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RAPID REGENERATION OF THE KOLKA GLACIER (CAUCASUS) AFTER THE 2002 GLACIAL DISASTER

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We have analysed changes in the Kolka Glacier cirque and in the Karmadon Depression after the glacial disaster of September 20, 2002 in the Republic of North Ossetia–Alania (Russia). We have estimated the rates of Kolka Glacier regeneration and the rates of the ice dam decay in the Karmadon Depression, on the basis of the field observations of 2002–2016, the topographical surveys of 2000–2004, 2009 and 2014, and analysis of digital elevation models generated from satellite image stereo pairs (Terra ASTER of 2002 and 2004; and SPOT-6 of 2014). The combination of four methods used in 2014 to survey the surface of the Kolka Glacier has helped to clarify the rate of regeneration of the glacier in the past and provides a reliable benchmark for the future. Remote and terrestrial survey methods have demonstrated good agreement. We established that in 2002–2014 about (40 ± 11) million m^3 of ice accumulated in the Kolka Glacier cirque, which is about 40 % of the volume of this glacier before the collapse in 2002. The forecast slowdown of the glacier mass recruitment is not yet happening: in 2009–2014 as much ice has accumulated in the cirque, as in 2004–2009. The regeneration of the Kolka Glacier comes amid adverse weather conditions for glaciation of the Caucasus, and in sharp contrast with the behaviour of other Caucasian glaciers experiencing rapid decline. The volume of the ice dam in the Karmadon Depression decreased by 75 % in 2002–2014. The progressive decrease in the melting rate, which we noted before, continued in 2009–2014. In comparison with the first year after the disaster, the rate of melting decreased by almost a factor of 50. In the following ten years, the repetition of events similar to the disaster in 2002 is unlikely, but by 2025 the Kolka Glacier can accumulate 60–70 % of its pre-disaster volume. It is necessary to continue monitoring the regeneration of the glacier and to measure the volume of accumulated ice every 5–10 years.

Kolka Glacier, glacial disaster, the Caucasus, glacier regeneration, digital elevation models

INTRODUCTION

In September 2002, a glacial disaster of the planetary scope occurred in Northern Ossetia. More than 100 mln m^3 of ice, water, and rock debris were thrown down from the Kolka Glacier cirque into the Karmadon Depression and covered the distance of nearly 20 km at the velocity of 50 m/s [*Evans et al., 2009*]. The gorge of the Skalisty Ridge stopped the ice mass, but the distal debris flow covered 17 more kilometers and stopped at the distance of 2 km from the village of Gizel with the population of more than 7000 people [*Popovnin et al., 2003*]. This disaster came totally unexpected both for the population and for the authorities. In the latest estimate, 135 people were killed, and the economic damage amounted to 1,385 mln rubles [*Kortiev et al., 2009*]. Over the years which passed after the disaster, many papers have been published dedicated to its causes, analysis of the role of different factors in its formation, and comparison with the preceding disasters which occurred at the same glacier in 1902 and in the other years [*Panov et al., 2002; Bogatikov and Gurbanov, 2003; Kotlyakov and Rototayeva, 2003; Osipova and Tsvetkov, 2003; Zaporozhchenko, 2003; Desinov, 2004; Gurbanov et al., 2004; Haeberli et al., 2004; Petrakov et al., 2004, 2013; Vas'kov, 2004; Zaalishvili et al., 2004; Huggel et al., 2005; Lindsey et al., 2005; Muravyev, 2005; Tutubalina et al., 2005; Bolov et al., 2006; Berger, 2007; Chernomorets et al., 2007; Nikitin et al., 2007; Petrakov et al., 2008; Poznanin, 2009; Drobyshev, 2012*], and to simulation of the ice and debris flow [*Bozhinsky, 2005; Evans et al., 2009; Chernomorets and Mikhailov, 2012*]. A large part of the information has been systematized in monographs [*Kotlyakov et al., 2014; Leonov and Zaalichvili, 2014*]. As a result, the complex nature of the disaster was established, a certain role in the origin of which was played by both endogenic and exogenic factors; the behavior of the ice and debris flow has been characterized.

Still topical is the issue of the probability, the time of recurrence and the scope of events which were similar to the disasters that happened at the Kolka Glacier in 2002 and in 1902. The probability of such a scenario depends on regeneration of the Kolka Glacier to the size close to that of the pre-disaster condition [*Kotlyakov et al., 2004; Poznanin, 2009; Petrakov et al., 2013*]. Although some researchers predicted slow regeneration of the Kolka Glacier due to the changed thermal balance in the cirque [*Chernov et al., 2010; Kotlyakov et al., 2014*], the glacier grew fast in its mass in 2004–2009, and it was assumed that in the future the mass growth rate should decrease [*Petrakov et al., 2013*]. The purpose of this study was to evaluate the changes that occurred in the Kolka Glacier cirque and in the Karmadon Depression after the disaster. For this purpose, in August 2014, we did the next, third, topographic survey of the Kolka Glacier cirque, the repeated survey of the ice body in the Karmadon Depression by three profiles, developed digital models of the relief of the disaster zone using stereo pairs of satellite images SPOT-6 (2014) and Terra ASTER (2002 and 2004), and analyzed and summarized the results of the annual land-based and remote observations conducted in the upper reaches of the Genaldon River after 2002. The focus was made on the changes after 2009, as the earlier changes were already analyzed in [*Petrakov et al., 2013*].

THE METHODOLOGY OF THE STUDY

1. Topographic survey

The Kolka Glacier cirque. To evaluate the regeneration rate of the Kolka Glacier in its cirque after the disaster of 2002, three topographic surveys were conducted at the scale of 1:5 000 [*Petrakov et al., 2013; Kovalenko et al., 2015*]. All the surveys were conducted using the same equipment – the 4T15P theodolite and the LP-1 reflectorless laser ranger. The reference points of the horizontal and vertical survey were on the orographically left flank moraine of the Kolka Glacier (Fig. 1). Their coordinates were determined in 2004 by the triangulation method with control by three reference points of the state geodetic survey network: Chizhit-hoh, Maili-rag, and Rekom-rag [*Petrakov et al., 2013*], and in 2009 and 2014, they

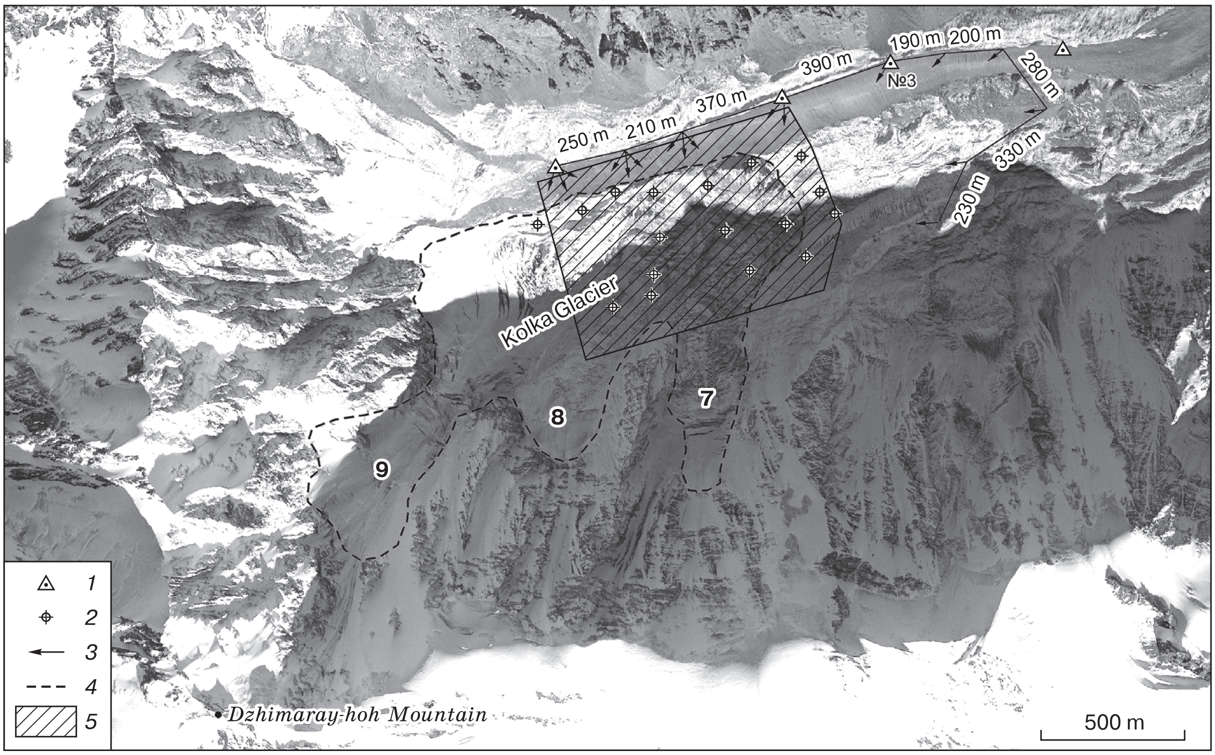

Fig. 1. Position of the survey points in the Kolka Glacier cirque in 2014.

1 – the reference points of the horizontal and vertical survey, the reference points of the land-based topographic survey; *2* – the reference points for drone-based topographic survey; *3* – survey directions from the point of repeated photographic survey; *4* – the boundary of the Kolka Glacier in 2016; *5* – the drone-based survey zone in 2014. Background: a SPOT-6 satellite image taken on 29.10.2014.

were adjusted using two-frequency GPS/GLONASS-JAVAD receivers. During the fieldwork conducted in 2004, coordinates of more than 1,000 survey points were determined for the Kolka Glacier cirque. In conducting the topographic surveys of 2009 and 2014, the number of the survey points was naturally reduced, as measurements were not repeated for relatively stable rock surfaces. The error of determining the horizontal and vertical coordinates x, y, z during the survey did not exceed 5 m. Based on the results of the topographic surveys of 2004, 2009, 2014, V.N. Drobyshev used the Surfer software program to make maps of the glacial surface and of its rocky margins at the scale of 1:10 000 in the same system of coordinates and altitudes. Digital elevation models (DEM) were developed for the location by trigonometric interpolation, and the maps and the model were superimposed. Here, too, the error of interpolation of x, y, z did not exceed 5 meters.

The Karmadon Depression. To determine the melting rate for the ice body accumulated in the Karmadon Depression, the data of the topographic survey conducted by V.N. Drobyshev and V.V. Maklikov on 28.09.2002, 8 days after the disaster day, were used, as well as the data of six measurements made on transversal profiles at different times. These surveys were conducted using the same equipment that was used for the survey of the Kolka Glacier cirque. Based on the survey of 2002, the DEM of the area of the ice dam was developed at the scale 1:10 000, and the volume of the deposited mass in the Karmadon Depression was determined [*Drobyshev, 2006*]. The measurements of 2003 (three measurements), 2004 and 2009 were conducted on three transversal profiles [*Petrakov et al., 2013*], the measurement of 2014 used two transversal profiles, as the ice dam melted in the upper profile. The data obtained were extrapolated onto the entire area of the ice body. The error of evaluating the volume of the ice body amounted to ±5 mln m^3.

2. Satellite monitoring

The Kolka Glacier cirque. Remote monitoring of the Kolka Glacier cirque and of the Karmadon Depression was traditionally carried out to evaluate changes in the area of the recovering glacier [*Petrakov et al., 2013*]. For this purpose, the data of the annual surveys made by different systems in low-snow periods were used (Table 1). Part of the acquisitions were made at the request of our team. All the images underwent orthorectification using the basic SRTM-90 digital terrain model, based on interferometric processing of the satellite survey conducted in February 2000.

Mutual coordinate referencing of the images was conducted using the programs ESRI ArcGIS and ScanEx Image Processor. Based on the satellite images, the boundaries of the recovering Kolka Glacier in 2004–2016 were identified. The error of determining the contours was taken to be equal to 1 pixel and varied from 0.7 to 10 m in different years depending on the image resolution.

The stereo pairs of the Terra ASTER 2002 and 2004 satellite images, as well as the stereo pair of the satellite images SPOT-6 NAOMI 014, were used for making the DEM of the locality. To make the DEM in the absolute values of altitudes, the digital SRTM90 model was also used. First, the digital model of the locality was made, based on the stereo pair of the SPOT-6 images. The DEM was developed using the program ScanEx ImageProcessor to include the following steps: epi-polar transformation, creating an anaglyphic 3D-image, making a DEM and its editing.

Table 1. **Satellite images used for remote estimates of changes that have occurred in the Kolka Glacier cirque after the Karmadon disaster of September 20, 2002**

Satellite sensor	The survey date	Spatial resolution, m/pixel	Availability (A) of a stereo pair
Quick Bird/PAN	25.09.2002	0.7	N/a
Terra/ASTER	06.10.2002	15/30*	A
Terra/ASTER	25.09.2004	15/30*	A
IRS 1D/PAN	30.09.2004	5.8	N/a
IRS 1D/PAN	24.08.2005	5.8	N/a
IRS 1C/PAN	16.08.2006	5.8	N/a
SPOT 4/HRVIR	02.09.2007	10	N/a
SPOT 2/HRV	17.08.2008	10	N/a
SPOT 4/HRVIR	25.08.2009	10	N/a
Ikonos/OSA PAN	29.08.2010	0.8	N/a
SPOT 5/HRS	15.10.2012	2.7	N/a
SPOT 5/HRS	23.08.2013	5.5	N/a
SPOT 6/NAOMI	29.10.2014	1.9	A
EROS B/PAN	10.08.2015	0.7	N/a
SPOT 6/NAOMI	14.07.2016	2.2	N/a

* The resolution of the image itself and of the generated DEM is shown.

During editing, filtration, smoothing, and correction of 'erroneous' values were carried out. Orthorectification of the obtained DEM and of the stereo pair image taken from the angle closest to the nadir was carried out based on a strict model, i.e., by recovering the elements of internal and external orientation of the image lines. As reference points, we selected the objects which did not change their position over the recent years: certain large rocks, the beginnings of the rock outcrops, and the prominent forms of the terrain located outside the Kolka and Maili Glaciers.

Then digital elevation models of 2002 and 2004 were developed based on the ASTER images. To ortho-transform these DEM, 3N images were used as a basic model, i.e., the images obtained for the nadir of the ASTER stereo pairs. To transform the ASTER digital models, 75 control points were used. The average error of horizontal referencing was 1.8 m. The same control points were used for the obtained digital models to be mutually referenced both in the horizontal coordinates and by the absolute altitude.

As a result, for each stereo pair, an ortho-transformed satellite image and the DEM of the locality were obtained, referenced with each other. The vertical error of the DEM according to SPOT-6 was 5 m, and according to Terra ASTER, it was 12 m. After superimposing of the DEM, the amounts of the material accumulated in the Kolka Glacier cirque in the periods of 2002–2004 and in 2004–2014 were evaluated. This allowed us to carry out independent control of the land-based survey. To visualize the changes which occurred in the Kolka Glacier cirque, 3D-models of the area were made (Fig. 2).

The Karmadon Depression. As after 2004, topographic monitoring of the melting rate of the ice accumulation in the depression was conducted only by a system of profiles, a decision was taken to compare the DEM obtained by the SPOT-6 satellite images with the maps of the ice accumulation surface of 2002 and 2004. The task was complicated by the fact that the topographic maps of the ice accumulations were made in the CorelDraw graphics vector editor in a local relative system of coordinates and altitudes; therefore, before comparing the models, special referencing of the vector data had to be done, and a hydrologically correct DEM had to be developed on the basis of terrain contours from topographic maps, the boundaries of water bodies and water flows, and then a constant value had to be added to the model data, characterizing the difference between the ellipsoid altitudes (WGS-84), in which the DEM was made according to SPOT-6, and the altitudes on the topographic map. Spatial referencing of the graphic data was conducted based on the reference points of the survey indicated on the maps, the coordinates of which were obtained during the field work in 2014, and on similar points of the locality. The error of referencing the topographic maps varied from 10 to 50 m. To export the data from CorelDraw to ArcGIS, the format AutoCAD DWG was used, which allowed storing the original information about the layers, to keep division of the map objects by types (terrain

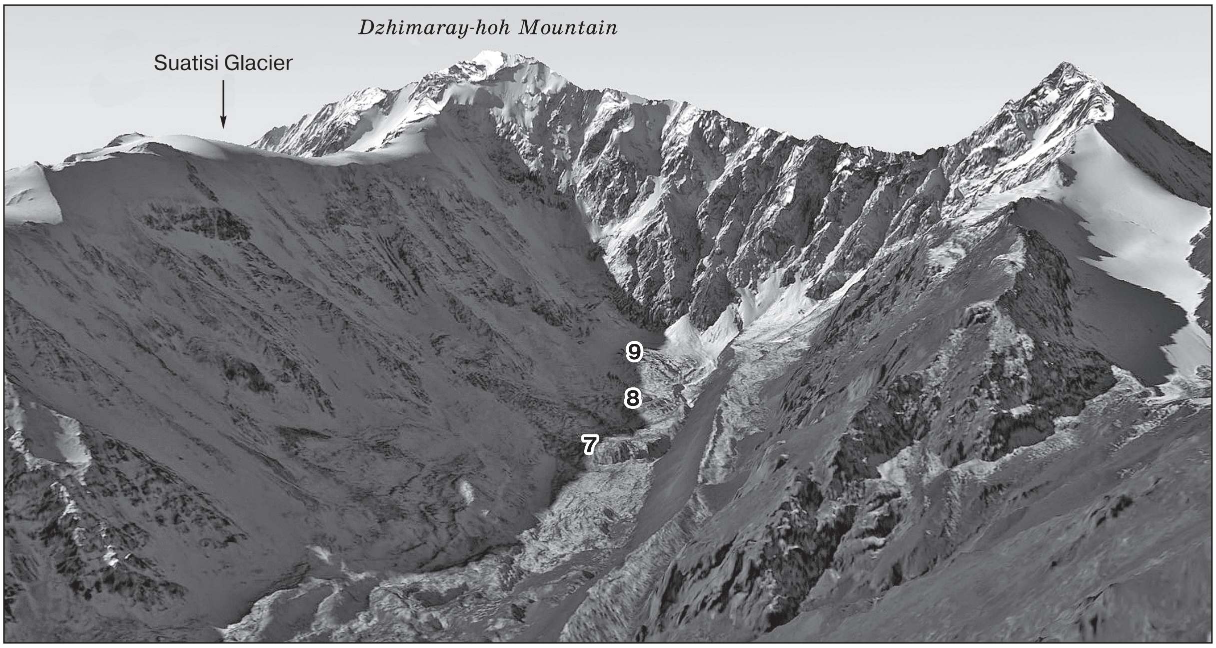

Fig. 2. A 3D-model of the Kolka Glacier cirque generated based on a stereo pair of SPOT-6 satellite images obtained on 29.10.2014.

7, 8, 9 – the numbers of glaciers which became autonomous after the Karmadon disaster of 2002 (they merged by 2014).

contours, water flows, etc.). The models were made, and the volumes were calculated in the ArcGIS SpatialAnalyst module.

3. Survey using an unmanned aerial vehicle

The number of studies in which surveys from unmanned aerial vehicles (drones) are used has been recently growing fast [*Bhardwaj et al., 2016*]. The undisputed advantage of this method is the possibility of developing a high-resolution DEM for the territory of several square kilometers, which is very important for the studies of hard-to-access glaciers [*Immerzeel et al., 2014*], such as the Kolka Glacier. In August 2014, we carried out an experimental survey of the lower part of the Kolka Glacier using drones (Fig. 1). Due to the technical problems caused by unsuccessful landing of the drone after one of the flights, we were unable to obtain the images of the upper part of the cirque. A detailed description of the survey technique is provided in [*Kovalenko et al., 2015*]. It is to be noted that the spatial resolution of the stereo images was 3.5 cm/pixel, more than by an order of magnitude higher than very high-resolution satellite images. The error of the obtained DEM by the surface height in relation to the survey reference points (Fig. 1) was 0.22 m, and the horizontal errors were even less. Thus, for the lower, fast changing part of the Kolka Glacier, a high-precision DEM was obtained, which in the future will allow essential reduction of the error in evaluating the regeneration rates of the Kolka Glacier.

RESULTS AND DISCUSSION

The Kolka Glacier cirque. As predicted earlier [*Petrakov et al., 2013*], fast accumulation of ice continued in the Kolka Glacier cirque. Judging by the results of superimposing the topographic maps for 2009 and 2014 we composed (Fig. 3), the volume of the Kolka Glacier increased in this period by (17 ± 7) mln m^3. This is practically the same amount that accumulated over the preceding five years (2004–2009) [*Petrakov et al., 2013*]. It is to be noted that the field of the change in the surface height has changed. In 2004–2009, the highest rise of the surface height reached 55 m and was noted in the middle part of the recovering glacier (Fig. 3, *A*). In 2009–2014, the zone of the maximum rise of the ice surface was found in the narrow area between glacier # 7 and the merged glaciers # 8 and 9, as well as in the area along the front of glacier # 7 (Fig. 1, 3, *B*). The rise in the glacier surface reached 65 m. As contrasted with the period of 2004–2009, small sites of the glacier surface depression are observed on the surface of the Kolka Glacier, which seem to be caused by the behavior of the regenerating glacier. In total, in the period of 2004–2014, (33 ± 7) mln m^3 of ice masses accumulated in the Kolka Glacier cirque. The maximum rise in the glacier surface was a little over 80 m; one such site was located at the foot of the glacier wall in the rear part of the Kolka Glacier, while the other site was in the zone of contact of glaciers # 7 and 8 (Fig. 3, *C*).

Somewhat different results are provided by comparison of the digital elevation models based on stereo pairs of satellite images. Judging by these data, in 2004–2014, (27 ± 11) mln m^3 ice accumulated in the Kolka Glacier cirque. Maximum rise of the height of the surface amounted to about 70 m (Fig. 4), whereas the position of these sites coincided with the maximum values in Fig. 3. In 2002–2014, (40 ± 11) mln m^3 ice accumulated in the Kolka Glacier cirque, while the maximum rise of the ice surface amounted to about 100 m (Fig. 4). It should be pointed out that all the data agree well, considering the error value.

In the monograph by [*Kotlyakov et al., 2014*], the volume of the self-recovering Kolka Glacier in 2014 was estimated to be minimum, 21 mln m^3, which is essentially less than the estimate of the post-disaster accumulation we made – (40 ± 11) mln m^3 of ice. In their estimation, V.M. Kotlyakov and his colleagues [*2014*] relied on extrapolation of the mean values of the thickness of ice obtained by radio sounding in June 2014 to the entire area of the glacier. Unfortunately, the radio sounding data were obtained only for a small area in the lower part of the Kolka Glacier [*Kotlyakov et al., 2014, Fig. 97*], and extrapolation of these data to the entire area of the glacier may result in large errors (therefore, this value was presented as the minimal possible value). The maximum thickness of ice, according to radio sounding data (50 m), was recorded in the central part of the flow from glacier # 7. This value agrees well with our estimate of the rise in the glacier height in 2002–2014 at the same place, practically from zero (the clean glacier bed) to 50–60 m (Fig. 4). The average ice thickness at the site of the radio sounding profile, according to the radio sounding data, was by about 25 % less than according to our data. Considering the measurement errors, the geophysical data on the thickness of ice confirm the estimations of mass accumulation in the Kolka Glacier cirque in 2002–2014 we made by comparing the DEMs made in different times.

Together with the fast increase of the mass, the glacier area was fast growing. However, the growth rates of the glacier area in 2004–2009 and in 2009–2016 differed: whereas by 2009 the glacier area in the bed of the Kolka Glacier was 0.60 km^2 [*Petrakov et al., 2013*], and considering the slope zones, it was estimated to be (0.80 ± 0.02) km^2; by 2014 it reached (1.08 ± 0.02) km^2, and by 2016 it was about (1.12 ± 0.02) km^2 (Fig. 5). Our estimate of the area of the Kolka Glacier in 2014 coincides with that made by V.M. Kotlyakov and his colleagues [*2014*] within 0.01 km^2.

Whereas at the earlier stages the increase in the glacier area took place due to both the glacier front advancement and to activation of the still masses of

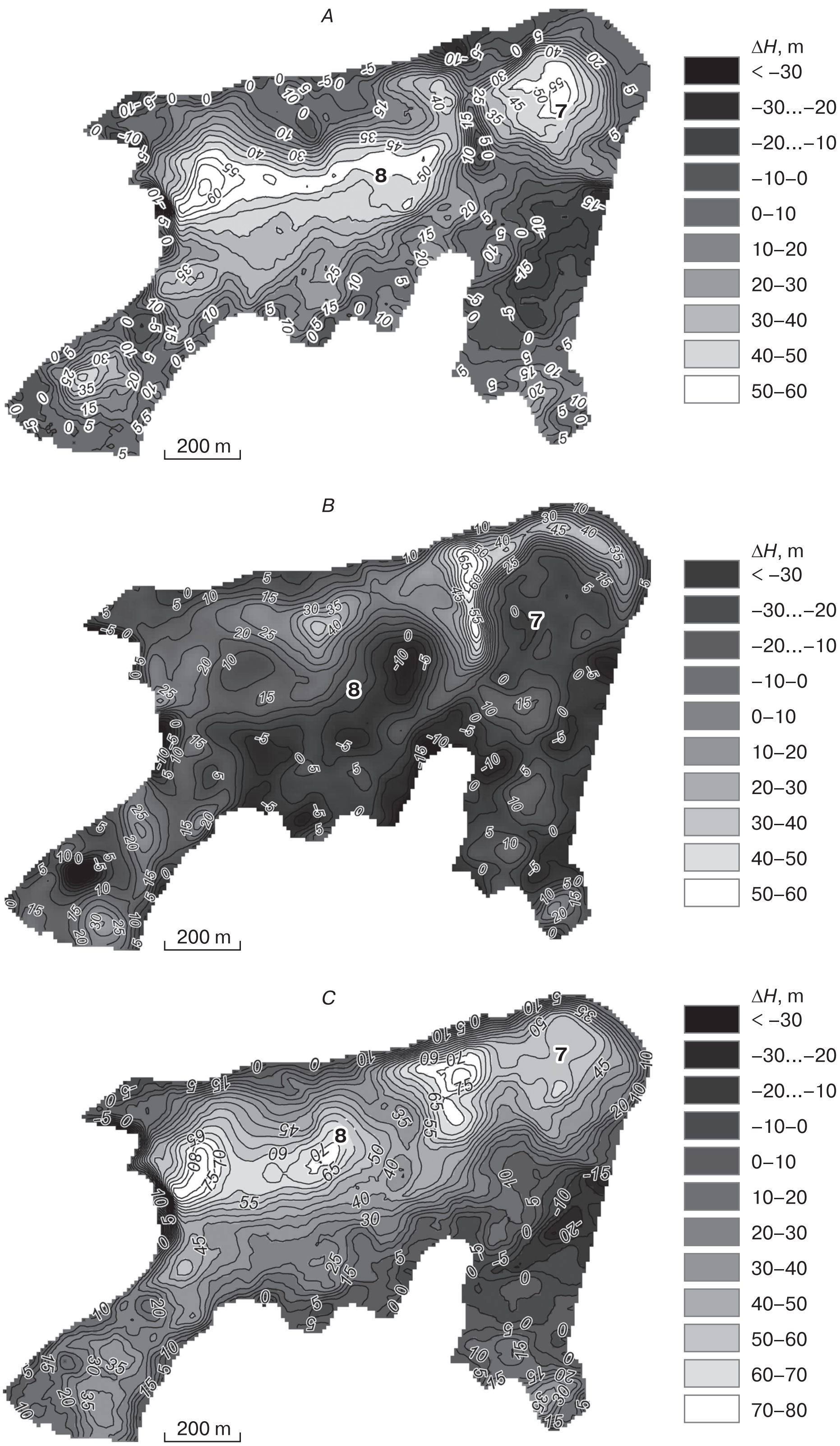

Fig. 3. A change in the surface height (ΔH) in the Kolka Glacier cirque according to the data of land-based topographic survey.

A – 2004–2009; *B* – 2009–2014; *C* – 2004–2014.

ice, over the recent years, the second factor has been missing. The advancement rate of the front of the former glacier # 7, which later became the front of the Kolka Glacier itself, was much lower in 2011–2016 than in the preceding period (Fig. 6). Whereas in some years of the period of 2004–2011, the glacier front advanced more than 100 m [*Petrakov et al., 2013*], in 2011–2016, the glacier front advancement rate did not exceed several dozens of kilometers per year, and in 2015–2016, it was 5 m/year, i.e., it was within the error margin of interpretation. At the same time, after the disaster, the front of glacier # 7 moved 900 m ahead. That was the only case of significant advancement of a glacier in the 21st century in the Caucasus.

The causes of such fast regeneration of the Kolka Glacier occurring in the situation of reduction in the mass of Caucasian glaciers [*Shahgedanova et al.,*

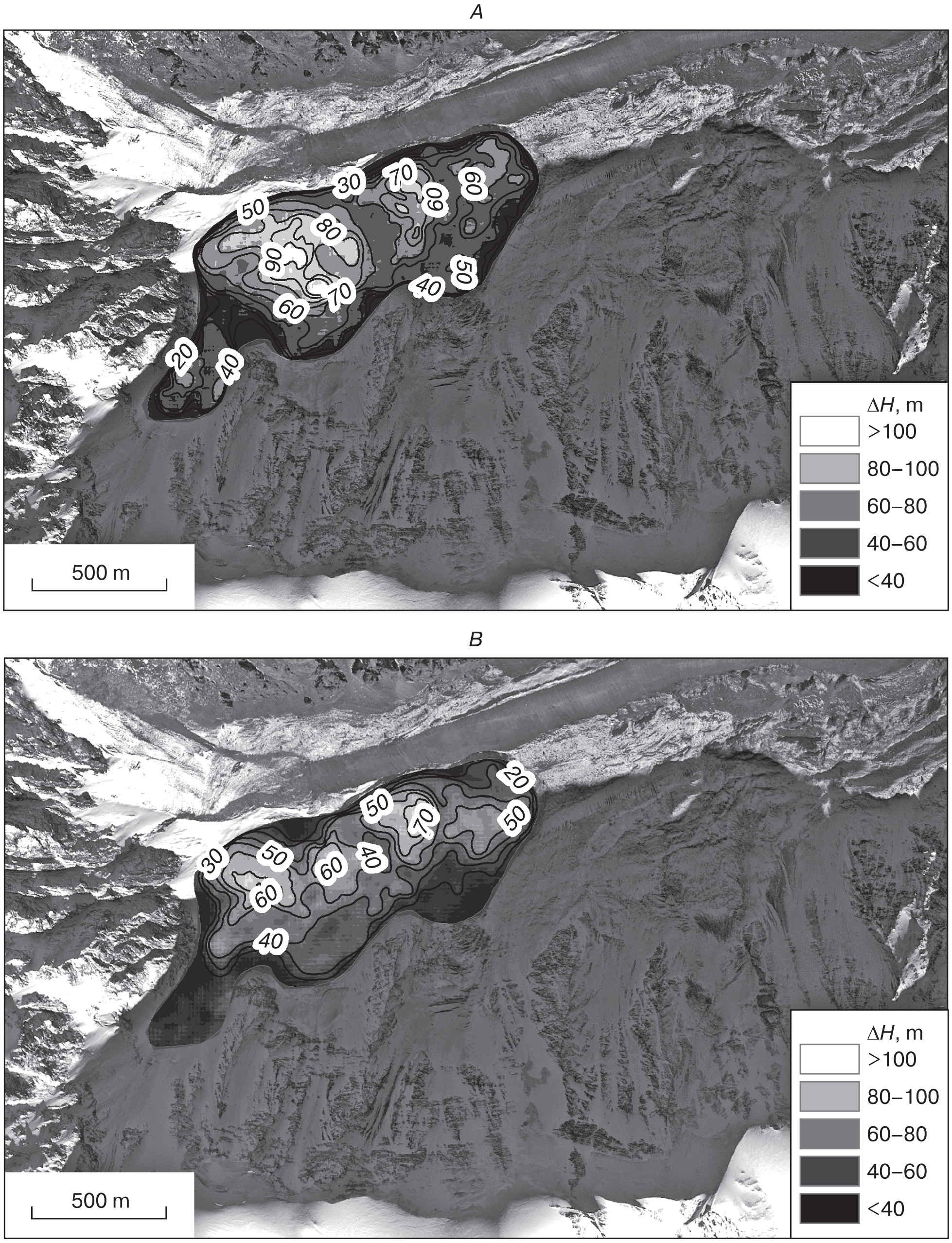

Fig. 4. A change in the ice surface height (ΔH) in the Kolka Glacier cirque on the basis of superposition of the DEMs generated on the basis of the stereo pairs of Terra ASTER (2002, 2004) and SPOT-6 (2014) satellite images.

A – 2002–2014; *B* – 2004–2014. Background: a SPOT-6 satellite image taken on 29.10.2014.

2014] have not been explained yet. The striking difference in the balance of the mass of the Kolka Glacier and of the Djankuat Glacier, which provides baseline data for the Caucasus, was noted earlier. In 1970–2002, the average balance of the Kolka Glacier was +1000 mm/year, or +2.5 mln t/year [*Petrakov et al., 2013*], the average balance of the Djankuat glacier in the same period was 120 mm/year [*Popovnin and Petrakov, 2005*]. In 2002–2014, the average balance of the Kolka Glacier was estimated to be +2.9 mln t/year, or +2600 mm/year (recalculated by the area of the Kolka Glacier in 2014), while the balance of the Djankuat Glacier in the same period was 560 mm/year (*the oral statement by V.V. Popovnin*) [*WGMS, 2013; WGMS, 2015*]. In 2009–2014, the contrast between the balances of the Kolka Glacier and of the Djankuat Glacier grew compared to 2002–2009: compared to the constant average balances of the Kolka Glacier, the balance of the Djankuat glacier in 2009–2014 became more negative by –400 mm/year.

The causes of the fast regeneration of the Kolka Glacier after the outbursts of ice were analyzed in a number of papers, for example, in [*Rototaev et al., 1983; Petrakov et al., 2013; Kotlyakov et al., 2014*]. *K.P. Rototaev et al.* [*1983*] noted a significant role of the wind transport from the Suatisi Glacier to avalanche catchments feeding the Kolka Glacier and evaluated the share of the avalanche source of the Kolka Glacier as 85 %. Judging by the field observations after the disaster of 2002, the role of avalanches in the alimentation of the Kolka Glacier grew due to the increase in the proportion of snow dumped from the slopes. In the first years after the disaster, snow did not stay on the bottom of the Kolka Glacier cirque. It is likely that this occurred due to an elevated air temperature related to the absence of ice and depression of the location altitude [*Chernov et al., 2010*]. Over the recent years, avalanche snow-patches remained in the rear part of the Kolka Glacier, which resulted in the emergence of a small firn area on the glacier (Fig. 6). This could have happened due to both depression of the air temperature under the influence of the glacier's cooling effect and the rise of the glacier surface by 50 m (Figs. 3, 4), and to the growth on the avalanche masses.

It has been previously considered that the balance of the Kolka Glacier after the disaster of 2002 is determined "by exclusively the conditions of the cold period" [*Petrakov et al., 2013, p. 44*] or "depends almost exclusively on the amount of the avalanche snow" [*Kotlyakov et al., 2014, p. 122*]. Summer melting was screened by the thick layer of the debris material on the glacier surface. The area of the sites of open ice and firn is not large yet, but expansion of these sites will contribute to the increase of summer melting and reduction in the rates of ice accumulation.

As of 2014, (40 ± 11) mln m^3 ice accumulated in the cirque of the Kolka Glacier, i.e., about 40 % of the pre-disaster mass of the glacier. Earlier, we predicted the possibility of recovery of the linear dimensions of

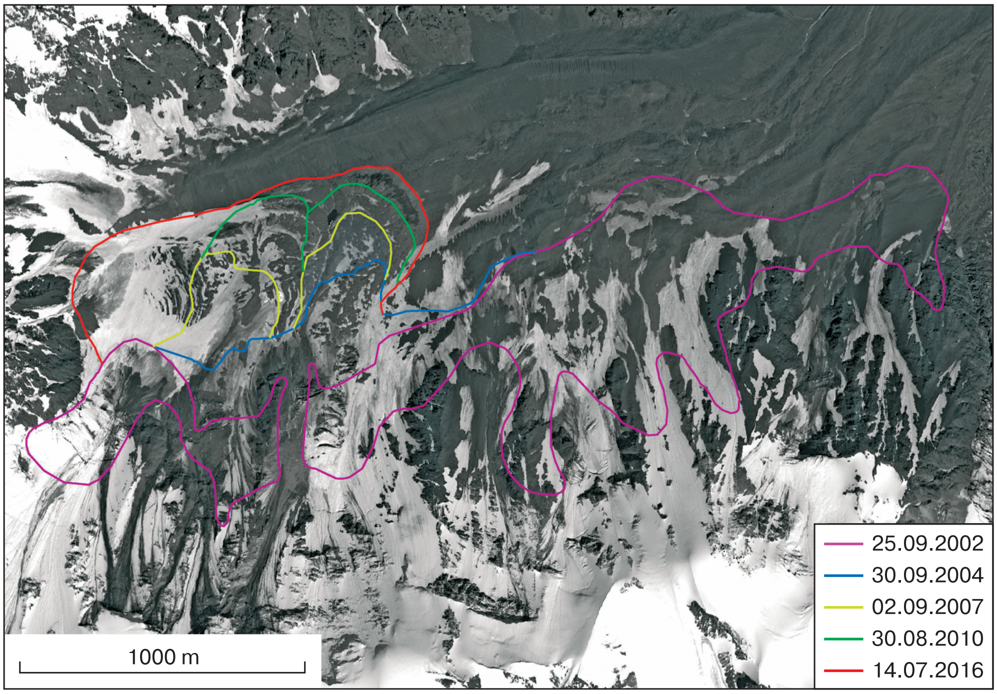

Fig. 5. Changing boundaries of the self-regenerating Kolka Glacier in 2002–2016.

See the data on the satellite images used for determining the glacier boundaries and the survey dates in Table 1. The upper boundary of the glacier is shown as of 2002. Background: a SPOT-6 satellite image taken on 14.07.2016.

Fig. 6. Regeneration of the Kolka Glacier in 2004–2016. A series of photos taken from the left flank moraine of the Kolka Glacier in different years from point 3 of the repeated photo survey (Fig. 1).

a – August 2004; *b* – August 2006; *c* – August 2009; *d* – August 2014 (*a*–*d* – the photos by D.A. Petrakov); *e* – September 2016 (the photo by A.A. Kolchin).

the Kolka Glacier by 2025. Judging by the slow-down of the glacier front advancement observed since 2011, the probability of such a scenario is low. On the contrary, the probability of predicted accumulation of 60–70 mln m^3 ice by 2025 is rather high.

The Karmadon Depression. The values of the melting rate of the ice mass of the glacier in 2002–2009 and analysis of their changes in this period are provided in [*Petrakov et al., 2013*]. According to the topographic survey, in 2014, the volume of the ice mass was (29 ± 5) mln m^3 (Fig. 7), which is 5 mln m^3 (or 15 %) less than in 2009. To verify the accuracy of the estimations of the volume of the ice mass and its changes obtained by extrapolation of the data from transverse profiles, we compared the maps of the ice dam of 2002 with the DEM on the basis of the stereo pair of the SPOT-6 satellite images taken in 2014. According to these data, in 2002–2014, the volume of the ice mass decreased by (84 ± 5) mln m^3, and in 2014 it was (26 ± 5) mln m^3 (Fig. 7), which is 3 mln m^3 less compared to the estimations based on extrapolation. The estimates obtained by the land-based and remote survey demonstrated good agreement. The maximum value of the decrease in the ice dam height exceeded 100 m (Fig. 8). In the axial part of the depression, there is a trench in which the dam surface went down by more than 80 m.

In fact, the changes in the dam volume are now within the estimate error limits. The value of reduction in the dam surface in 2009–2014 did not exceed 15 m, and on average, it was essentially less. As previously predicted [*Petrakov et al., 2013*], the reduction rates of the ice mass volume are asymptotically decreasing. Whereas in 2002–2003 the reduction rate of the ice mass volume was 44 mln m^3 per year, in 2003–2004 it was 15 mln m^3 per year, in 2004–2009, it decreased to 3.5 mln m^3 per year, in 2009–2014 it dropped to 1 mln m^3 per year. Thus, over the years that passed after the disaster, the reduction rate of the ice mass volume has dropped nearly 50 times.

This seems to be attributed to progressing increase in the thickness of the soil and stone debris cover on the surface of the ice dam. The curve of reduction in the ice mass volume is quite similar to the curves of reduction in the melting rates depending on the thickness of the moraine cover on glaciers [*Nicholson and Benn, 2006*]. The major mass of the dam is now composed not of ice carried here during the events of 2002 but of the debris material and of alluvial sediments. In the estimate of V.N. Drobyshev, in 2002–2004, a ten-meter layer of fluvial sediments ac-

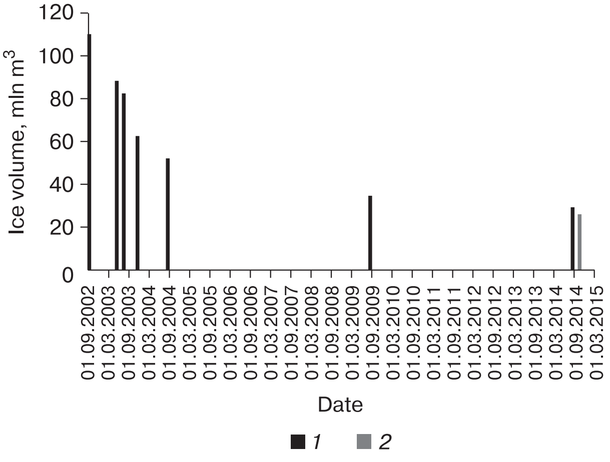

Fig. 7. Changes in the volume of the ice mass in the Karmadon Depression in 2002–2009 according to the data of repeated tacheometric measurements of the surface height of the ice mass (*1*) and to the comparison of the topographic map of the ice dam of 2002, scale 1:10 000 with the DEM generated from the stereo pair of SPOT-6 satellite images taken in 2014 (*2*).

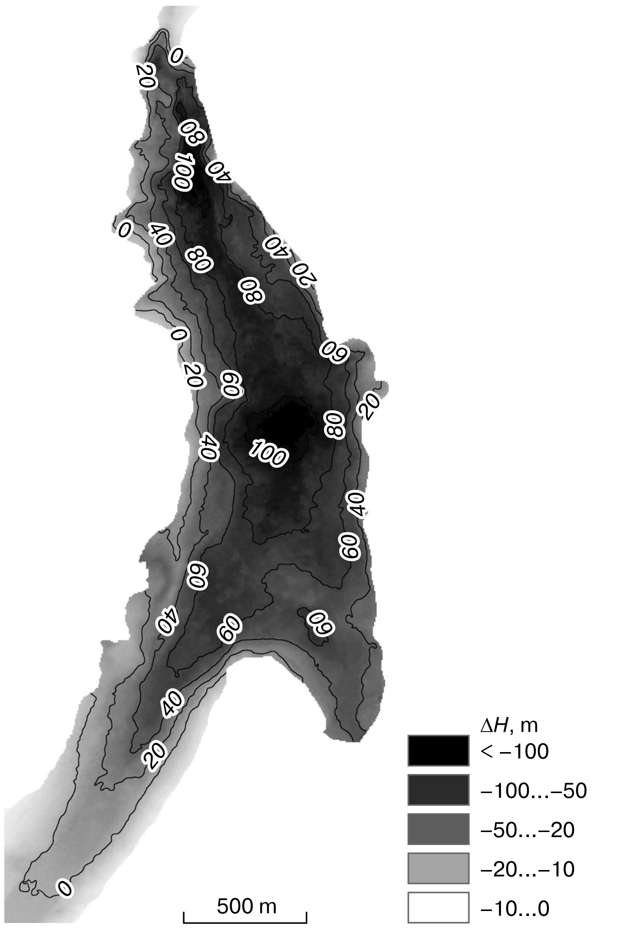

Fig. 8. Changes in the surface height (ΔH) of ice dam in the Karmadon Depression in 2002–2014, evaluated according to the results of the land-based topographic survey carried out by V.N. Drobyshev and V.V. Maklikov on 28.09.2002 and to the DEM generated from the stereo pair of SPOT-6 satellite images taken on 29.10.2014.

cumulated above the ice dam. The same process could have occurred inside and under the ice dam due to reduction of the river bed slope and of the stream velocity of the Genaldon River.

We estimated the contribution of melting of the ide dam to the water supply for the Genaldon River in 2002–2003 as 50 %, that in 2003–2004 was estimated as 12 %, that in 2004–2009 – 4 % [*Petrakov et al., 2013*], and in 2009–2014 – only as 1 %. It can be stated that now the melting of the ice mass does not play a hydrological role.

CONCLUSION

Fast accumulation of ice is continuing in the cirque of the Kolka Glacier. In 2014, the maximum thickness of the regenerated glacier reached 90 m. In 2002–2014, about (40 ± 11) mln m^3 ice accumulated in the glacier cirque, which is about 40 % of the volume of the Kolka Glacier before the disaster of 2002. Our data on the thickness of the regenerating glacier are confirmed by the results of radio sounding of the area of the Kolka Glacier conducted in 2014. No reduction of the glacier mass increment rate took place: in 2009–2014, as much accumulated as in 2004–2009. The positive mass balance resulted in the growth of the area covered by the Kolka Glacier and in advancement of its front, which became the only case of significant advancement of a glacier in the Caucasus in the 21st century. The advancement rate of the front of the Kolka Glacier has slowed down over the recent years. Regeneration of the Kolka Glacier is taking place against the background of unfavorable weather conditions for the Caucasus and is in sharp contrast with the behavior of the other Caucasian glaciers. The mass balance of the regenerating Kolka Glacier, covered by a significant mass of the debris material, mainly depends on snow accumulation. Expansion of the areas of open ice and firn may result in the increase of the role of ablation and in the slowdown of the regeneration rate of the glacier.

The mass of the ice dam in the Karmadon Depression decreased by 75 % in 2002–2014. Progressing reduction in the ice melting rate, which we previously noted, continued. In 2009–2014, compared to the first year after the disaster, the ice melting rates decreased by nearly 50 times. Ice may stay long in the depression, and regeneration of the pre-disaster surface will not occur due to accumulation of a large amount of the debris material brought by the disaster and of sediments of the Genaldon River. The hydrological role of the ice mass in the runoff of the Genaldon River has been negligibly small over the recent years.

In the nearest 10 years, it is highly unlikely that an event similar to the disaster of 2002 may take place. It should be remembered, though, that by 2025 the Kolka Glacier may regain 60–70 % of its pre-disaster volume, which, given a certain combination of the trigger mechanisms, could result in recurrence of the events of 2002. Monitoring of regeneration of the glacier should be continued, and survey of the glacier should be conducted every 5–10 years, to measure the volume of the accumulated ice. In addition, the studies of the endogenous processes taking place in the depths of the Kazbek-Dzhimaray massif and potentially influencing the likelihood of recurrence of the glacial disaster should be expanded.

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