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FLUCTUATIONS OF TERSKOL GLACIER, NORTHERN CAUCASUS, RUSSIA

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Reconstruction of fluctuations of Terskol Glacier situated on the south-western slope of Elbrus is presented. The reconstruction is based on remote sensing images of 1957, 1971, 1987, 1997, 2001, 2007 and 2009, maps, plans and photographs of the late 19th–20th centuries, as well as on modern photographs of the late 20th – the beginning of 21st centuries. As a result, 13 positions of the glacier's edge have been created, and 10 moraines have been identified. Behind the last moraine complex (at the height of 2,550 m), indistinct remnants of the older moraines partly covered by a debris-flow have been revealed. Dating of junipers growing on these surfaces demonstrated that over the last 300 years Terskol Glacier had not moved below these levels. Therefore, over the last 300 years Terskol Glacier has fluctuated not more than 1,150 m in plane and 460 m in elevation. The glacier's area has decreased over this time by 0.74 km^2.

Dendrochronology, Earth remote sensing, glacier fluctuations, lichenometry

INTRODUCTION

A tendency for recession of mountain glaciers has been recently observed in all the regions of the Earth. This tendency is in agreement with the meteorological data testifying to the global rise of the mean annual air temperatures on the Earth by 0.85 °C in the period from 1880 to 2012 [*Stocker et al., 2013*]. Thus, mountain glaciers are sensitive indicators of the climate changes, and their fluctuations may serve and do serve as an important source of paleo climatic information, allowing the modern changes of the climate to be viewed in a wider time context [*Oerlemans, 2001*].

The information about the past conditions of glaciers may be obtained from the historic descriptions of glaciers, old maps, photographs, paintings, as well as by dating moraines, which are formed by glaciers as a result of glacier advances or prolonged steady conditions. Moraines are dated by using historic, bio indication or radiometric methods. The degrees of precision of this dating vary, depending on the availability of material for dating and the natural limitations of the methods of age determination. The highest degree of precision (up to a year) is reached when referring to historic information and dendrochronology, if the researchers are lucky to find the trees directly affected or destroyed by an advancing glacier and buried in the moraines. Usually the precision degree of dating is much lower and constitutes several decades or even centuries.

Glaciation of the Caucasus Mountains has been investigated for a century and a half [*Abich, 1875*], and significant progress has been achieved in this area. However, compared to many other glacier-covered mountain regions of the Earth (the Alps, the Rocky Mountains, the mountains of Scandinavia), the degree of precision of the Caucasian reconstructions is still very low, and the foundations underlying many conclusions are shaky; many episodes of the glaciation history of the Caucasus are still based on the analogies with the Alpine history. A serious challenge is spatial reference of the positions of the glacier ends and their moraines. So far, for the vast majority of the Caucasian glaciers, there are only general plans of the positions of the glacier ends, which totally disagrees with the potential offered by modern mapping. The absence of such reference complicates, and in some cases, simply makes it impossible to use the rich materials relating to fluctuations in the 20th century of glacier ends collected by several generations of the researchers [*Dinnik, 1890; Podozersky, 1911; Bush, 1914; Solovyev, 1933; Oreshnikova, 1936; Kovalev, 1961; Tushinsky, 1968; Seynova and Zolotarev, 2001; Panov et al., 2008; Zolotarev, 2009*]. Only precise spatial positioning of the glacier boundaries allows building continuous series of observations, extending them into the past with historic and bio indication methods and using them in mathematical modeling.

All-round application of the modern mapping, bio indication and radiometric methods aimed at reconstructing fluctuations of the Caucasian glaciers, is an important task, which is of both fundamental and applied interest.

This study continues the series of publications devoted to fluctuations of the Caucasian glaciers over the recent centuries [*Bushueva and Solomina, 2012; Solomina et al., 2012*]. The reconstructions are based on the data of instrumental observations of the positions of the glacier ends, Earth remote sensing (ERS), historic evidence and the results of using bio indication methods (lichenometry and dendrochronology) [*Volodicheva and Voitkovsky, 2004; Bushueva and Solomina, 2012; Solomina et al., 2012*]; they also include evaluation of the changes in the glacier sizes based on computer simulation data. The main purpose of these studies is to implement as precisely as possible the reference of the glacier boundaries in space and time and to evaluate the current rates of deglaciation considering the historic context.

THE RESULTS OF RECONSTRUCTING FLUCTUATIONS OF TERSKOL GLACIER

Glacier fluctuations according to maps and photographs

Terskol Glacier (43°18′ N; 42°30′ E) originates on the glacier slope of Elbrus Volcano and flows in the south-eastern direction into the valley of the River Terskol. During our expeditions to Terskol Glacier in 2009 and 2014, its end was located in the upper part of a huge riegel (Fig. 1). Comparison of the current photos of the valley with the photographs taken in the early 20th century demonstrates significant reduction of the glacier over this period.

Judging by the satellite images GeoEye (October 16, 2009), CARTOSAT (September 12, 2007) and ASTER (September 15, 2001), in the period from 2007 to 2009 the glacier reduced in size by 12 m, and in the period from 2001 to 2007 the reduction was 25 m. The above values correspond to reduction of the glacier in plane, i.e.in the projection upon a horizontal surface, whereas the glacier is located on a tall and nearly vertical riegel. The aerial photos taken on July 24, 1957, on September 26, 1987 and in 1997 and the satellite image from the CORONA satellite of 1971 allow the following reconstruction: in the period from 1997 to 2001, the glacier reduced by 29 m, in the period from 1987 to 1997, the reduction was 55 m, and in the period from 1971 to 1987 Terskol Glacier advanced by 50 m. Thus, in the late 1970s – early 1980s, the glacier advanced. In those years, Terskol Glacier was studied by N.A. Volodicheva and by other researchers of the geography department of the Moscow State University, who recorded advancement on Terskol Glacier in 1960–1970s [*Panov et al., 2008*]. In the period from 1957 to 1971, the glacier reduced by 25 m. According to the report of *V.N. Kostousov* [*1959*], in 1957–1958 Terskol Glacier had five tongues, and the rightmost one was dying; *V.B. Nefedova* [*1958*] also indicated that the end of the glacier looked like a five-fingered paw; *G.K. Tushinsky* [*1958*], who visited the glacier on August 18, 1957, noted that the end of the tongue looked like a four-fingered paw. Five tongues are identified in the configuration of the end of Terskol Glacier of those years shown in the paper by *A.V. Bryukhanov* [*1958*]. Such discordance is most likely related to subjective interpretation of the shape of the glacier end. A photo theodolite survey was carried out from the same basic site on July 3, 1956 and on July 25, 1957, which showed that "...the most significant recession of the glacier is observed in the eastern part of the glacier end, crowned with three elongated tongues. Here the glacier has recessed by 10–15 m on average. The maximum recession values constituting 37 and 30 m were recorded for the leftmost and middle tongues. The position of the western part of the end of Terskol Glacier has nearly not changed during the year. Insignificant recession, about 5–6 m, is observed here only for two

a *b*

Fig. 1. A painting of Terskol Glacier by an unknown author dated by the beginning of the 20th century (*a*) and a photograph of Terskol Glacier by I.S. Bushueva, 2009 (*b*).

most elongated sites...” [*Bryukhanov, 1958, pp. 75–78*]. Before 1957, reconstruction of the glacier is based on maps, schematics, photographs, and descriptions of the glacier. The position of the glacier end in 1936 was determined by the photo taken by an unknown author (Fig. 2). In the period from 1936 to 1957, the glacier recessed by 160 m.

In the photograph taken in 1948 by Ya.I. Frolov (Fig. 3) [*Frolov, 1950*], Terskol Glacier is of approximately the same size as in 1936; it may be likely that in 1948 it was even somewhat larger. The photographs were taken from different positions; therefore it is impossible precisely to define the changes that occurred. According to the data presented by P.A. Ivankov, in 1946 the glacier end was 1,300 m higher above the confluence of three creeks in the area of the upper boundary of a group of trees on the eastern slope of the valley (the absolute height of the location is 2,483 m). The height of the point indicated by *P.A. Ivankov* [*1960*] does not correspond to the height of the same point on the Global Digital Elevation Map (GDEM) and on the topographic map of 1989 of the 1:100 000 scale we used. It seems that the distance is indicated considering the elevation, whereas the degree of precision of the GDEM use of such data.

P.V. Kovalev [*1961*] visited Terskol Glacier in 1947. He wrote: “The glacier ends in four small sleeves forming a waterfall with numerous tall seracs. The left part of the glacier end goes down from the cliff lower than the right one, but already in 1947 it did not reach the valley bottom. From the second left sleeve located on the cliff fragments of ice drop, which at the foot of the cliff freeze again, forming a new small glacier...” [*Kovalev, 1961, p. 91*]. From 1925 to 1936, Terskol Glacier recessed by 180 m. The location of the glacier in 1925 has been reconstructed based on the photograph taken by *V.Ya. Altberg* [*1928*]. In this period (1932–1933), the glacier was visited by E.I. Oreshnikova, who wrote that “...the left part of the glacier end is tapered and reaches the valley bottom, while the remaining part is located much higher and is hanging almost on the edge of the cliff...” [*Oreshnikova, 1936, p. 265*]. The glacier demonstrated evident signs of recession, which occurs mostly due to the fall of ice from the steep cliff. Comparing the glacier end and the photograph taken by Moritz von Déchy, the author makes a conclusion that the general configuration and the position of the glacier tongue end have changed considerably. S.P. Solovyev, who visited the glacier in 1929–1932, noted that the glacier end was hanging, and a nearly vertical granodiorite wall cropped out more and more from year to year. “...Earlier the glacier end was situated on the bottom of the upper reaches of the River Terskol valley, and currently this part of the glacier is entirely missing...” [*Solovyev, 1933, p. 153*]. S.P. Solovyev also indicated that, compared to the topographic map of 1887–1889, rather significant changes were observed towards reduction of the glaciers’ areas.

In 1911, N.A. Bush visited the glacier [*Bush, 1914*]. He reported asymmetry of the glacier he observed: the right part of the lower end was overlying a vertical rocky cliff polished by the glacier; the left part went down much further, to the bottom of the gorge. He noted the beginning of the glacier’s advancement, as the glacier was moving a small new end moraine in front of it. N.A. Bush also noted that the moraine was formed due to the glacier’s ploughing of the gorge bottom rocks, as the glacier surface was clean, and rocks could not fall down from it. I.V. Mushketov referred in his papers to K.V. Poggenpohl and wrote that the glacier “...reached the bottom of the River Terskol valley in the photograph taken three years ago, and now it has risen by about 120 meters, having left the moraine and opened the river bed rocks...” [*Mushketov, 1898, p. 620*]. In his second paper [*Mushketov, 1899*], he wrote that Terskol Glacier receded by 7 m, which is insignificant reduction for

Fig. 2. A photograph by an unknown author, 1936.

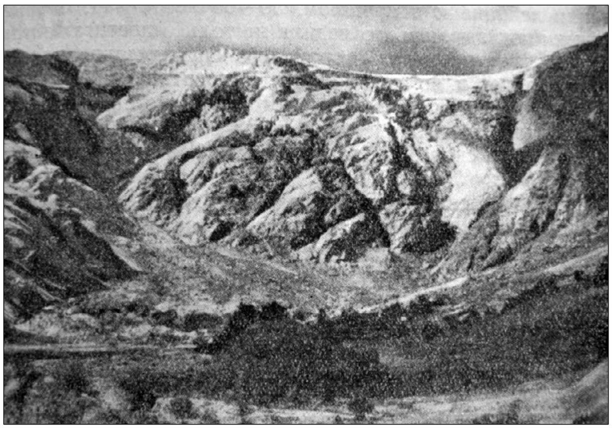

Fig. 3. A photograph of Terskol Glacier by Ya.I. Frolov, 1948.

such a large glacier. Gottfried Merzbacher did not describe the glacier end; however, he published several concurrent photographs of Terskol Glacier [*Merzbacher, 1901*].

In 1889, Terskol Glacier was photographed by the pioneer Italian topographer and mountaineer Vittorio Sella (Fig. 4) [*Freshfield, 1896*]. In 1889, the glacier was 230 m longer, compared to the year of 1925 [*Altberg, 1928*]. Comparison of the photograph taken by Vittorio Sella and of the one-verst map prepared by topographers from the military topographers' corps in 1887 shows that in the period from 1887 to 1889 the glacier was supposed to advance by 115 m, which is hardly probable. The degree of precision of referencing the glacier boundaries by photographs may constitute several dozens of meters; however, in this case there are good reference points, such as moraines, flood gullies and detrital cones of mudslides, which excludes the possibility of a serious error. At the same time, the glacier boundary on the military topographers' map is drawn not very clearly: it merges with the hypsographic curves, and this may lead to a mistake in interpreting the map. Thus, both sources provide reasons to assume that in late 1880s the end of Terskol Glacier was in the area of the moraine, which in the authors' schematic is indicated as *M4* (Fig. 5), but at that moment it had not formed yet. It is impossible to give more precise assessments of these two sources due to their errors. In general, the contours of Terskol Glacier provided on the tourist map "Elbrus" of 1933 coincide with the boundaries of the glacier on the one-verst map of 1887; however, on the Elbrus map the glacier is shown as being more elongated. It is rather likely that this happened due to the wrong interpretation of the glacier boundaries on the military topographers' map. Therefore, we did not use these data in our reconstruction.

In 1884, Terskol Glacier was visited by *D.L. Ivanov* [*1884*] and Moritz von Déchy [*Déchy, 1905*], and in 1881 it was visited by *N.Ya. Dinnik* [*1884*] and *I.V. Mushketov* [*1882*]. According to Dinnik, in 1881 "Looking up at the glacier from below, it looks like a right-angled triangle with blunted angle points..." [*Dinnik, 1884, p. 35*]. According to D.L. Ivanov, in 1884 the left edge of the glacier was at the height of 2,590 m, while the right one was at the height of 3,500 m. According to I.V. Mushketov, in 1881 the height of the end of Terskol Glacier was 2,620 m, which better agrees with our reconstruction, in particular, with the position of the glacier reconstructed in accordance with the painting provided in the book by Gottfried Merzbacher [*Merzbacher, 1901*]. There is another photograph of the glacier in the archives of the Sella Foundation (Biella, Italy) which is used in this study (Fig. 6). Unfortunately, the end of the glacier is hardly discernible in this photograph and in the other photographs by Moritz von Déchy [*Déchy, 1905*]; therefore, it is difficult to reconstruct its location. In his book, Gottfried Merzbacher [*Merzbacher,*

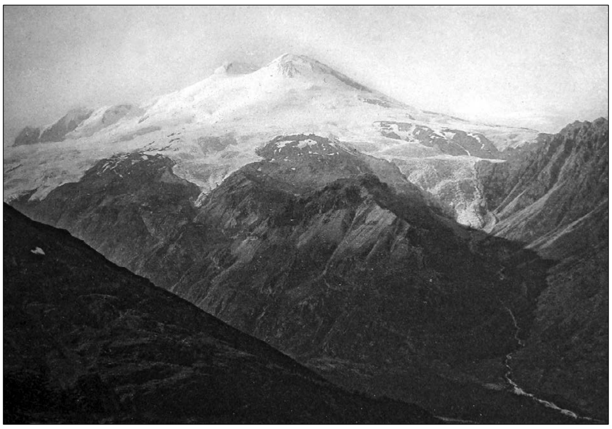

Fig. 4. A photograph of Terskol Glacier by V. Sella, 1889 [*Freshfield, 1896*].

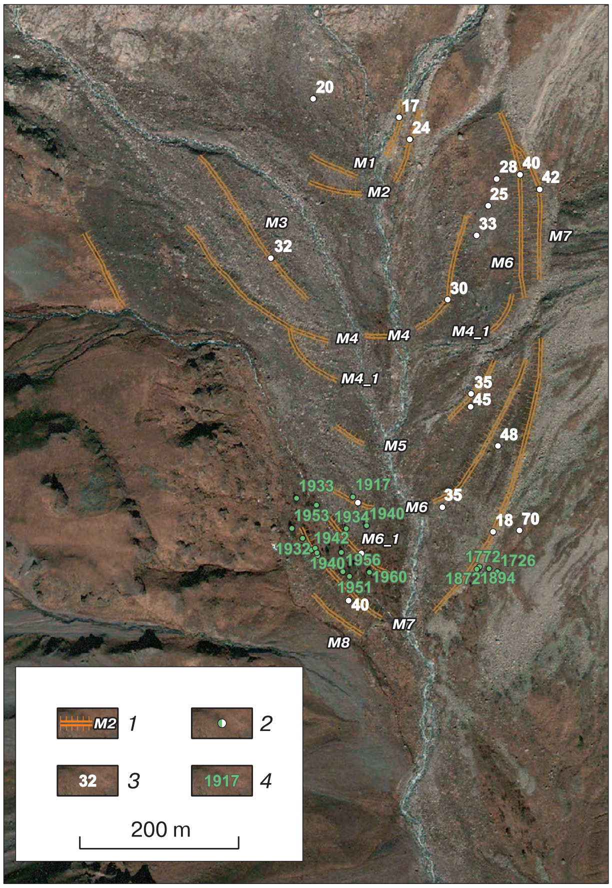

Fig. 5. Moraines situated on the foregrounds of Terskol Glacier (the results of dating the samples with the dendrochronological and lichenometric methods).

1 – moraines; *2* – places of sampling; *3* – the maximum lichen diameter; *4* – the year of the first ring's formation for the dendrological samples.

Fig. 6. A photograph of Terskol Glacier by M. von Déchy, 1884 [*Déchy, 1905*].

Fig. 7. A photograph of Terskol Glacier and of Elbrus Mountain by D.I. Ermakov, 1885 [*Sysoev, 1900*].

1901] publishes a photograph and a drawing of Terskol Glacier; however, it is difficult to use them for reconstruction, as proportions are distorted in the drawing and the photograph is of poor quality. In 1874, Englishman F. Grove, accompanied by the local guides, climbed Elbrus Mount [*Grove, 1875*]; however, they climbed up Bolshoy Azau Glacier and further up the southern slopes of Elbrus, therefore he mentions Terskol Glacier only in passing.

Glacier fluctuations according to historic, geomorphological and bio indication data

Shown in Fig. 5 is a schematic showing the location of the moraine lines of Terskol Glacier and the results of lichenometric and dendrochronological studies conducted on its foregrounds. The details of the lichenometric method and the growth curve of the *Rhizocarpon geographicum* lichens are described sensu lato in [*Bushueva and Solomina, 2012*]. The approximate growth rate of the lichens, which serve as glacier growth indicators, is about 0.25 mm per year in the first three or four centuries of the glacier's existence [*Bushueva, 2013*]. In [*Bushueva and Solomina, 2012*] the method of dendrochronological dating, which the authors used on the foregrounds of the Caucasian glaciers, is described in detail. Pines populated the moraines in the area under study 10–15 years ago, and their age at the altitude of sampling (about 150 cm) was assessed to be about 10 years. These corrections are made when assessing the minimum age of the surface of moraines and of other glacial formations of the relief and are added to the number of the growth rings established by dendrochronological analysis.

The authors investigated the moraines in the valley of Terskol Glacier primarily on the left side of the valley, where most of the moraines are concentrated. The moraines of the right side are well visible from the left side and can be identified on the satellite images and aerial photos. Based on the notes made by *N.A. Bush* [*1914*] and on old photographs, one can suppose that he described the moraine line *M2* as a push-moraine. Lichens grow on it, the maximum diameter of which is 24 mm, which corresponds to the lichen age of about 70–80 years. The younger moraine *M1* is most likely to have been formed in 1920s: the quality of the photograph taken by V.Ya. Altberg in 1925 is very poor; therefore, it is impossible to discern clearly whether there is a moraine near the end of the glacier; the end of the glacier was situated at the time approximately in the area of moraine *M1*. The photograph by Sella (1889) clearly demonstrates the left flank moraine and several terminal moraines originating from it. Judging by their location, these must be *M4_1*, *M5*, *M6*, and *M7*. It can be seen in the photograph that in 1889 the glacier approached moraine *M4* close by. Therefore we can assume that moraines *M4* were formed in the first half of 1890s [*Mushketov, 1898*]. Lichens growing on the crest of moraine *M4* have the maximum diameter of 29 mm, which does not contradict the above assessment of the age of the moraines taking into account the historical data. We have a photograph taken by D.I. Ermakov in late July of 1885 at our disposal (Fig. 7) [*Sysoev, 1900*]. Three moraines located on the right side of the valley can be seen there (*M5*, *M6* and *M7*). As moraine *M5* is indicated there, we can conclude that in 1885 the glacier was shorter than in 1889 (according the photograph by Sella), i.e., formation of the moraine started from 1880s. Lichens with the diameter reaching 45 mm grow on moraine *M5*, suggesting the moraine age of about 140 years.

Older moraines still look fresh, and young forest (pines about 100 years old) grows on the surfaces of moraines *M6*, *M6_1* and *M7*. It can be seen on the photographs of 1880s that two external moraines *M6* and *M7* were not turfed and seemed to be only several decades old. These moraines are most likely to date back to the middle or beginning of the early 19th century. Lichens sized up to 48 mm occur in the distal part of moraine *M6* on the right side of the valley. The age of the oldest tree found on the right side of the valley in the set of moraines *M6*, *M6_1*, and *M7* corresponds to 1917, with allowance for the settlement of the trees and the drilling height – 1892.

On the left side of Terskol valley, moraine line *M7* is partly overlapped by moraine deposits. Juniper aged 140 years grows on its external side. Thus, the minimum age of this moraine line is 160–180, with allowance for the settlement of the trees.

This agrees with our estimation of the age of moraine *M7* on the right side made in accordance with the photographs (see above), so, this moraine seems to date back to the middle of the 19th century. Behind moraine *M7* on the left side of the valley, there are several more moraine lines of unclear origin (moraine or mudslide lines), overlain by mudslide deposits. Junipers aged 240–280 years grow on them. This indicates that Terskol Glacier has not advanced below this level over the recent 300 years.

On the right side of the Terskol Glacier valley, there has remained a small fragment of a short moraine *M8*, which consists of large boulders, the surface of which is fully covered with lichens (*Rhizocarpon* spp.). Judging by the moraine's look, this moraine is much older than the previous moraine *M7*, although the distance between them is only 30 m.

In the study of *I.B. Seynova and E.A. Zolotarev* [*2001*], the following sizes of the lichens growing on the moraines of Terskol Glacier are indicated: 17, 24, 30, 40, 51, 85, and 115 mm. Unfortunately, due to the absence of its spatial references of the moraines, it is difficult to compare our data with these earlier results of the lichenometric studies.

Changes in the size of Terskol Glacier over the recent 300 years

Calculation of the main parameters of the glaciers (length, area, height of the glacier end, and volume) was made using the software product ArcGIS 10.0. The first three parameters were evaluated with the standard functions ArcMap 10.0 on the basis of recommendations posted at the website of the GLIMS project (www.glims.org) [*Raup and Khalsa, 2010*]. The glaciers' volumes were calculated using empirical dependences of the area upon the volume suggested by *S. Adhikari and S.J. Marshall* [*2012*], by the formula of Mazo-Glazyrin [*Macheret et al., 2013*], as well as by the GlapTop model allowing reconstruction of the glacier bed [*Linsbauer et al., 2012*]. For the sake of convenience, this model was programmed as a toolbox for ArcMap.

Table 1. **Metric characteristics of the fluctuations of Terskol Glacier**

Year	Moraine	Length (by central line), km	Height of glacier end, m	Area, km^2	Volume, km^3		
					S. Adhikari method	Mazo–Glazyrin formula	GlabTop* model
Beginning of 19th century	*M7*	7.409	2555	6.891	0.419	0.400	
–	*M6*	7.257	2589	6.844	0.416	0.391	
–	*M5*	7.179	2602	6.813	0.413	0.385	
1881	–	7.154	2609	7.415	0.457	0.418	
–	*M4_1*	6.927	2666	7.161	0.439	0.393	
1889	–	7.095	2640	7.257	0.447	0.406	
1880–1890s	*M4*	7.093	2634	6.792	0.412	0.380	
1887	–	7.041	2640	6.747	0.409	0.375	
1910s	*M2*	6.843	2688	6.656	0.402	0.362	
1920s	*M1*	6.805	2695	6.645	0.401	0.359	
1925	–	6.696	2712	6.492	0.390	0.346	
1936	–	6.514	2841	6.439	0.387	0.335	
1948	–	6.514	2841	6.447	0.387	0.336	
1957	–	6.353	2980	6.376	0.382	0.325	
1971	–	6.335	2991	6.378	0.382	0.325	
1987	–	6.378	2955	6.346	0.380	0.325	
1997	–	6.323	2991	6.345	0.380	0.322	
2001	–	6.295	3000	6.203	0.370	0.314	
2007	–	6.269	3007	6.183	0.368	0.312	
2009	–	6.257	3007	6.153	0.366	0.310	0.393

* The glacier volume is calculated by the GlabTop model only for 2009, for which there is a digital elevation model.

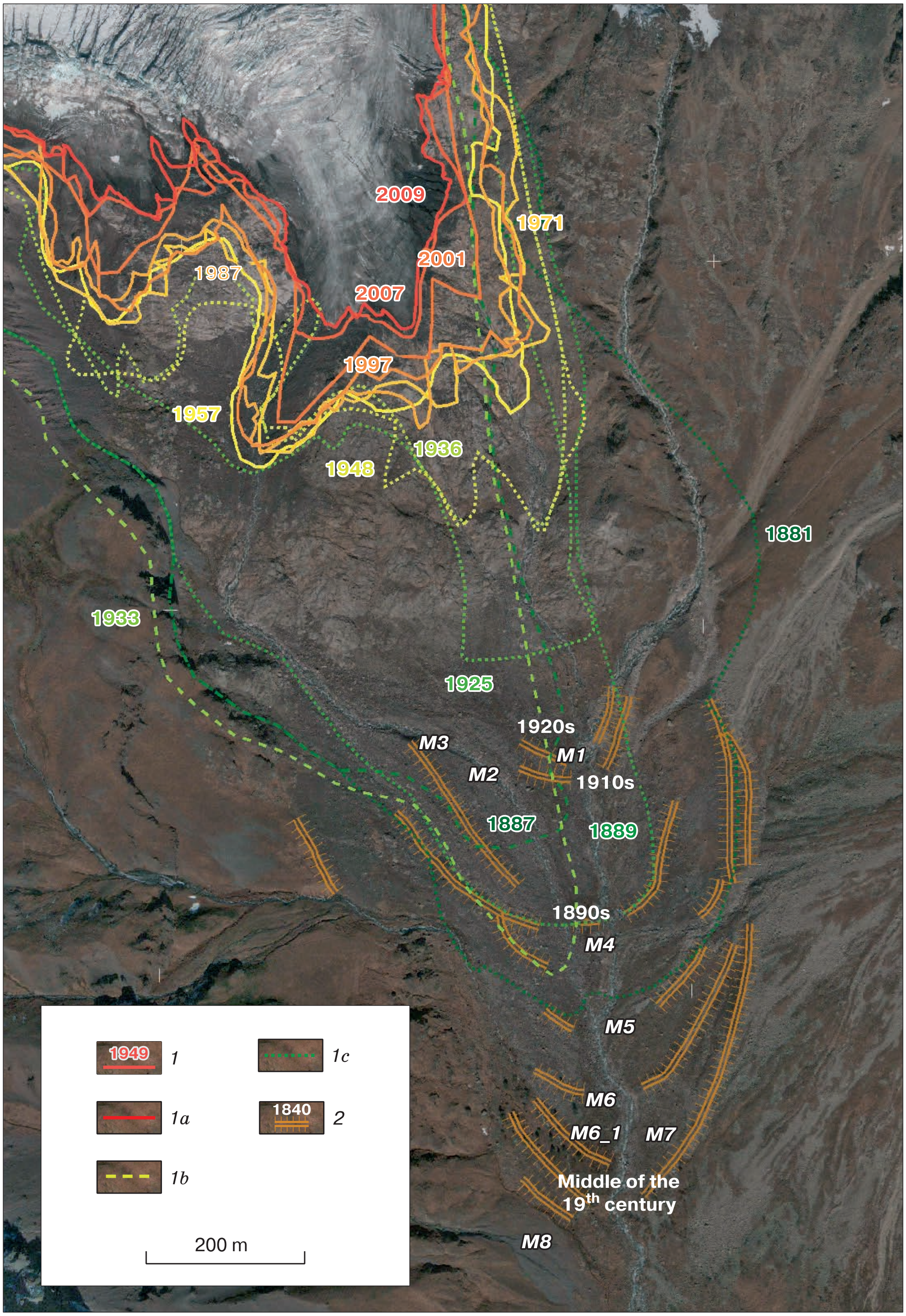

Fig. 8. The fluctuations of the end of Terskol Glacier.

1 – the position of the glacier in a certain year: *1a* – according to the Earth remote sensing data, *1b* – according to maps and schematics, *1c* – according to photographs; *2* – moraines and their age.

Shown in Table 1 are the results of the calculations of the main metric characteristics of Terskol Glacier of several time scans. The schematic of the fluctuations of the glacier end is shown in Fig. 8.

We compared the results obtained with the most detailed schematic of the fluctuations of Terskol Glacier published by *V.D. Panov et al.* [*2008*]. Unfortunately, due to the absence of its spatial references, we were unable to use the results of V.D. Panov to correct our reconstruction. Thee comparison shows that the cumulative curves of the fluctuations in the length of Terskol Glacier built in accordance with our data and the data provided by V.D. Panov [*Panov et al., 2008*] are similar (Fig. 9). They differ for the periods of 1910–1920s, 1940s, and 1960s. For the first one of these periods, Panov's curve is based on the data provided by N.A. Bush; however, this must be a confusion, as N.A. Bush last visited the Caucasus in 1913 [*Bush, 1914*], i.e., the reference to Bush for the period from 1926 to 1932 must be a mistake. The differences between the curves for the 1940s should be attributed to the absence of points for this period on Panov's curve. Reduction of the glacier, followed by its advancement at the turn of the 1960s, is not expressed, as contrasted to our curve, which is related to the absence of materials relating to spatial reference of the glacier end in this period at our disposal.

In general, the chronology of the glacier advancements and the scope of fluctuations of Terskol Glacier over the recent two or three centuries agree with the fluctuations of the other Caucasian glaciers [*Bushueva, 2013*]. Especially clear similarity is observed in the fluctuations of Terskol Glacier, Ullukam Glacier, and Kashkatash Glacier. Ullukam Glacier also belongs to the Elbrus system, although at the beginning of the 20th century it separated itself from the main icefield, and the valley-lying Kashkatash Glacier is in the vicinity of Terskol Glacier but is not related to the glacial system of Elbrus. According to our data, Terskol Glacier advanced in 1970–1980s, 1920s, 1910s, and 1880–1890s, Ullukam Glacier advanced in 1970–1980s, in the first third of the 20th century, and in the 1870s. Kashkatash Glacier advanced in the 1970–1980s, 1920s, 1910s, 1870–1880s, and in the 1840s [*Bushueva, 2013*]. For the range of fluctuations, the glaciers are also similar – over the recent century (since 1880s), they have reduced by 700–900 m [*Bushueva, 2013*]. The periods of activation of Terskol Glacier in the 19th–20th centuries approximately coincide with the dates of advancement of Bolshoy Azau Glacier, although the latter decreased much more, as at the end of the 19th century its end was very low, at the altitude of 2,330 m. Essential variations in the dynamic changes of Terskol Glacier and Bolshoy Azau Glacier were recorded in 1930s, when Bolshoy Azau Glacier began to shrink fast. This is not surprising: Bolshoy Azau Glacier is located in a narrow gorge and is much larger than Terskol Glacier. In addition, it is considered pulsating, and many advancement cases of pulsating glaciers have dynamic, not climatic, causes.

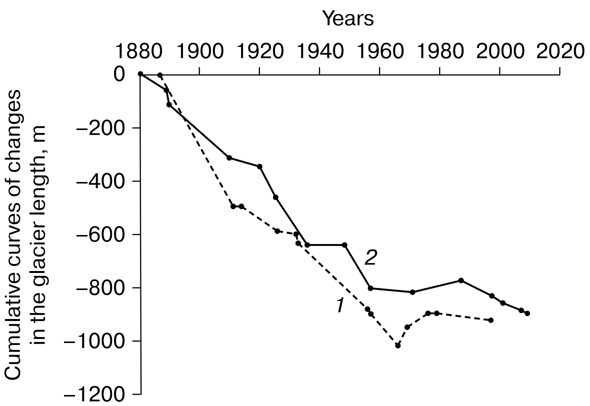

Fig. 9. Cumulative curves of fluctuations in the length of Terskol Glacier according to the data provided by *V.D. Panov et al.* [*2008*] (*1*) and the data provided in this study (*2*).

CONCLUSIONS

1. From the beginning of 1880s to 2009, Terskol Glacier reduced in its length by 900 m, and the glacier tongue rose by 400 m.

2. According to the Earth remote sensing data, the glacier has advanced since 1970–1980s, which agrees with the instrumental observation data.

3. Moraines of the 1920s, 1910s, and 1880–1890s were dated based on historic sources.

4. Below these moraines, four other moraine lines were recorded, which are well discernible on land and look fresh. In the photographs taken at the end of the 19th century, these lines are not yet covered with vegetation, suggesting that they were most likely formed in the 19th century or later. According to the dendrochronological data, the minimal age of the external moraine line is 160–180 years.

5. On the external periphery of this moraine complex, at the altitude of 2,550 m, which is 460 m below the modern end of the glacier (2009), there are vague traces of older moraines, partly overlapped by mudslide deposits. Dating of the junipers growing these locations shows that Terskol Glacier has not advanced below these surfaces over the recent 300 years. Thus, variations in the fluctuations of the end of Terskol Glacier over the recent 300 years have not exceeded 1,150 m in plane and 460 m in height.

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References

Abich, H., 1875. Geologische Beobachtungen auf Reisen im Kaukasus um Jahre 1873. Moskau, Universitätsbuchdr. (Katkoff & co.), 138 pp.

Adhikari, S., Marshall, S.J., 2012. Glacier volume-area relation for high-order mechanics and transient glacier states. Geophys. Res. Lett., vol. 39, 6 p., doi:10.1029/2012GL052712.

Altberg, V.Ya., 1928. On the condition of the glaciers of Elbrus and of the Main Caucasian Ridge in the basin of the River Biksan in the period of 1925–1927. A reprint of the GGI bulletin 22, 79–89.

Bryukhanov, A.V., 1958. On the results of processing of repeated photo theodolite survey of 1956 and 1957 performed on the glaciers of the southern slope of Elbrus. Bulletin of Studies of the International Geophysical Year, No. 2, 73–82.

Bush, N.A., 1914. On the condition of the glaciers of the northern slope of Caucasus in 1907, 1909, 1911 and 1913. Izvestia Russkago Geograficheskogo Obshchestva po Obshchey Geografii, vol. L, iss. V, IX, 461–510.

Bushueva, I.S., 2013. Fluctuations of glaciers in the Central and Western Caucasus determined by mapping, historical, and bio indication data over the recent 200 years: a candidate thesis (geography), Moscow, 169 pp. (in Russian)

Bushueva, I.S., Solomina, 2012. Fluctuations of Kashkatash Glacier in the XVII–XIX centuries determined by mapping, dendrochronological, and lichenometric data. Led i Sneg 52 (2), 121–130.

Déchy, M. von, 1905. Kaukasus Reisen und Forschungen im kaukasischen Hochgebirge. Berlin, Bd. 1, 348 pp.; Bd. 2, 346 pp.

Dinnik, N.Ya., 1884. The mountains and gorges of Terskaya Region. KORGO notes XIII (1), 1–48.

Dinnik, N.Ya., 1890. Modern and ancient glaciers of the Caucasus. KORGO notes XIV (1), 282–416.

Freshfield, D.W., 1896. The Exploration of the Caucasus: Vol. 1. London, New York, 278 pp.

Frolov, Ya.I., 1950. From the observations of the glaciation of the Elbrus region. Conquered peaks. In: A bulletin of Soviet mountaineering. Gosgeografgiz, Moscow, pp. 258–273. (in Russian)

Grove, F.C., 1875. The Frosty Caucasus. Longmans, Green and Co., London, 342 pp.

Ivankov, P.A., 1960. Glaciation of Elbrus. Proc. of the All-Union Geographical Society, 92 (2), 124–135.

Ivanov, D.L., 1884. Climbing Elbrus. Proc. of the Russian Geographical Society, 20 (5), 474–496.

Kostousov, V.N., 1959. A glacyological survey of thr southern glaciation sector of Elbrus. Bulletin of the works on the International Geophysical Year, No. 4, 54–77.

Kovalev, P.V., 1961. Modern glaciation of the River Baksan basin. Materials of the Caucasian expedition under the program of the International Geophysical Year. Kharkov University Press, Kharkov, vol. 2, 3–106.

Linsbauer, A., Paul, F., Haeberli, W., 2012. Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: Application of a fast and robust approach. J. Geophys. Res., vol. 117, 1–17, F03007, doi: 10.1029/2011JF002313.

Macheret, Yu.Ya., Kutuzov, S.S., Matskovsky, V.V., Lavrentyev, I.I., 2013. On evaluation of the amount of ice in mountain glaciers. Led i Sneg 53 (1), 5–15.

Merzbacher, G., 1901. Aus den Hochregionen des Kaukasus. Wanderungen, Erlebnisse. Duncker & Humblot, Leipzig, vol. 1, 958 pp.; vol. 2, 964 pp.

Mushketov, I.V., 1882. A geological trip to Caucasus in 1881. Proc. of the Russian Geographical Society, 18, 112–138.

Mushketov, I.V., 1898. A study of the Russian glaciers in 1897. Proc. of the Russian Geographical Society, 34 (50), 619–623.

Mushketov, I.V., 1899. Proc. of the Russian Geographical Society. Proc. of the Russian Geographical Society, 35 (2), 228–230.

Nefedova, V.B., 1958. On the history of investigating modern glaciation of Elbrus. Bulletin of Studies of the International Geophysical Year, No. 2, 5–22.

Oerlemans, J., 2001. Glaciers and climate change. Balkema Publ., Lisse, 148 pp.

Oreshnikova, E.I., 1936. The glaciers of the Elbrus region: the studies of 1932–33. Caucasus: Proceedings of Glacier Expeditions, iss. 5, 239–297.

Panov, V.D., Ilyichev, Yu.G., Salpagarov, A.D., 2008. Fluctuations of the Glaciers of Northern Caucasus in the 19–20th centuries. Pyatigorsk, MIL Publishing House of Northern Caucasus, 330 pp. (in Russian)

Podozersky, K.I., 1911. The Glaciers of the Caucasus Ridge. Proc. of the Caucasian department of the Imperial Russian Geographical Society, 29 (1), 200 pp.

Raup, B., Khalsa, S.J.S., 2010. GLIMS Analysis Tutorial. 15 pp. URL: http://www.glims.org/MapsAndDocs/assets/GLIMS_Analysis_Tutorial_letter.pdf (submittal date: 01.03.2015).

Seynova, I.B., Zolotarev, E.A., 2001. The Glaciers and Mudslides of the Elbrus Region (The evolution of glaciation and mudslide activity). Nauchnyi Mir, Moscow, 203 pp. (in Russian)

Solomina, O.N., Bushueva, I.S., Kuderina, T.M., Matskovsky, V.V., Kudikov, A.V., 2012. On the Holocene history of Ullukam Glacier. Led i Sneg 1 (117), 85–94.

Solovyev, S.P., 1933. On the condition of the glaciers of the Elbrus region and on the cause of their recession. Proceedings of the Chief Geophysical Observatory LXV, 151–166.

Stocker, T.F., Qin, D., Plattner, G.-K., et al. (eds), 2013. IPCC. Summary for Policymakers. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, N.Y.; Cambridge, 28 pp.

Sysoev, V.M., 1900. Elbrus. Proc. of the Society for Studying the Kuban Region, iss. 2, 75–196.

Tushinsky, G.K., 1958. Glaciological works on Elbrus. Bulletin of works of the International Geophysical Year, No. 1, 3–28.

Tushinsky, G.K., 1968. The Glaciation of Elbrus. Moscow University Press, Moscow, 345 pp. (in Russian)

Volodicheva, N.A., Voitkovsky, K.F., 2004. The evolution of the glacial system of Elbrus. In: The geography, society, and the environment. The structure, dynamics, and evolution of natural geosystems / Ed. by V.I. Konishchev and G.A. Safyanov. Gorodets Publishing House, Moscow, vol. I, pp. 44–50.

Zolotarev, E.A., 2009. The Evolution of Elbrus Glaciation. Nauchnyi Mir, Moscow, 238 pp. (in Russian)

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