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ICE THICKNESS, VOLUME AND CURRENT CHANGES OF THE SARY-TOR GLACIER AREA (AK-SHYIRAK MASSIF, INNER TIAN SHAN)

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In the paper we present and discuss results of radio-echo sounding and ice thickness modeling of Sary-Tor Glacier (Ak-Shyirak massif, Inner Tian Shan). The ability for correct assessment of the regional glacier volume in Tian Shan is limited due to the small amount of direct ice thickness measurement data. 17 km of ice thickness measurements tracks were done on 18–20 May, 2013 using monopulse VIRL-6 GPR with central frequency 20 MHz. Maximum measured ice thickness was 159 m, whereas average thickness was 51 m. Detailed ice thickness and bedrock topography maps were compiled for Sary-Tor. The glacier volume was defined as (0.126 ± 0.001) km^3. In addition, ice volume was calculated using the Glab-Top model calibrated by direct data and volume-area scaling. Both approaches could be used to determine the ice volume of the Sary-Tor glacier with high accuracy. The Sary-Tor glacier area shrinkage rate in 2003–2012 slightly decreased compared to 1977–2003.

Tian Shan, Ak-Shyirak massif, Sary-Tor glacier, radio-echo sounding, glacier volume, glacier change

INTRODUCTION

Mountain glaciers are the key indicator of climate changes [*IPCC, 2007*] and an important freshwater reservoir, accumulating, in different estimates, from 51·10^3 km^3 [*Ohmura, 2004*] to 166·10^3 km^3 of water [*Radic and Hock, 2010*]. The role of glaciers as freshwater reservoirs is especially large in the mountains surrounded by arid or semiarid areas. Tian Shan belongs to such mountain systems: rivers flowing from its slopes provide water to about 100 million people [*Aizen et al., 2007a*]. An important role in the supply of water to rivers is played by glaciers providing from 6 % of the total runoff in the Syr-Darya River catchment to 47 % of the runoff in the Tarim River catchment [*Glaciation..., 1995*]. In the summer season, which is especially essential for agriculture, the role of the glacier flow sharply increases, reaching on average 20–40 % in Central Asia, and in extremely hot years – 70–80 % [*IPCC, 2007*].

Over the recent decades, the glaciers of Tian Shan are consistently retreating. To take an example, from 1960 to 2006, the glacier covered area here was reduced, according to evaluation of *M.B. Dyurgerov* [*2010*], by nearly 17 % (from 15,416 to 12,815 km^2). The glaciers' volume over this period reduced by 219 km^3. At the end of XX – beginning of XXI centuries, the reduction rate of the Tian Shan glaciers has accelerated [*Khromova et al., 2003; Aizen et al., 2007b; Bolch, 2007; Kutuzov and Shahgedanova, 2009*]. At the current stage river runoff is not diminishing: reduction of the glacier covered area is so far compensated by increased ablation [*Aizen et al., 2007a*]. It is likely that the continuing climate change will lead to change in the regime of the Tian Shan rivers. To ensure accurate estimates of change in the region's river runoff, information on the volume of the Tian Shan glaciers is required because existing estimates of glacier volume vary from 1,048 km^3 [*Aizen et al., 2007a*] to 1,369 km^3 [*Liu and Han, 1992*] and 1,840 km^3 [*Aizen et al., 2008*]. Direct data on the thickness and volume of the glaciers are so far insufficient to make correct regional assessment [*Hagg et al., 2012*].

The goal of this study was to measure ice thickness of the Sary-Tor glacier (Inner Tian Shan), to assess its volume on the basis of instrumental data and by modeling with the GlabTop model [*Paul and Lindsbauer, 2012*], to adapt the model to the conditions of Inner Tian Shan and to evaluate the current changes in the glacier area.

THE SARY-TOR GLACIER

The Sary-Tor glacier is located in the northwestern part of the Ak-Shyirak massif (Fig. 1). This typical valley glacier having north-northwestern exposition is referred as Glacier No. 356 in Cataloque of Glacier of USSR [*1977*]. In the first half of 20th

century Sary-Tor glacier flew from three corries located in the right part of the main valley; at the beginning of the second half of the 20th century, the glacier from the lower corrie detached from Sary-Tor (Fig. 1). Therefore currently it makes sense to speak about two glaciers existing in the location of the Sary-Tor glacier. Debris cover is almost missing on the glacier, therefore change of the Sary-Tor glacier rather clearly reflects the climate change occurring in Inner Tian Shan.

In 1943–1977, the glacier terminus was quasistationary, and insignificant (by 0.08 km^2) reduction of the glacier area occurred due to separation of its right hanging tributary. The elevation of the glacier surface reduced by 19.4 m during the same period. In 1977, the length of the Sary-Tor glacier was somewhat greater than 4 km, while its area was 3.54 km^2 [*Kuzmichenok, 1988*]. The glacier's highest point was at the altitude of 4,756 m, and its lowest point was at the altitude of 3,859 m asl. After 1977, the shrinkage rate of the glacier has been accelerated: from 1977 to 2003, the glacier lost about 20 % of its area [*Aizen et al., 2007b*].

In 1985–1991, Sary-Tor was the subject of mass-balance monitoring [*Dyurgerov, 1992; Glaciation..., 1995*]. The glacier data were used to calculate the balance of the total glacier area in the Ak-Shyirak massif [*Mikhalenko, 1993*]. In 1987, topographic survey and radio-echo sounding were conducted under guidance of S.A. Nikitin, who used a TGU pulse radar with central frequency 700 MHz, and the measurement points were reliably tied to the local system of coordinates. Maps of ice thickness, glacier bed and surface topography of the Sary-Tor glacier are kept in the archives of the Institute of Geography, RAS. Unfortunately, the methodology of compilation of the ice thickness map was not described, therefore we did not compare it to the current data.

The Sary-Tor glacier seems to be the best studied glacier in the Ak-Shyirak massif. The previous studies [*Mikhalenko, 1993*] showed a general possibility of using the Sary-Tor glacier data for calculating the glacier turnover for the entire Ak-Shyirak massif. Yet, the Sary-Tor glacier change since 2003 until present has not been analyzed. Reliable data on the volume of ice contained in the Sary-Tor glacier are missing.

THE STUDY METHODOLOGY

Field geophysical works. Geophysical methods have been widely used in glaciology since 1960s [*Bogorodsky, 1968; Robin et al., 1971*]. Since 1970, the method of radio-echo sounding has become one of the basic tools for measuring glacier thickness, having nearly replaced the other previously used geophysical contact methods, including seismic sounding and gravimetric measurements [*Reynolds, 2003; Macheret, 2006*].

To measure the thickness of the Sary-Tor glacier, in 2013 we used a VIRL-6 GPR with 20 MHz central frequency and a system of digital recording of radar and navigation data. This radar was specially designed to measure thickness of temperate, polythermal and cold glaciers by the joint efforts of the researchers and engineers of the Akadempribor research and production company of the Uzbek National Academy of Sciences, of the Madrid Polytechnic Institute and of the Institute of Geography, RAS [*Vasilenko et al., 2003; Berikashvili et al., 2006*]. This GPR allows sound glaciers up to 600 m thickness [*Macheret, 2006*]. To measure glacier thickness, VIRL-6 has been long and successfully used in Svalbard [*Vasilenko et al., 2006; Lavrentyev et al., 2011; Martin-Espacol et al., 2013*], Caucasus [*Lavrentyev et al., 2010; Kutuzov et al., 2012; Lavrentyev et al., 2014*], in Antarctica [*Macheret et al., 2009*] and proved to be as the most universal one. The GPR is easily mounted on two backpacks, so it is possible to conduct ground-based measurements in hard-to-reach mountain glaciers by a team of three persons (Fig. 2). The total

Fig. 1. Sary-Tor glacier (19.05.2013). Photo by R.A. Usubaliyev.

Fig. 2. GPR measurements at the Sary-Tor glacier. Photo by N.V. Kovalenko.

weight of the VIRL-6 GPR is about 10 kg, considering two 7–9 A·h batteries, i.e., it is much lighter than the widely used similar instruments (Ramac, Loza, et al.). The radar has a system of digital recording of radar and navigation GPS data and includes a receiver and a transmitter. To synchronize these devices, optic fiber cable is used. The receiver is launched automatically with an interval of 0.2–1.0 s.

Radio-echo sounding measurements at the Sary-Tor glacier in the Ak-Shyirak massif were conducted in walking routes by a team of four people. Measurement tracks were located according to the grid of longitudinal and cross sectional tracks and traverses, covering the maximum possible and accessible part of the glacier. Radio-echo sounding was performed at the Sary-Tor glacier within three working days from May 18 to May 20, 2013. During this time, about 17 km measurement tracks were carried out, including hardly accessible crevassed zones in the accumulation area (Fig. 3).

An example of an original radargram made by VIRL-6 GPR at the Sary-Tor glacier is shown in Fig. 4. Here layers of cold and temperate ice are clearly seen, as well as the contact with the glacier bed. Such records are typical of glaciers of a polythermal type, with a bottom layer of water-containing temperate ice. In the given record, this layer is characterized by increased reverse dissipation of radio waves in the inclusion of water in temperate ice.

Processing of radio echo sounding data for the Sary-Tor glacier, compilation of ice thickness and glacier bed maps. To allow visualization and processing of the obtained radio echo sounding and navigation data, a software RadexPro2011.1 issued by GDS Production was used [*Kulnitsky et al., 2001*]. This method is described in detail in [*Vasilenko et al., 2014*]. To recalculate the measured delay times of the signals reflected from the glacier bed into icepacks, we used the average velocity of radio wave propagation in temperate ice equal to 168 m/μs [*Macheret, 2006*].

Ice thickness values were recorded in the database simultaneously with the navigation data in a table. In this study, a portable GPS-receiver Garmin GPS 76 CSX, previously calibrated by the sea level, was used. Navigation data were registered in the UTM WGS-84 format, zone 44. Its application was limited to work during radio echo sounding in the glaciers to record planned coordinates and the glacier surface elevation along radio echo sounding profiles.

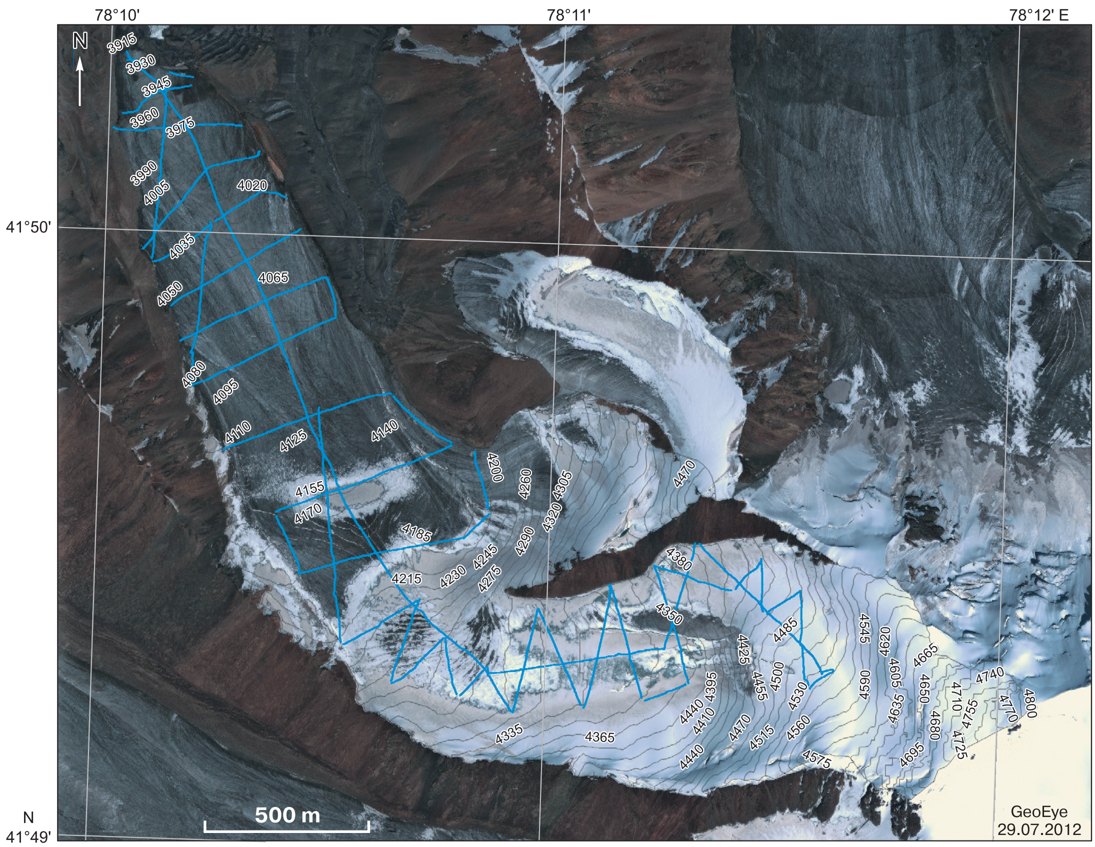

Fig. 3. GPR tracks on the Sary-Tor glacier. Background: GeoEye satellite image. ©2012 DigitalGlobe Inc., 29.07.2012.

Contour lines were extracted from ASTER GDEM V2.

Surface elevation data obtained from GPS were compared to the data extracted from ASTER GDEM V2 (*gdem.ersdac.jspacesystems.or.jp*) with horizontal resolution 30 m and vertical accuracy 12 m for mountain areas. In some cases (where steep slopes are nearby), using of the DEM essentially improved the quality of the GPS data. Then GPR and navigation data were exported into the text format and were used to transform the delay time of the signal into ice thickness (considering the mean velocity of radio wave propagation in the glacier) and to compile ice thickness and glacier bed topography maps.

In most profiles, easily identifiable reflections from the glacier bed were obtained (Fig. 4). In some profile fragments, interpretation of radargrams was difficult due to the presence of a large number of crevasses in the glacier (a transition zone between the accumulation area and the glacier snout) and strong dissipation in the ice thickness, typical of temperate and polythermal glaciers saturated with thawed water. Data on 35 crossings of the radio echo sounding showed good convergence: the standard deviation in the difference of ice thickness is 1.1 m with mean ice thickness value at the crossings of the profiles being 76.2 m, which corresponds to the measurement accuracy of up to 1.5 %.

For compilation of ice thickness and glacier bed maps we used the contour of the Sary-Tor glacier, obtained as a result of manual delineation of the satellite image GeoEye with spatial resolution of 0.6 m/pixel as of 29.07.2012, and ASTER GDEM V2 digital terrain model. The maps were made on the basis of GPS data with minimum use of interpolation and extrapolation on the ArcGIS program, version 10.1. The values of ice thickness along the glacier margins were taken to be equal to zero, while along the border with unmeasured parts of the glacier they were obtained by direct measurements.

The map of the glacier bed topography was obtained as a difference between the elevation of the glacier surface according to the DEM ASTER GDEM V2 and ice thickness data. It is evident that the elevation of the glacier bed has errors admitted for the use of the DEM (12 m), a standard error of determining ice thickness, which is 1.1 m, according to our calculations, as well as an error arising due to a change in the altitude of the glacier surface in 2009–2013. Thus, the accuracy of the glacier bed altitude could be assessed as 15–20 m.

Simulation of ice thickness and calculation of the volume of the Sary-Tor glacier. It is believed currently that simulation of ice thickness is most promising on the basis of the physical laws of glacier movement [*Frey et al., 2013*]. To model the ice thickness of the Sary-Tor glacier, we used the GlabTop (Glacier bed Topography) model, which had been previously used in the Alps [*Linsbauer et al., 2012*], in the Himalayas and in the Karakorum [*Frey et al., 2013*]. Detailed description of this model is given in [*Paul and Linsbauer, 2012*]. For the model to work, information is required regarding the relief of the glacier surface and its borders.

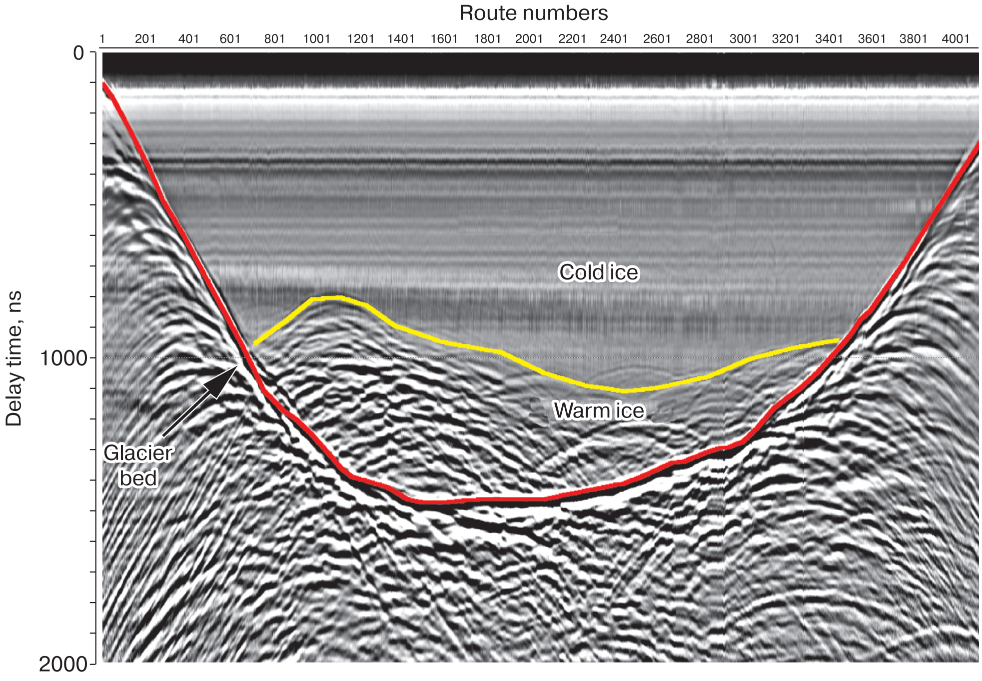

Fig. 4. A radargram of cross section profile in the medial part of the Sary-Tor glacier.

Sections with cold and temperate ice are clearly visible.

It is assumed in the model that the shear stress in the glacier bed along the central line of the glacier is constant [*Nye, 1952*], and the glacier flow is laminar. Then ice thickness along the glacier's centerline may be calculated by the formula

$$h=\frac{\tau}{f\rho g\sin\alpha}, \quad (1)$$

where h is ice thickness, m; τ is basal shear stress, kPa; f is the shape factor; ρ is density of ice (900 kg/m^3); g is gravity acceleration constant (9.81 m/s^2); α is surface slope along the centerline of the glacier, degrees.

The basal shear stress τ could be calculated for each glacier by the empirical relation based on the difference of altitude (ΔH) between the highest and lowest points of this glacier [*Haeberli and Hoelzle, 1995*]:

$$\tau = 0.005 + 1.598\Delta H - 0.435\Delta H^2. \quad (2)$$

The shear stress τ could be found by way of reverse calculation, by substituting in equation (1) the known values of ice thickness. In our case, the difference of altitude for the Sary-Tor glacier was extracted from ASTER GDEM V2.

The shape factor f is related to resistance arising on the glacier borders as a result of friction between moving ice and valley slopes and may vary from 0.5 to 0.9 [*Paterson, 1994*]. For valley glaciers with elliptic cross section f is recommended to be 0.8 [*Nye, 1965*].

The centerlines were manually digitized along two main branches of the glacier in perpendicular to all contours. The slope calculation along the centerlines was done over a horizontal distance of 50 m. The ice thickness was interpolated between the points along the flowlines and the glacier boundaries with ice thickness equal to zero using Topo to Raster tool in ArcGIS.

In addition, we tried to calculate the volume of the Sary-Tor glacier basing on power law which relates glacier volume to surface area. For this purpose, a regional formula was used [*Kuzmichenok, 2006*], later modified by *S.S. Kutuzov* [*2012*], considering newly acquired knowledge of changes in the geometry and volume of the glaciers. The error of such calculation does not exceed 10 % of the measured values of the glacier volume or the values calculated otherwise [*Kutuzov, 2012*].

The glacier volume as a function of its area was determined by the formula

$$V = 0.0356F^{1.53}, \quad (3)$$

where V is the glacier volume, km^3; and F is the area of the glacier, km^2.

Change of the Sary-Tor glacier area. Changes of the glacier area were analyzed by comparison of multi-temporal Terra ASTER satellite images, with resolution of 15 m/pixel in 2003 and in 2012. All images were overlayed and transformed into a single projection UTM WGS-84, zone 44. The glacier boundaries in 2012 were firstly manually delineated using a GeoEye image with resolution of 0.6 m/pixel, after this the same was done for Terra ASTER images. In addition, a topographic map of 1987 and scale 1:10 000 was overlayed on the images. All measurements were fulfilled using ArcGIS software, version 10.1. Considering the image resolution of 15 m/pixel, the systematic error for determining of the Sary-Tor glacier area was estimated as 0.12 km^2, or 5 % of the measured value.

RESULTS AND DISCUSSION

Thickness and volume of the Sary-Tor glacier according to the radio-echo sounding data. The maps of ice thickness and glacier bed topography obtained as a result of radio-echo sounding are schematically shown in Fig. 5.

The ice thickness map provides data on ice distribution in the Sary-Tor glacier. The average ice thickness is 51 m, the maximum ice thickness being 159 m. The zone of maximum ice thickness is tied to the glacier centerline; as the flow moves towards the valley sides, ice thickness inevitably decreases. Two zones of increased ice thickness could be identified: in the flat upper part of the glacier snout; in the lower and middle part of accumulation area (Fig. 5, *a*). These zones are separated by a belt of decreased ice thickness, related to the steep part between the accumulation area and the glacier snout. In the medial part of accumulation area, the zone of maximum ice thickness is shifted towards the right slope of the valley. The zones of minimum ice thickness are tied to the steep parts of the ice apron above the accumulation area, as well as to the marginal parts on the glacier snout, especially near its terminus. Ice volume was calculated using the approximation Topo to Raster ANUDEM [*Hutchinson, 1989*] in the ArcGIS software, considering the hydrological correctness of the glacier bed topography. It was established that volume of the Sary-Tor glacier is (0.126 ± 0.001) km^3.

The map of the Sary-Tor glacier bed topography is shown at Fig. 5, *b*. The pattern of the isolines on the glacier bed generally reflects the pattern on its surface (Fig. 3). We note that glacier bed slope under the snout is essentially lower than glacier surface slope, and greater than it in the upper part of the accumulation area. Such a pattern is typical of most of the valley glaciers and could be explained as result of glacier erosion.

Thickness and volume of the Sary-Tor glacier by the simulation data. Joint analysis of simulation and instrumental data allowed us to adjust the model parameters. The best agreement between the measured and calculated values of ice thickness occurs when using the shape factor $f = 0.6$ in formula (1) as a parameter. The volume of the Sary-Tor glacier calculated using GlabTop model is 0.125 km^3, which

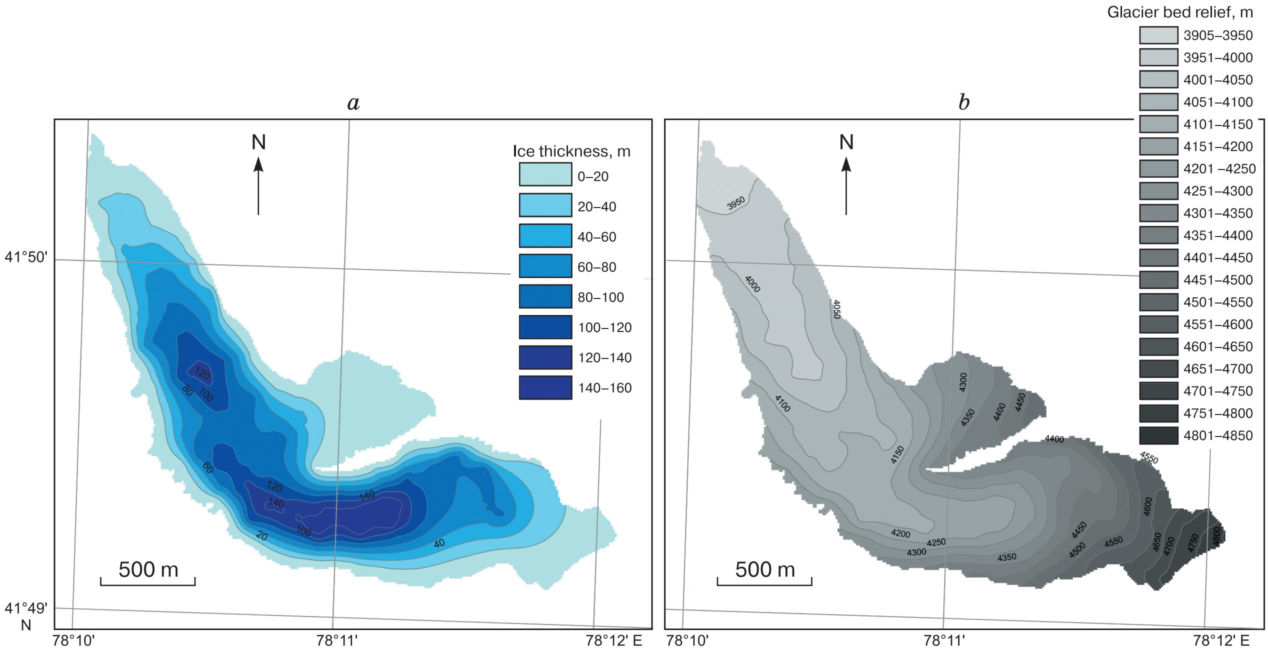

Fig. 5. Maps of the Sary-Tor glacier ice thickness (*a*) and glacier bed topography (*b*), based on GPR measurements over the glacier area.

by less than 1 % differs from the results of radio-echo sounding. At the same time, the use of the value $f = 0.8$ recommended for valley glacier [*Nye, 1965*] would lead to essential underestimation of the glacier volume (by 25 %). A map of ice thickness compiled according to the GlabTop model is shown in Fig. 6, *a*. We note that the model generally satisfactorily describes distribution of ice thickness of the Sary-Tor glacier and may be used for evaluation of ice resources contained both in individual glaciers and for glacier covered area for the Ak-Shyirak massif. However, deviations of the modelled values of ice thickness in some areas are rather large (Fig. 6, *b*; 7).

For the glacier snout, the modeling values of ice thickness are essentially higher than the results of instrumental measurements (Fig. 7, *b*). Such deviation

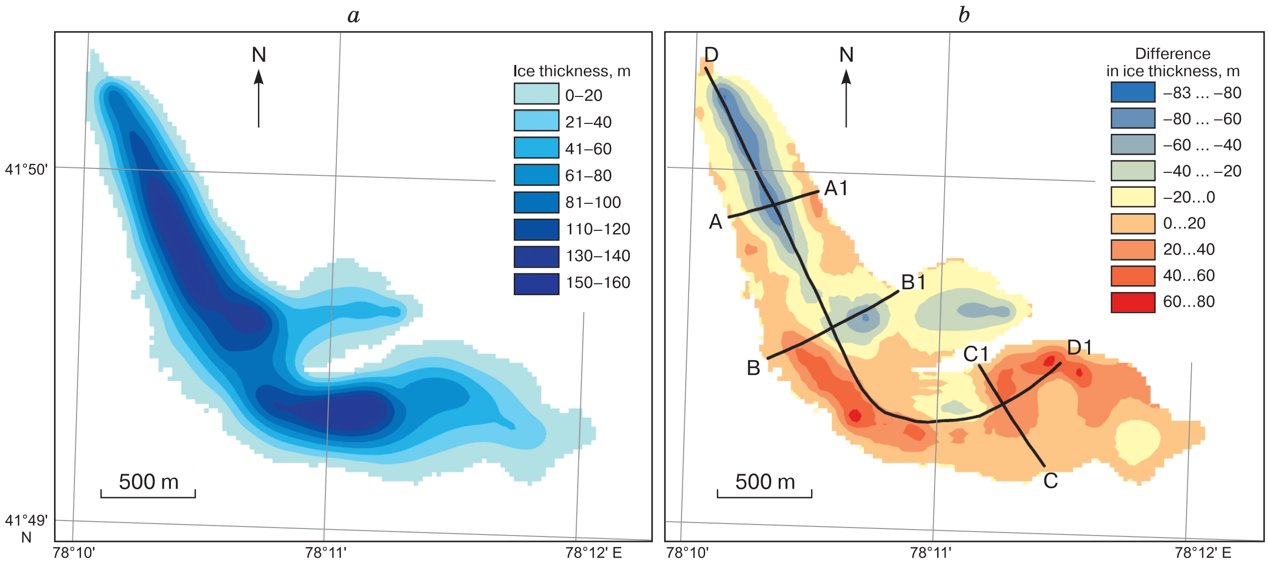

Fig. 6. Ice thickness at the Sary-Tor glacier according to GlabTop model (*a*), differences between ice thickness maps according to GPR measurements and modeling (*b*).

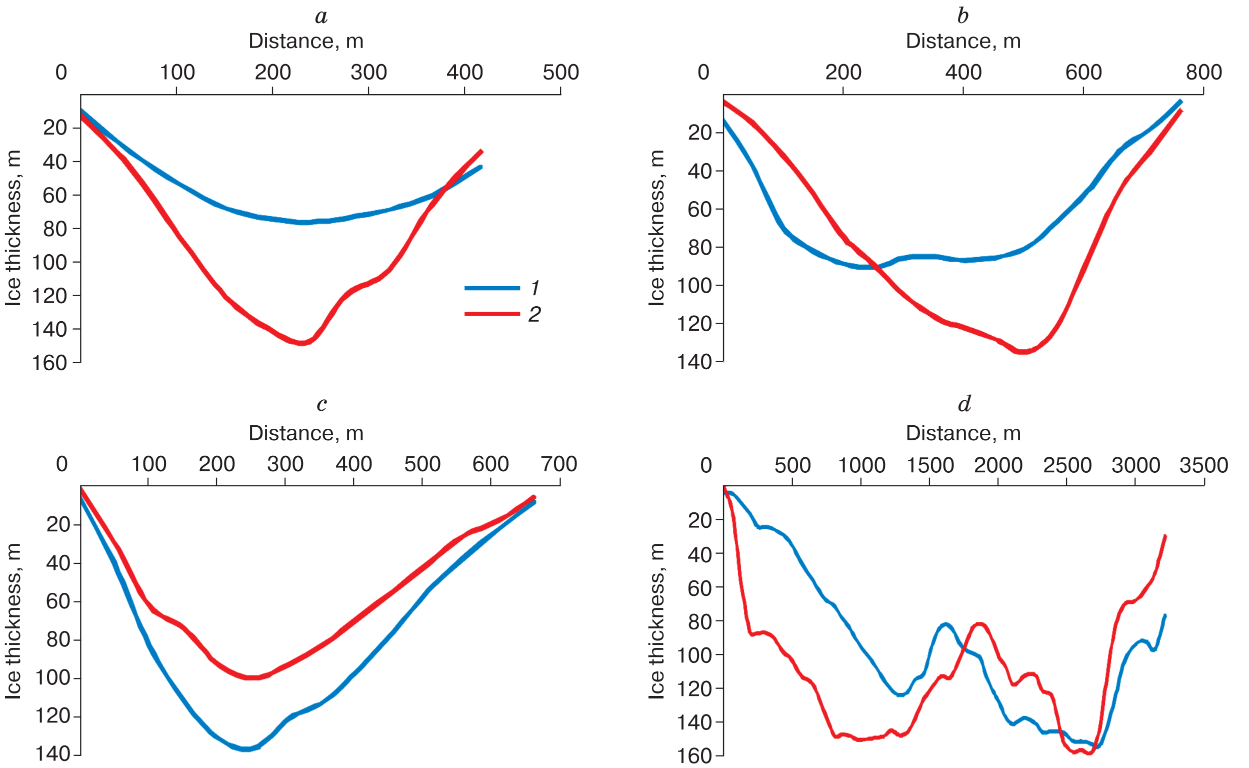

Fig. 7. Ice thickness in longitudinal and cross-section profiles according to GPR measurements (curve *1*) and simulation results (curve *2*):

a – A–A1; *b* – B–B1; *c* – C–C1; *d* – D–D1 (Fig. 6).

may be partly attributed to the specific features of glacier shrinkage in continental areas, at certain stages manifesting itself in lowering of its surface when the glacier terminus does not retreat. In 1943–1977, the surface of the Sary-Tor glacier lowered by 19 m, with the glacier terminus remaining quasistationary [*Kuzmichenok, 1988*]. Quite reversely, in the accumulation area of the Sary-Tor glacier, the model underestimates ice thickness (Fig. 7, *c*).

The glacier volume calculated by equation (3) amounted to 0.135 km^3. The area of the Sary-Tor glacier determined through GeoEye image taken on 29.07.2012 was 2.39 km^2. As opposed to [*Aizen et al., 2007b*], the area of the hanging glacier was not included into this value, which had previously been a tributary to Sary-Tor but which had completely separated from it by already 1977. Thus, the method error was 6 %. This confirms the conclusions made by *S.S. Kutuzov* [*2012*] regarding the possibility of obtaining correct values of the volume of the glaciers of Tian Shan on the basis of volume vs. area scaling.

Change of the Sary-Tor glacier area in 2003–2012. Comparison of the topographic map and of multi-temporal satellite images is shown in Fig. 8.

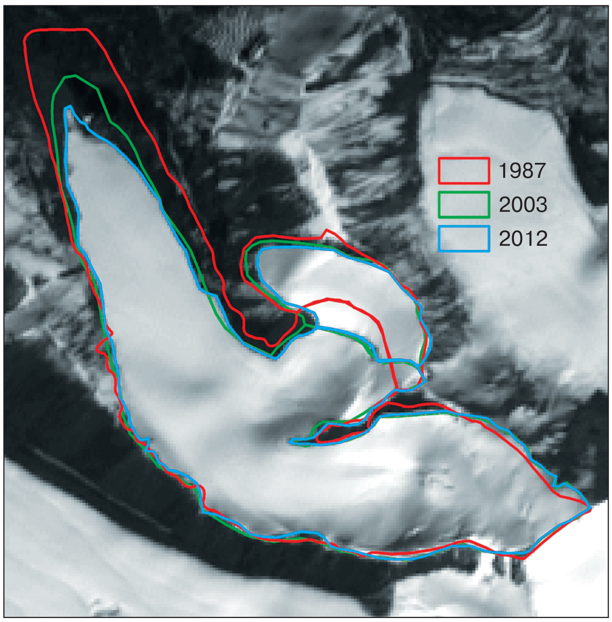

Fig. 8. The Sary-Tor glacier outlines in 1987, 2003 and 2012.

Background: Terra ASTER satellite image on 30.09.2012.

The area of the Sary-Tor glacier at the end of the summer of 2012 was 2.39 km^2 excluding separated hanging glacier with area 0.33 km^2. Compared to the period of 1977–2003, the shrinkage rate of the Sary-Tor glacier slightly slowed down in 2003–2012. In 1977–2003, the annual reduction of glacier area was 0.77 % [*Aizen et al., 2007b*], in 1987–2003, the reduction rate was 0.80 %, and in 2003–2012, it was 0.67 %. It could be explained by both the absence of a statistically significant trend for the rise of the summer temperatures in 2002–2010 and by partial adjustment of the glacier to the changed climatic conditions. We also note that in 1977–2003 the Sary-Tor glacier reduction rate was more intensive than the reduction rate of glacier covered area for the entire Ak-Shyirak massif [*Aizen et al., 2007b*]. At the same time, the shrinkage rate of the Sary-Tor glacier in 1977–2012 agrees well with the reduction rates of the glaciers in the Upper Naryn catchment [*Hagg et al., 2012*].

CONCLUSION

The measurements of the ice thickness over the whole area of the Sary-Tor glacier (Ak-Shyirak massif) were conducted in the period of May 18–20, 2013 with a VIRL-6 GPR. During the field campaign, 17 km of GPR tracks were sounded. According to our data, the standard error of the measurements made was 1.1 m, or 1.5 %. The maximum ice thickness on the glacier reached 159 m, with the average value of 51 m. For the first time, we compiled detailed maps of ice thickness and bed topography of the Sary-Tor glacier and determined the volume of glacier to be (0.126 ± 0.001) km^3. In addition we calculated ice volume using GlabTop model, calibrated by the radio-echo sounding data and the regional relation between glacier volume and area. It was found that both approaches could be used for adequate assessment of the Sary-Tor glacier volume. It is essential that a reduced value of the shape factor $f = 0.6$ is preferrably to be used for GlabTop modeling in the conditions of Inner Tian Shan. It was established that the shrinkage rate of the Sary-Tor glacier in 2003–2012 insignificantly slowed down compared to the period of 1977–2003.

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