickness of 57.7 m for a particular range was determined for the North-Chuysky Range, and the least thickness of 47 m for the Katunsky Range. The average thickness of the South-Chuysky Range glaciers is 53.1 m. The ice volumes accumulated on the various mountain ranges are as follows: 13.581 km^3 of ice in 338 glaciers of the Katunsky Range, 11.076 km^3 in 213 glaciers of the South Chuysky, and 8.870 km^3 in 181 glaciers of the North-Chuysky Range (Table 2).

The distribution of ice volume between glaciers of different morphological types is as follows: the greatest volumes are concentrated in complex-valley and valley glaciers 18.742 km^3 (56% of the total ice volume), in

cirque-valley glaciers 7.127 km^3 (21.2%), in cirque and cirque-hanging glaciers 5.201 km^3 (15.5%), in hanging glaciers 1.419 km^3 (4.2%), and 1.038 km^3 (3.1%) in glaciers of other morphological types.

Using the relationships (1)–(4) between glacier area and volume for different types of glaciers we also have calculated ice volumes in other mountain ranges of the Altai – in the South Altai, the Karaalakhinskiye Mountains, the Tabin-Bogdo-Ola, the Saylyugem, and the Chikhacheva etc. where 97 glaciers with an area of 92.87 km^2 (12.5%) and volume of 4.66 km^3 are situated (Table 2).

Hence, we can conclude that in all the Altai glaciers in the Russian Federation 37.222 km^3 of ice or 34.5 km^3 of water are contained at the beginning of the 21st century, and these figures correspond to a glacier-driven component of river runoff for ~ 35 years (taking into account that the mean glacial melt run-off is about $1 \text{ km}^3/\text{year}$).

To detect glacier volume changes over the 56-years period (1952–2008) we have calculated glacier volumes related to 1952. In order to obtain glacier ice volume estimates for 1952, the statistical dependencies of the volume on the area of a glacier (1)–(4) derived for the inventory period of 1996–2003 have been applied assuming that these dependencies are valid for different periods of time. The estimate of ice volume for 1952 was 42.565 km^3 , i.e., the volume has decreased by 5.793 km^3 (13.6%) since 1952. Over the same period, the loss of the glacier area was 80.7 km^2 , or 10.2% (Table 2). Thus, declining ice volume proceeded more intensively than glacier area. Moreover, 80% of the ice loss has been caused by thinning of glaciers, and only 20% by reduction of their area.

Changes in Number of Glaciers and Morphological Types in the Altai Mountains

Due to the reduction of area and general retreat of the Altai glaciers, their number has changed. For the last 50–100 years, this process is marked in many mountainous, glacier covered regions of the globe: in some regions the number of glaciers has increased, whereas in others it has decreased. Similar contrasting situations have been observed in the Altai.

The total number of glaciers has decreased from 1030 to 953 (by 7.5%) with variations on different ranges from 5.2 to 18.7%. The number of glaciers with an area exceeding 0.1 km^2 has decreased also, from 830 to 747 (10%), and the number of glaciers with area less than 0.1 km^2 increased by 3%: of 200 small glaciers, 97 disappeared, but 103 small glaciers were formed by shrinkage of larger-sized glaciers. Twenty glaciers have been formed by the separation of tributary glaciers and disintegration of large valley and ice-dome glaciers (6 glaciers on the Katunsky Range, 5 on the

North-Chuysky Range and 9 in the South Altai). As a result, the proportion of larger glaciers ($\geq 0.1 \text{ km}^2$ in area) has slightly decreased from 80.6 to 78.4%.

The change of number of glaciers has taken place by extinction, separation of small glaciers from tributary glaciers and disintegration of larger glaciers.

The first process (extinction) is prevailing in the Altai—97 glaciers became extinct. They represented an area of 3.78 km^2 , i.e., 0.5% of the glacier area in 1952 or 6.6% of the area reduced over the 56-years period. The extinct glaciers were generally cirque or hanging glaciers. Their sizes varied from 0.02 to 0.1 km^2 , and their altitudinal difference was 50–200 m. Most of them were situated below the long-term mean equilibrium-line altitude associated with large glaciers. They were basically located in lateral offsets of the main mountain ranges or peripheral parts of the basic centers of glaciation.

Another process, which also has changed the structure of the glacial system quantitatively and morphologically, is the replacement of extinct glaciers by larger-sized ones that have been redefined as belonging to this category (area $< 0.1 \text{ km}^2$) due to reductions in area. One hundred and three such glaciers were formed in the following morphological types: 54 hanging glaciers (52% of the total number), 29 cirque glaciers (28%), 14 cirque-hanging glaciers (14%), and 6 glaciers (6%) of other types. The majority of them (up to 70%) were located on southern slopes of ranges, their length did not exceed 0.2–0.7 km, their absolute altitude varied from 2400–2700 m in the West-Katunsky glacier centre up to 2800–3200 m on the North-Chuysky and South-Chuysky Ranges, and the difference of altitudes of the bottom and top points of the glaciers was 100–300 m. The reduced area of such glaciers is about 3.1 km^2 .

Only about 20 cases of glacier disintegration and tributary separation have been observed. Large complex-valley glaciers were characteristic subject to disintegration. For example, the Bolshoy Aktru glacier has divided into two significant valley glaciers—the Levyi and Praviy Aktru. One of the basic causes of glacier disintegration is a general lowering of their surface, and not only in a tongue area, but also in the accumulation zone.

CONCLUSIONS

This study has provided detailed information on the behavior of glaciers of different morphological types, sizes and aspects during recent climate change in the Altai. A great variety of instrumental, aerial photographic and satellite imagery data have made it possible to confidently estimate size and water resource characteristics of the Altai glaciers and to study their changes from the mid-twentieth century.

It has been determined that for the last 56 years (1952–2008), summer air temperature has increased on average by 0.2°C per decade. The process of climate warming has accelerated particularly since 1985. At the same time, the increase of annual precipitation was rather insignificant. The Altai glaciers were decreasing in size and number over this period. The rates of glacier area degradation were from 7–10% for large valley glaciers to 15–20% for cirque-valley glaciers with a maximum of 25–30% for plateau and dome ice glaciers. In total, the glacier-covered area has decreased by 80.7 km², or 10.2% over the 56 years. The smallest reductions were characteristic for glaciers of the central part of the glacier covered area (9–11.5%). Along the periphery of this centre, losses of area became more and more significant (20–27%). On average, the glaciers of the Altai decreased by 1.441 km²/year, or 0.18%. However, the volume of ice decreased even more intensively, by 0.08 km³/year, or 0.2%.

The dominant trend in fluctuations of the annual mass balance for 1957–2008 was increasing negative values and this trend seems as if it will continue into the future. The components of the mass balance, accumulation and ablation, demonstrate different trends since 1985.

The high sensitivity of mass balance and morphometric characteristics of glaciers to climate change reinforces the importance of: (1) continuing and expanding glaciological monitoring and (2) using glacier dynamics as a proxy of climate change, i.e., an inverse of task 1. It is, therefore, extremely important to continue the annual observations begun in 1957 of glaciers in the Aktru basin and expand them to the Altai Mountains as a whole. These observations should include mass balance and its components, change of glacier volume and area, dynamics of the tongue fronts and other glacial-hydroclimatic parameters such water content of glaciers and the amount and timing of run-off that can affect flooding and clean water supply of inhabited areas down-stream.

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