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SNOW COVER AND GLACIERS

ESTIMATION OF THE GREATER CAUCASUS GLACIERS VOLUME, USING RADIO-ECHO SOUNDING DATA AND MODELING

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This work presents and discusses the results of ice-thickness measurements and modeling of the Greater Caucasus glaciers, using radio-echo sounding data, *GlabTop* model and satellite imagery. Ground and airborne radio-echo sounding measurements were conducted at selected Caucasus glaciers, including the biggest Bezengi glacier, reference glaciers Djankuat and Marukh as well as glaciers of the southern and eastern slopes of Mt. Elbrus in 2011–2013. The *GlabTop* model was calibrated using the measured ice-thickness data and ice-thickness and bedrock topography maps were completed for 224 glaciers (13 %) which cover 719 km^2 or 64 % of the total glacier area in the Caucasus. New dataset of the Caucasus glaciers outlines was completed using available satellite imagery. There were 1713 glaciers with the surface area of 1121 ± 30 km^2 in Caucasus in 2010–2013. The data obtained were used to calibrate volume-area scaling relationship and to calculate the total volume of Greater Caucasus glaciers, which is 43.5 ± 5.0 km^3.

Caucasus, glacier thickness and volume, modeling, radio-echo sounding

INTRODUCTION

Despite the knowledge of mountain glaciation is advancing, ice thickness and volume of mountain glaciers are still the least studied parameters. According to the recent data provided by the Randolf Glacier Inventory [*Pfeffer et al., 2014*], there are ca.198 thousand glaciers in the world which cover the area of 726,800 ± 34,000 km^2. The values of glaciers surface values allowed for the calculations of their volume and ice mass, corroborated by area–volume (A–V) relations [*Grinsted, 2013; Radić et al., 2014*], and by a balance-dynamic model [*Huss and Farinotti, 2012*]. However, the data from direct measurements of ice thickness necessary for a reliable determination of glaciers volume and evaluation of water reserves stored in them, are available only for 0.13 % of the total number of glaciers [*Grinsted, 2013*]. To this extent, the results of such estimations of ice storage may contain significant errors that are difficult to assess. It can be illustrated by the fact, that owing to the changes introduced into the methodology alone, the volume of Himalayan glaciers in recent years "has shrunk" by several times [*Bolch et al., 2012*].

Most data were obtained by measuring ice thickness along individual profiles or through discrete points, while the spatially distributed data fit for determining glaciers volume have proven to be scarce. Radio-echo sounding (RES) techniques provide high (2–3 %) accuracy of measurements of glacier ice thickness using ground-based and airborne types of their transportation, or adjusted for walking routes, which is why appear the best suited for such estimations. Given that the existing approaches are labor intensive and often fail to perform adequate measurements equally on individual glaciers and in the entire mountain system, this prompted the need for developing alternative techniques for estimating glaciers volume.

Glacier ice thickness modeling is one of the fast developing methods for assessment of glaciers volumes on the basis of simplified glaciological principles of ice flow, glacier outlines and the surface topography in the form of digital elevation models (DEM) [*Farinotti et al., 2009; Li et al., 2012; Paul and Linsbauer, 2012*].

Despite the widespread application of these techniques, each contains significant errors in estimations of ice volume and glacier bed topography. Recent works on measuring thickness of glacier ice with a helicopter-towed device, conducted in the Alps [*Gabbi et al., 2012*] have shown that direct measurements data can be supplemented with the modelled glacier ice thickness values.

Estimates of ice volume on the basis of glaciers area–volume (A–V) scaling have been applicable in glaciology for quite a long time [*Chen and Ohmura, 1990; Meier and Bahr, 1996; Macheret, 2006; Grinsted, 2013; Radić et al., 2014*]. Regional A–V relations were calculated for the Alps [*Abermann et al., 2009; Farinotti et al., 2009*], the Svalbard [*Macheret and Zhuravlev, 1985*], the Dzhungar/Djungar Alatau [*Macheret et al., 1988*], and the Tien Shan mountains [*Kutuzov, 2009, 2012*]. The feasibility of application of the modelled glaciers volumes was assessed by a series of statistical tests [*Farinotti and Huss, 2013; Macheret et al., 2013*]. In particular, it has been shown [*Macheret et al., 2013*] that in order to obtain reliable area-volume relations on a regional level, it would be reasonable to utilize the data on volumes of a limited number of glaciers of dominant morphological types and sizes within glaciated system.

To date, the largest wealth of data on glaciers volume and thickness measurements is available for the Altai Mountains, Russia [*Nikitin, 2009*]. Similar data sets exist for some other areas of mountain glaciation, e.g. the Alps [*Fischer and Kuhn, 2013*], the Svalbard [*Martín-Español et al., 2013*], and the work on processing and storing the records of glaciers thickness measurements in the Tien Shan mountains is still in progress [*Petrakov et al., 2014*]. The information of this kind so far has been very limited on the Caucasus glaciers.

The very first data on ice thickness distribution of the Mount Elbrus glaciers were collected in 1934–1938 during the Elbrus expedition of the Academy of Sciences of the USSR, when the method of electrical sounding was applied to measure ice thickness in the upper part of Garabashi Glacier [*Mikhailov, 1939*]. Back in 1958, its ice thickness was measured with a seismic sounding technique, but the results were compromised by imperfections of the equipment and raw measuring techniques, applicable for glaciological purposes at that time [*Bokanenko and Isaev, 1960*]. In 1967, however, ice thickness map was compiled for Mt. Elbrus glaciers, relying on the proxy data and measured depth of crevasses and ice falls [*Kravtsova, 1967*].

During the International Hydrological Decade (IHD) ice thickness of Marukh Glacier in W. Caucasus was measured by gravimetric and radar sounding techniques [*Kotliakov, 1988*], and in the early 1970s the pioneering radio-echo sounding measurements were conducted on Bezengi [*Macheret and Luchininov, 1973*] and Djankuat glaciers [*Boyarskii, 1978*]. During the period of 1987–1989 three boreholes to bedrock were drilled at the Garabashi glacier [*Zagorodnov et al., 1992*], and the first radio-echo measurements of ice thickness made with TGU high-frequency (700 MHz) impulse radar, which served as a basis for generating a glacier ice thickness map for the southern slope of Mt. Elbrus [*Rototaeva et al., 2002*].

Over the two years 2005–2007, radio-echo sounding surveys were conducted at an altitude of 5,115 m on the ice plateau of W. Elbrus [*Lavrentyev et al., 2010*], the saddle and crater of the East Summit (*the data are still unpublished*). In 2011, the ground-based radio-echo sounding was used for measurements of ice thickness of Marukh and Marushonok glaciers in the Western Caucasus [*Kutuzov et al., 2012*], and Djankuat Glacier in 2012–2013.

The full-scale airborne radio-echo sounding measurements were first launched in 2012 and 2013, to measure thickness of the Caucasus glaciers. On September 15, 2012 ice thicknesses of Bezengi, Dykh-Su, Ailama, Agashtan and Mizhirgi largest complex-valley glaciers, in the upper reaches of the Cherek river, was measured with the survey resulting in more than 130 km of radio-echo sounding profiles. On July 1, 2013 more than 200 km long RES-derived profiles were obtained at eight glaciers of the southern and eastern sectors of Mt. Elbrus glaciers – Bolshoy Azau, Malyi Azau, Garabashi, Terskol, Irik, Irikchat, Chungurchatchiran and Birdzhalychiran. This substantially complemented the glaciers thickness database for the Caucasus region (the materials from ground-based radio sounding of mountain glaciers in the Caucasus span the period from 2002 to present), which has allowed the *GlabTop* model-based estimations of uncertainties in calculating ice thickness [*Linsbauer et al., 2012; Paul and Linsbauer, 2012*].

In recent years, the satellite based glacier inventories of the areas of mountain-glaciation were created within *GLIMS* program and *Randolph Glacier Inventory (RGI)* (satellite images spanning 1999–2010) [*Pfeffer et al., 2014*] (www.glims.org). However, the quality of the existing databases does not always permit to utilize the data on the regions of mountain glaciation. In some areas, the inaccuracies in glaciers delineation stemmed from the seasonal snow and debris cover, thus causing erroneous estimates of the extent of individual glaciers. Glacier outlines often prove not consistent with the delineations in the modern orthorectified images, which is most likely to prompt incorrect estimates on a regional scale. This situation has therefore called for more recent (2010–2013) data on glaciers outlines for the Greater Caucasus glaciers, with an aim to conjugate these with RES measurements of glaciers ice thickness.

The paper provides the results of and discussion on ice-thickness measurements and modelling of the Greater Caucasus glaciers, derived from radio-echo sounding, modelling and satellite images.

RESEARCH METHODS

Ground-based radio-echo sounding. The field works included measurements of ice thicknesses using the ground-based and helicopter-borne modifica-

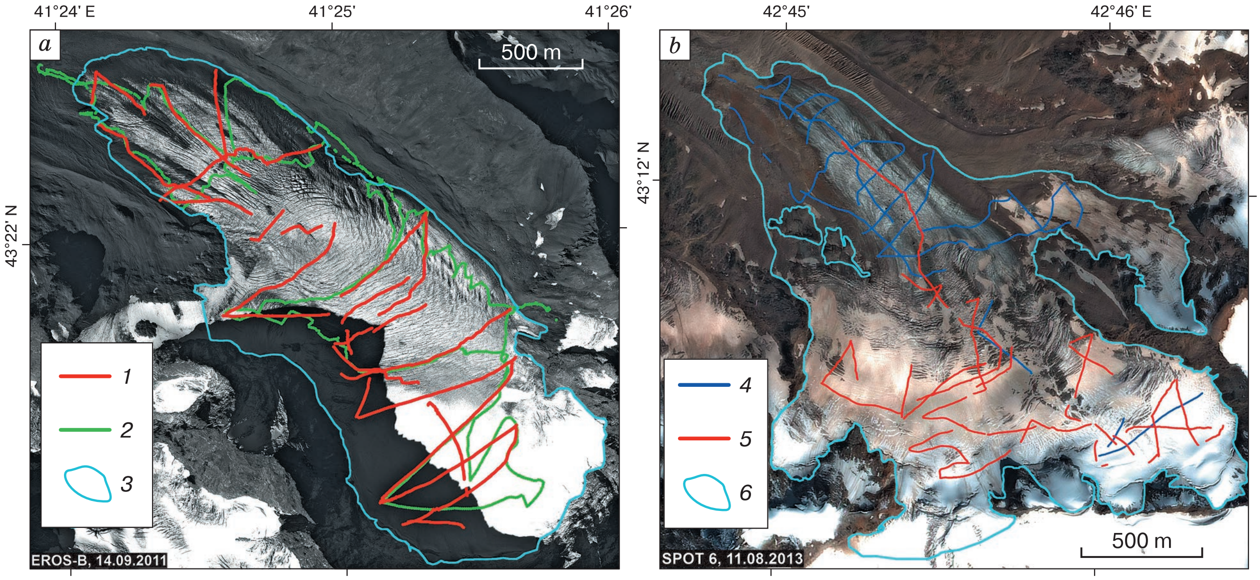

Fig. 1. Ground-based radio-echo sounding and DGPS-survey profiles at Marukh Glacier (*a*) in 2011, and on Djankaut Glacier (*b*) in 2012–2013.

a: *1* – ground-based RES profile, 2011; *2* – DGPS-survey profile , 2011; *3* – glacier contours, 2011; *b*: *4* – ground-based RES profile, 2012; *5* – ground-based RES profile, 2013; *6* – glacier contours, 2013.

tion of VIRL-6 radar locator. The applications of ground-based radio-echo sounding methodology for measuring glaciers ice thickness with VIRL-6 monopulse radar (with frequency 20 MHz) equipped with digital recording device and GPS have been discussed in e.g. [*Lavrentiev et al., 2010*]. In the years 2011 through 2013, the same methodology (ground-based radio-echo measurements) was applied to Djankuat and Marukh glaciers, the two reference glaciers of the Caucasus [*Kutuzov et al., 2012; Lavrentyev et al., 2014*]. The data obtained proved to be sufficient for mapping glaciers ice thickness, and for comparing the measured and modelled values (Fig. 1).

Airborne radio-echo sounding. Aiming to accrue massive data on glaciers thickness and extent on the northern slope of the Greater Caucasus we have tested the airborne radio-echo sounding technique for measuring ice thicknesses of glaciers of different morphological types. Previously, it had shown good results in the studies of Svalbard glaciers in 2011 (*Vasilenko E.V., personal communication*) with a helicopter-borne modification of VIRL-6 monopulse radar with 20 MHz frequency and 10 m-long antennas employed for that purpose. The equipment was mounted on a special frame, suspended from the helicopter fuselage.

Given that air-borne sounding Frame (FAZL-2) designed for glaciological applications is substantially heavy (weight: about 150 kg), it is equipped with tail stabilizer, to ensure a well-balanced position during the flight. During its operation, the entire structure with the equipment attached to it was lowered from the helicopter on a polypropylene rope and fixed in a suspended state at a distance of 15 m from the fuselage. The measurements were taken in the automatic mode with 0.2 seconds frequency (sample rate), at average flying speed of about 70 km/hr at altitude ranges from 10 to 500 m above the glacier surface. The video camera incorporated into the digital data logger block enabled us to monitor the radar operation in real time during the flight [*Lavrentiev et al., 2013*].

In the Cherek river catchment area, the total length of RES-derived profiles exceeded 130 km, with 50 % of them bearing reflections from the glacier bedrock (Fig. 2). In 2012, the airborne radar was equipped with a receiver with logarithmic amplifier for equalizing weak and strong amplitude of reflections from englacial inhomogeneities, crevasses and steep slopes of the glacier, which often provided challenges in discerning reflections from the glacier bed. In 2013, a novel receiver with linear amplification and automatic temporal gain control (ATGC) was introduced into the system, which improved the results. Its outputs are differentiated well by the amplitude and, when slightly scattered, produce regular reflections from the glacier bed clearly visible in the form of tracks, although they may fail to be seen in case of a strong attenuation or large depths. As a result, the 2013 measurements recorded in southern and eastern sectors of Mt. Elbrus glaciers yielded clearer signals reflected from the bedrock than those obtained in 2012 for glaciers in the Cherek Rv. basin (Fig. 3, *b*).

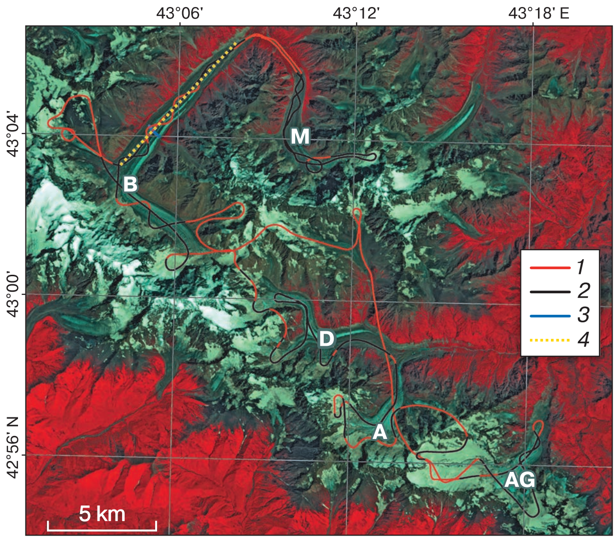

Fig. 2. Airborne radio-echo sounding surveys profiles at the Central Caucasus glaciers in the satellite image Landsat (2011).

B – Bazengi, M – Mizhirgi, D – Dych-Su, A – Ailama, AG – Agashtan; *1* – RES-survey flight route; *2* – profile sections with identified reflections from glaciers bed; *3* – ground-based RES-survey flight; *4* – longitudinal profile with multiple reflections from valley walls revealed on radargram.

Taking into account the liftoff maneuvers to/from the Kabardino-Balkaria Emergencies Ministry helipad, village Terskol, the total length of flight routes added up to about 270 km. Of these, over 200 km-long distance travel ran directly above the glaciers, and the length of the profiles where reliable signal was received from the glacial bedrock totaled 152.8 km, which accounts for 72 % of the full-length track kilometres flown over the glaciers (Fig. 4).

Radio-echo sounding (RES) data processing. The radio-echo sounding data were processed with the use of *RadexPro 2011.1* software package (www.radexpro.ru). The processing technique for the data derived from surface-based radio-echo surveys was described in detail by [*Vasilenko et al., 2014*] and appears not essentially different from the airborne data processing. The application of this software allows to visualize radar recordings, to apply static corrections to the probe pulses onset, to process the radar-recorded signals using Fourier analysis for obtaining real geometry of the bedrock topography, owing to rectified lateral reflections position, and to interactively digitize the delay time of the reflections from the glacier bed. Additionally, the flying altitude above glacier is recorded during the ongoing airborne radio-echo sounding. However, this may provide unforeseen challenges in the interpretation of reflected signals, since reflections recorded along the longitudinal profile come not only from the glacier bed, as the signals might as well be reflected from the valley walls. Given altitude *H* at specific distance *D* from the glacier margin, and *S* from the valley wall, it is possible to identify noise signals outbound from the valley wall.

Maximal acquisition of outbound and reflected signals occur on the plane normal to the axis of the antennas, and along the shortest distances to the glacier surface, bedrock and mountain slopes. The delay time *t* of these reflections can be estimated assuming that their range is commensurable with distances *D*

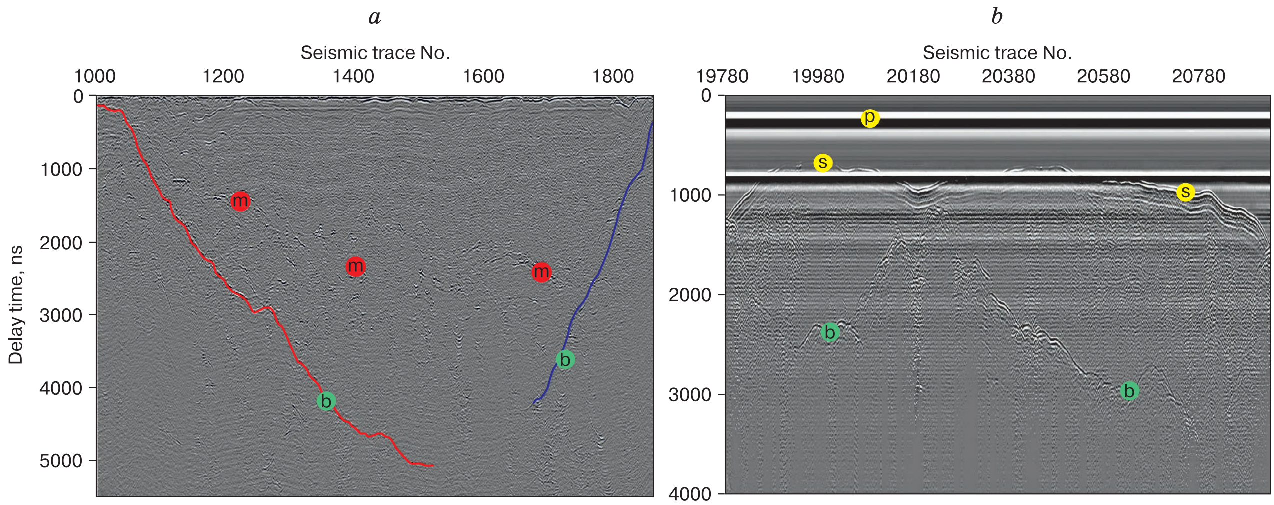

Fig. 3. Examples of radargram obtained on the longitudinal profile at Bezengi Glacier (*a*) and at Chungurchatchiran on Mt. Elbrus (*b*).

b – radar signal reflected from glacier bed; m – radar signal reflected from rimming ridges; s – radar signal reflected from glacier surface; p – sounding impulse. Position of profiles cf. Figs. 2, 4.

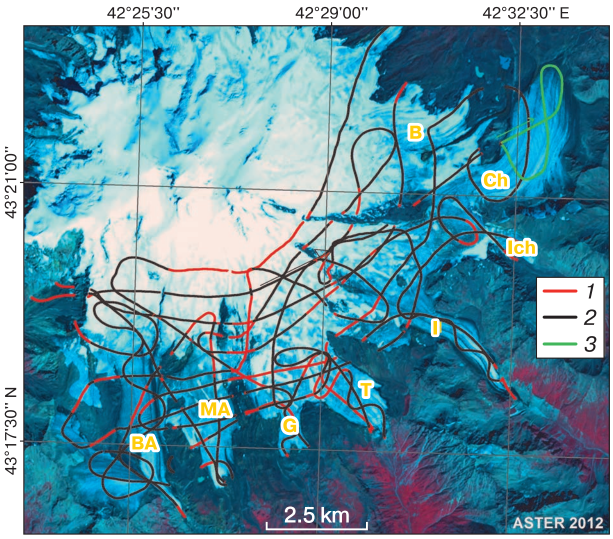

Fig. 4. Airborne RES profiles at glaciers on the southern sector of Elbrus glaciation.

BA – Bol. Azau, MA – Mal. Azau, G – Garabashi, T – Terskol, I – Irik, Ich – Irikchat, Ch – Chungurchatchiran, B – Birdzhalychiran; *1* – RES-survey flight route; *2* – profiles with identified reflections from glaciers bed; *3* – profile at Chungurchatchiran Glacier on the Dzhikiugankez plateau (cf. Fig. 3).

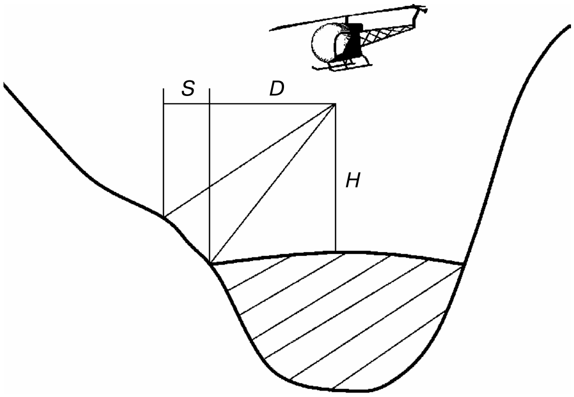

Fig. 5. Schematic representation of identification of coherent reflections (non-target) from mountain slopes during the helicopter-borne RES survey along the longitudinal profile (cf. the text for details).

and $D + S$ from the measurement point to the lateral moraines, or the valley slopes (Fig. 5):

$$ct/2 > [(H^2 + (D + S)^2)^{1/2}]/c, \quad (1)$$

where c is radio-wave propagation velocity (300 m/μs); t – delay time of signal, ns; H, D, S – distance, m.

In the episode of RES surveying Bezengi glacier from helicopter in 2013 (Fig. 3, *a*) the reflection depth from the valley walls in the deepest part of the glacier terminus was $ct/2$ ~ 2300 ns, which is significantly less than the travel time delay for reflections from the glacier bed (t_B ~ 5000 ns). These data were verified against the transverse profile measurements, and then, the ground profile measurements (Fig. 6). With Mt. Elbrus towering above the rest and in the absence of high rocky walls surrounding its glaciers, the radar recordings did not show such anomalies there.

After processing the resulting radarogramms all the data (radar- and navigation-derived) were converted to the tabular format, to be further translated into ice thickness values. The average radio-wave propagation velocity in the glacier is assumed to be constant and equal to 168 m/μs. At the final stage, these data become readily available for generating glacier thickness maps and for ice volume estimations.

Glacier ice thickness maps were compiled with the *TopotoRaster ANUDEM* algorithm in *ArcGIS* software, designed for mapping hydrologically correct bedrock topography.

Estimation of glaciers volume and thickness using *GlabTop* model. Among the existing approaches for measurement-based volume estimation of glaciers the most recent one is ice thicknesses modeling on the basis of simplified glaciological principles of ice flow dynamics, complemented by digitized glacier outlines and surface topography data in the form of digital elevation models (DEM). As was mentioned above, given the direct measurements are available, one can have the model parameters refined, to obtain reliable results.

We used the *GlabTop* (Glacier bed topography) [*Paul and Linsbauer, 2012*], one of the currently most applicable modeling approaches for ice thickness and the bedrock topography simulations. Initially, the model was used for computing glaciers thicknesses, derived from radio-echo sounding measurements (Marukh, Djankuat, glaciers of the Bezengi region, and glaciers from southern sector of Mt. Elbrus), which allowed to assess the accuracy of and to apply corrections to the *GlabTop* model. Then, calculations were made for 224 of the Caucasus glaciers, each with surface area of more than 1 km^2. A detailed description of the model application to one of the studied glaciers is provided in [*Lavrentyev et al., 2014*].

Creating outlines database for the Caucasus glaciers. The analysis of accessible data on the Caucasus glaciers outlines from the database of the *GLIMS* Glacier Database (www.glims.org), that originally meant to be used for the estimation of glaciers volume, unfortunately, have proven not suitable for our purposes, partly, because some of the Eastern Caucasus glaciers are not included in the detailed glacier inventories RGI, and besides, the glaciers outlines are not always delineated accurately, specifically, those located in the Western Caucasus.

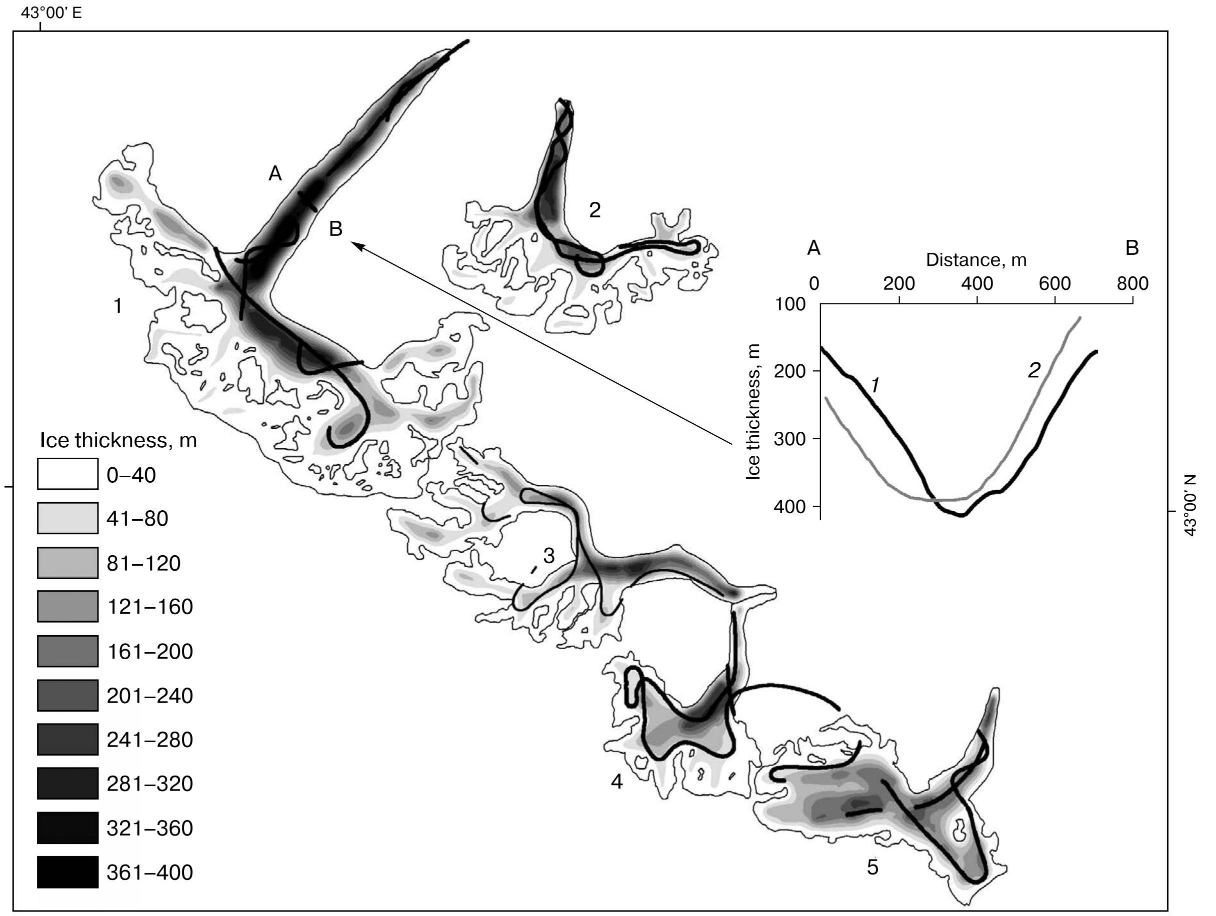

Fig. 6. Ice thickness map for the Bezengi region glaciers (1), Mizhirgi (2), Dych-Su (3), Ailama (4) and Agashdan (5), RES survey profiles (2012).

On the insert: measured (*1*) versus modeled through *GlabTop* (*2*) ice thicknesses on the transverse A–B profile at Bezengi glacier.

Moreover, the glaciers outlines are not consistent with the available DEMs, since the glacier borders delineation was performed relying on non-orthorectified *ASTER* images. Thus, the decision was urged to create a new database for the Caucasus mountain glaciation, that would include glaciers outlines, the main elevation parameters, and digitized major flow lines of the glaciers.

The *LandsatETM+* and *LandsatTM* imagery were used with almost close to zero cloudiness, and at the end of ablation period, to avoid misinterpretations stemming from the presence of the seasonal snow cover. The outlines of Mt. Elbrus glaciers were determined by at *ASTER* image (2012).The imagery processing was carried out using *ArcGIS 10* software. The interpretation of glaciers borders for *Landsat ETM+* and *Landsat TM* images was performed semi automatically using the ratio of "red" (TM3) near infrared (TM5) spectral bands (TM4/TM5 ratio image).

This method has proven widely applicable to creating digital outlines of glaciers around the globe. Moreover, particularly this method is recommended as a standard approach for estimations of changes in glaciers extent in the mountainous areas [*Paul et al., 2013*]. After that, the automatically obtained glaciers outlines were checked back for errors and corrected, manually. When mapping glacier boundaries, we used the field data, photographs and video materials obtained during the helicopter-borne surveys.

According to earlier research on this subject, the accuracy of determining glaciers dimensions has remained practically unchanged within the imagery resolution range 5–30 m, except for glaciers smaller than 0.1 km^2 [*Paul et al., 2013*]. Standard deviation error in determining the extent of individual glaciers proved to be less than 5 %. The error in estimates of glacial areas was reduced down to 3 % for a larger sampling of glaciers (more than 100), as it tends to be offset with both positive and negative errors [*Kutu-*

zov, 2012]. Major inaccuracies are largely associated with the presence of debris cover. A surface moraine does provide additional challenge in evaluating potential errors objectively. However, according to our estimates, the latter would be also inconspicuous, less than 1 % of the total area of glaciation. Mapping of ice-divides was performed using digital elevation model *ASTER GDEM V2* (gdem.ersdac.jspacesystems.or.jp) with 30 m horizontal resolution and 12 m vertical accuracy for mountain areas. Given the glacial system of Mt. Elbrus is exceedingly complicated in this respect, its specificity is discussed separately. The semi-automated approach was applied for ice-divides delineation, utilizing the data on glaciers surface topography and hydrological modelling results [*Kienholz et al., 2013*]. A digital elevation model (DEM) was used as a basis for determining ice-drainage basins borders of individual glaciers. The DEM-based flow direction maps were completed within Mt. Elbrus glaciation outlines. Then, using a series of flow accumulation points along the boundaries of outlet glaciers the principal flow lines were mapped. The resulting data allowed to delineate the ice-catchment areas of Mt. Elbrus, with the outlines corrected manually.

RESULTS AND DISCUSSIONS

The results of satellite imagery analysis served as a basis for compiling a new dataset of the Caucasus glaciers with their reference extent in the period of 2010–2013, en compassing 1,713 glaciers with a total area of 1,121 ± 30 km^2. Noteworthy is that a group of 43 large glaciers (with coverage over 5 km^2) represent 40 % of the total area, and Mt. Elbrus glaciation also stands out with its ice cover area of 112.7 km^2. It is remarkable that this value differs from the published earlier 120 km^2 with respect to Mt. Elbrus glaciation [*Zolotarev and Kharkovets, 2012*], which is primarily explained by the facts that rock outcrops and nunataks with their cumulative area of about 5 km^2 were included into the extent of Mt. Elbrus glaciation by [*Zolotarev and Kharkovets, 2012*], and that the glaciers continued to retreat in the period from 2007 through 2012.

Using the *GlabTop* model, we calculated glaciers ice thickness and volume, and generated maps for the bedrock of Bezengi, Mizhirgi, Dykh-Su, Ailama and Agashtan glaciers (Fig. 6) and for the entire glaciation of Mt. Elbrus (Fig. 7, *b*). After the model accuracy was validated and refined the maps were built for 224 glaciers of the Central Caucasus, each with an area over 1 km^2. The calculations were made for glaciers with total area of 719 km^2, which accounted for 64 % of total glaciation of the Caucasus. Ice thickness of the examined 224 glaciers on the Greater Caucasus averaged at 34 m, while the maximum thickness (412 m) was measured on Bezengi glacier.

Ice thickness measurements on Mt. Elbrus revealed a thickness anomaly on the so-called Dzhikiugankez ice field in the ablation zone of Chungurchatchiran glacier, which contradicts previous views on ice thickness there (Fig. 7, *a*). According to the results of the work during the International Geophysical Year (IGY) and International Hydrologic Decade (IHD) it was suggested that ice thickness in most part of Dzhikiugankez ice field is about 13–25 meters, which allowed for an inference on the rapid melting of the glaciers in this area [*Glaciation..., 1968*]. Our data have demonstrated that ice thickness in the middle part of the ice field is in excess of 200 m and that Elbrus glaciation holds appreciable ice reserves in this area.

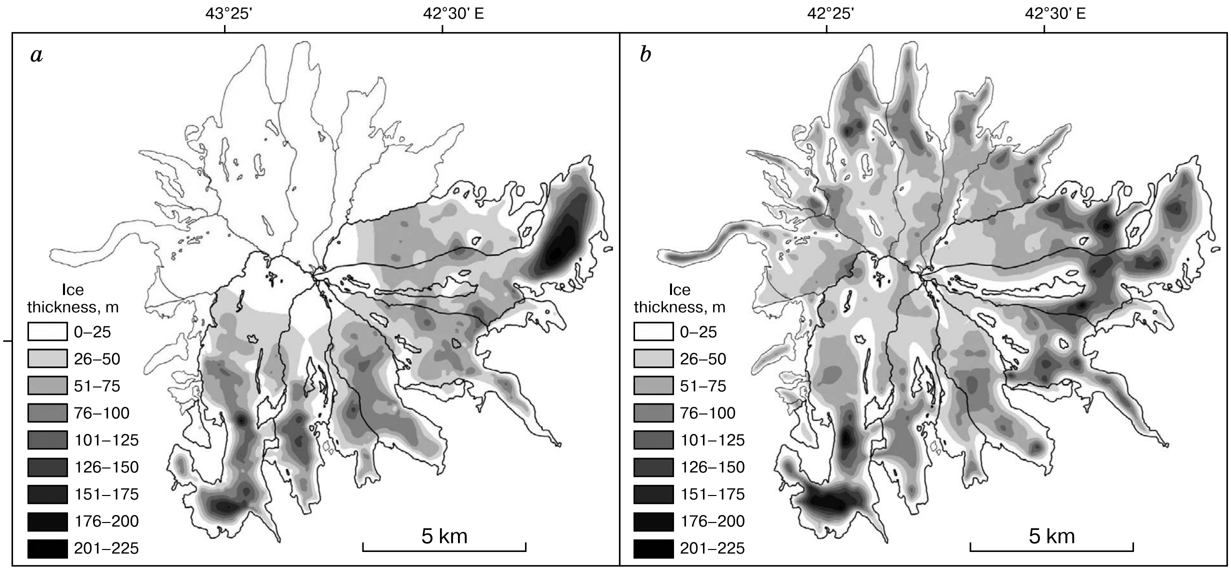

Fig. 7. Thickness map for Mt. Elbrus glaciers on the basis of RES measurements (*a*) and modeling (*b*).

Table 1. **The Caucasus glaciers volume estimates derived from measurements and modeling**

Glacier	Volume of ice, km^3		Discrepancy, %
	GlabTop model data	Measured data	
Marukh	0.150	0.276	46
Djankuat	0.081	0.077	–5
Bolshoi Azau	0.951	0.822	–16
Malyi Azau	0.346	0.353	2
Garabashi	0.113	0.156	28
Terskol	0.382	0.433	12
Irik	0.464	0.440	–5
Irikchat	0.020	0.021	5
Chungurchatchiran	0.754	0.960	21
Birdzhalyrchiran	0.557	0.374*	–49
Total	3.818	3.912	–2.5
Bezengi	2.963	–	–
Mizhirgi	0.770	–	–
Dykh-Su	0.957	–	–
Ailama	0.696	–	–
Agashtan	1.404	–	–

* On the basis of three RES profiles.

Joint analysis of the modeling and observations data allowed for parametrization of *GlabTop* model. For this purpose, an empirical calibration factor was applied to the formula for ice thickness calculation [*Haeberli and Hoelzle, 1995*]:

$$h = \frac{\tau}{f \rho g \sin\alpha}\kappa, \qquad (2)$$

where h is thickness of ice; τ – shear stress on the glacier bed; f – coefficient of glacier cross-sectional geometry; ρ – density of ice, assumed equal to 900 kg/m^3; g – gravity factor; α – surface slope angle; κ – empirical correction factor.

Processing of the data resulting from ice thickness measurements and modeling showed that the best fit of the measured and calculated ice thicknesses were obtained with application of coefficient $\kappa = 1.266$ in (2). Without it, ice thickness values obtained by modeling were systematically underestimated, as compared with measurements on the glaciers (Djankaut, Bashkara, glaciers in the Bezengi region and on the southern slope of Mt. Elbrus). The glaciers volume modeling and measuring results are given in Table 1. The available data on helicopter-borne radar-sounding of the Bezengi glaciers were not sufficient for generating reliable ice thickness maps, which explains why no values of measured volume are provided in Table 1. The measurements-derived data were used for adjustments of the model parameters.

The error in the estimates of Marukh glacier volume being conspicuous, it is largely accounted for the specific bedrock topography with remarkably large area (2.7 km^2) for a valley type glacier, and its ice thickness reaching 330 m in the accumulation zone positioned in a deep cirque. The glaciers of the southern slope of Mt. Elbrus are characterized by the biggest inconsistency in the modeled and measured ice volume values for Birdzhalychiran, Chungurchatchiran and Garabashi glaciers, due to a paucity of measurements and inaccuracy of digital elevation model *ASTER GDEM*.

The calculations of the total volume of ice in glaciers in Mt. Elbrus southern sector has shown that, despite differences in estimates of individual glaciers, the calculated total value agrees well with the measurements.

Estimates of ice reserves in the glaciers of the Greater Caucasus. The data resulting from RES measurements and modeled values for thickness and extent of the Greater Caucasus glaciers allowed to refine regional coefficients of glacier volume (V) and area (S) power relationship in equation:

$$V = kS^p. \qquad (3)$$

The feasibility of this formula applications to calculations of ice volume in the mountainous glacier system was discussed in detail by [*Macheret et al., 2013*]. For large (>3 km^2) and complex valley-type glaciers of the Greater Caucasus coefficient k equals to 0.03, and $p = 1.255$, whereas $k = 0.024$, $p = 1.37$ for cirque and cirque-valley glaciers with a coverage less than 2 km^2 each (Fig. 8).

Resulting from the above approach, the formula (3) was used to calculate volumes of all the glaciers of the Greater Caucasus, cumulatively amounting to 43.5 ± 5.0 km^3. At this, glaciers of Mt. Elbrus massif and 15 individual largest complex valley-type glaciers comprise 47 % of ice volume of the entire mountain glacier system. It has always been arduous task to evaluate the accuracy of calculations of the total volume, and the more so, when different approaches are applied. According to [*Paul and Linsbauer, 2012*], the

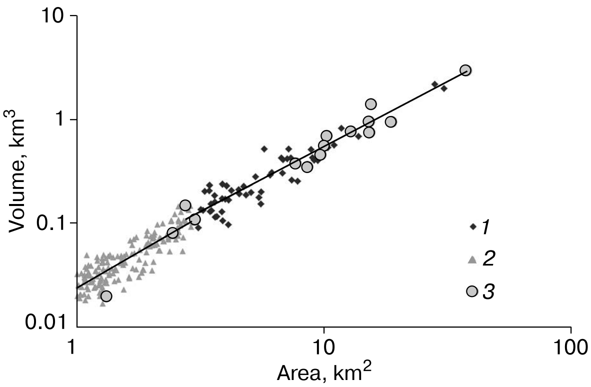

Fig. 8. A–V dependence for 224 glaciers of the Greater Caucasus and relying on *GlabTop* modeling.

1 – for valley-type and complex-valley types glaciers; *2* – for cirque and cirque-valley type glaciers, with extent less than 2 km^2; *3* – adjustment was done for the *GlabTop* model using ice thickness measurements data.

GlabTop method allows to calculate glacier volume with accuracy up to 30 %. Ice thickness measurements were used to adjust the modeled values . For accuracy evaluation we analyzed the differences between measured and modeled values for total glaciers volume. Statistically tested possibilities of application of different methods for glaciers volume estimations have provided conflicting results. Thus, in [*Farinotti and Huss, 2013*] it was assumed that the use of glaciers area–volume (A–V) scaling produced bigger errors (30–40 %), even in case of large sampling of glaciers with predetermined volumes. It should be mentioned that in this paper the authors relied on the synthetically generated sampling, premised on the data on glaciers coverage with allowances made for possible volume variations. Our investigations [*Macheret et al., 2013*] have shown that the measurements of glacier surface area and actual ice thickness, when complemented by volume estimates, yield more accurate calculation results for the total volume of glaciers.

The volume of the Greater Caucasus glaciers, estimated by A–V scaling (3), amounted to 43.5 ± 5.0 km^3, which is less than the value of 80 ± 6 km^3 provided in research by [*Radić and Hock, 2010*], and less than 61 ± 6 km^3 obtained by [*Huss and Farinotti, 2012*] on the basis of balance-dynamic method for glacier volume calculation. These estimates were underpinned by the *GLIMS* Glacier Database, which as was shown, implies substantial gaps in the data with regard to the Caucasus region. The model parameters involved in the calculations were identical to those applied to the Alps region, which also might influence the results. Interestingly, the computations conducted by *A.B. Zhuravlev* [*1982*], who opted for the input data sourced from the Catalogue of Glaciers in the USSR (1967–1976) and A–V relations obtained for 21 glaciers of temperate type, located in the Alps, the Rocky Mountains and the Caucasus, resulted in the values closest to 50.6 ± 2.7 km^3.

CONCLUSIONS

The study provided the estimates of ice thickness distribution for many glaciers of the Caucasus, including Marukh and Djankaut (the reference glaciers), the largest glaciers in the upper reaches of the Cherek Rv., and Mt. Elbrus glaciers. The work was corroborated by the development and successful implementation of the methodology for ice thickness measurements on the basis of helicopter-borne radio-echo sounding. In 2011–2013, about 250 km long profiles were obtained with confidently identifiable reflections from the glacier bed. The instrumental data served as the basis for the refinement of approaches for glaciers ice thickness and volume estimation. A new geospatial database of vector outlines for the Caucasus glaciers consistent with the delineations within the period of 2010–2013 was created, covering 1,713 glaciers with the total area of 1121 ± 30 km^2. Our research results included the assessment of total ice reserves in the Caucasus. It has been established that the total volume of the Greater Caucasus glaciers constitutes 43.5 ± 5.0 km^3 of ice mass.

Both the results obtained and the research approach using a complex of remote and ground-based sounding techniques, complemented with the modelled computations not only open up the possibility for more profound refining of estimates of mountain glaciation parameters for the Caucasus alone, but they can be applicable in any other mountain systems all over the globe. As is known, mountain glaciers present by themselves a substantial and at times vital freshwater resource for irrigation, commercial and industrial needs, and electricity generation. In terms of prospect development of the methodology discussed, one of the key candidate direction of research is to estimate changes in glaciers volume, which is exceedingly important for predicting the Caucasus glaciers responses to climate changes, and for assessment of their contribution to rivers runoff and to the worldwide changes in the sea level. Non the less important is the ability to evaluate the probability of glacial lakes formation in the aftermath of glaciers shrinking, and to assess potential risk of catastrophic lahars in case of activity of dormant volcanoes covered with glaciers (e.g. Elbrus, Kazbek). Such works can be carried out on the basis of the data on bedrock topography and predictions of future changes in glaciers parameters and behavior.

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