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EVOLUTION OF THE ELBRUS GLACIATION SINCE THE MID XIX CENTURY UNDER CHANGING CLIMATE. KEY FINDINGS OF THE GLACIO-CARTOGRAPHICAL MONITORING

ABSTRACT

Changes in the area and volume that have been occurring from the middle of the XIX century within the largest in Europe Elbrus glaciation were studied using lichenometry and digital cartography methods. There were cyclical, approximately 55 years long, frontal fluctuations of glaciers Bolshoi Azau (the largest Elbrus glacier) and Dzhankuat (which is representative of all Central Caucasus glaciation).

Quantitative data on changes in the area and volume of the Elbrus glaciation indicated that the greatest rates of its retreat coincided with the 1850–1887 period. Beginning in 1887, the area reduction was occurring practically evenly through time while the decrease in its volume has even slowed down. These facts suggest that global climate warming, which alternated with short-term cooling periods, began in the middle of the XIX century after the end of the Little Ice Age. The warming was most likely due to natural rather than anthropogenic causes.

KEY WORDS: Elbrus glaciation, global warming, digital mapping.

INTRODUCTION

Numerous studies conducted recently by climatologists suggest global climate warming, which started in the second half of the XX century as a result of greenhouse gases effect. A number of global climate warming models have emerged in Russia and the world [World..., 2003; Climate Change, 2001]. Mountain glaciers are sensitive to climate change. Increase in global temperatures should affect their regimes and parameters, specifically, the area and volume. This hypothesis can be tested through cartographic and aerial-satellite monitoring of the largest in Europe Elbrus glaciation which physical surface exceeds 140 km^2. The monitoring of this glacier has been conducted for over a century – from the end of the XIX century to the present time.

THE FRONT FLUCTUATIONS – THE GLACIER'S RESPONSE TO CLIMATE CHANGE

Russian Academician G. Abich [Abich, 1875] has established a foundation for long-term observations of some Elbrus glaciers. These observations are crucial in defining the glaciers' response to climate change. In 1849

Fig. 1. Location of the Bolshoi Azau glacier tongue on October 21, 1849. Picture by G. Abich [Abich, 1875].

and 1873, G. Abich made two trips to the Bolshoi Azau glacier. During his first trip, G. Abich found that the glacier had intruded on a mature pine forest. This fact was later accepted as a fundamental evidence of the glaciation expanse in the Central end Caucuses in the middle of the XIX century [Tushinski, 1958]. It was assumed that the glacier's was at a well defined moraine line at the bottom of the river Azau valley at 2295–2300 m elevation in the vicinity of the present-day M.V. Lomonosov Moscow State University (MSU) Elbrus station. There were no cartographic surveys in Elbrus prior to 1887 and many researchers of that time [Dinnik, 1890; Mushketov, 1882; Salatskyi, 1866] provided contradicting assessments of the spatial position of the glacier. Such assessments are hard to interpret and reconcile without G. Abich's data.

G. Abich's work, for some reason, still remains unknown to most researchers and, therefore, deserves a detailed presentation especially of its parts related to the Bolshoi Azau glacier. G. Abich conducted thorough studies of the Bolshoi Azau glacier tongue fluctuations in 1849–1873 using instrumental observations. He defined the glacier's elevation (on October 21 1849) at 2322 m from barometric leveling and a known benchmark near the city of Pyatigorsk. He did not expect to return to the area in the future and limited his studies to the use of angular measurements with a portable sextant to draw general boundaries of the glacier (Fig. 1). This drawing was made from a point located at a well-marked rocky ledge of Mt. Terskolak's slope above the forest level across from a modern hotel Cheget.

During his second visit to the glacier in September 17, 1873, G. Abich found the retreating glacier (Fig. 2). He made the same barometric leveling using the same instrument and benchmark. Different environmental conditions (atmospheric pressure and temperature) in 1873 compared to 1849 resulted in a different end moraine elevation measurement (2317 m). G.Abich accepted this measurement as the final result. The glacier linear retreat from 1849 to 1873 was measured at 180 m. The third measurement taken by G. Abich was the difference in the elevations of the foot of the moraine line at the glacier end in 1849 and the elevation of the point of the upper apex abutted against a more ancient end-lateral moraine covered with mature pine forest. This difference appeared to be 37,5 m. The moraine slope of such relative height exists only in the area of the lower station of the cable-way "Elbrus".

The difference in the elevation of the moraine crest and the low water line of the river Azau in the vicinity of the MSU Elbrus station is 27 m. Therefore, the glacier could not be located there in 1849.

Fig. 2. Location of the Bolshoi Azau glacier tongue on October 17, 1873 Picture by G. Abich [Abich, 1875].

We found the point from which G.Abich made his drawings of the glacier in 1849 and 1873 showing the end moraine line in front of the glacier. A phototheodolite survey conducted from this point in August 1981 showed well preserved traces of recent glaciation. However, from this point, the end moraine line can't be seen in the vicinity of the MSU station (it is obstructed by the river Garabashi mudflow cone); but the end moraine line in the vicinity of the cable-way "Elbrus" is well visible. Furthermore, it was the far most moraine end line where a buried pine was found in 1968; the analysis showed that this tree's annual rings growth is similar to that of pines appeared in the Azau valley in the first half of the XVII century. Modern elevation of the foot of this line at the bottom of the valley is 2315 m, which corresponds well with G. Abich's measurement of 2317 m. These data are sufficient for a precise determination of the spatial location of the end of the ice-flow of the Bolshoi Azau glacier in 1849 (Fig. 3).

Later research activities of the end XIX – beginning XX centuries documented by maps describe the exact location of the glacier tongue. These maps are a 1:42000 scale topographic map compiled from the 1887–1890 Corps of Topographical Engineers surveys and a 1:20 000 scale map compiled from the data of the 1911 phototheodolite survey by G. Burmester [Burmester, 1913].

Elevation benchmark systems of these maps should be reconciled with the modern map compiled from the phototheodolite survey conducted during the International Geophysical Year (IGY). I.A. Labutina (1968) determined the elevations of the 1991 map to be 20 m lower than that of the modern map. Therefore, the elevation of the end of the ice-flow of the Boshoi Azau glacier in 1911 was actually 2345 m (or 2325 m on the G. Burmester's map). This also corresponds well with the actual glacier's location. The 1911 map shows the glaciers tongues at approximately 70–80 m higher than the waterfall of the river Malya Azau in the canyon. The modern map shows the elevation of 2345 m, which is 75 m higher than the elevation of the same waterfall.

Fig. 3. End moraine in the mid. XIX century at the bottom of the Azau river valley. Phototheodolite image taken on July 15, 1981.

Fig. 4. The tongue of the Bolshoi Azau glacier. Image by A.V. Pastuhov on August 5, 1890.

The 1887 and modern (of the Elbrus southern slope) maps benchmark systems correspond well with each other. Therefore, the 1887 Bolshoi Azau ice-flow end elevation can be obtained by overlaying the 1887 and 1957 maps, which excludes distortion caused by dead ice near the glacier tongue. This elevation is 2330 m. On the photo taken on August 5, 1890 by A.V. Pastuhov (1893), the location of the glacier's front at the end of the lava line, which some time ago had blocked the Azau canyon, can be seen clearly (Fig. 4).

It is also helpful to review observations of other investigators According to 1881 N.I. Dinnik (first after G. Abich to visit the glacier in 1881, but who unfortunately did not conduct any instrumental measurements), the lower part of the ice-flow ended with a steep slope crossed by cracks; the right part of the ice-flow was adjacent to the open rocks which were at about 2327 m elevation from the low river level. In 1911, G. Burmester described the glacier as growing or as about to be ready to transition to the growing phase. The evidence of that were: a steep glacier's front, absence of the end moraine, intense cracking of the entire glacier below the icefall, and the presence

Fig. 5. The tongue of the Bolshoi Azau glacier. Phototheodolite image by A.V. Blryuhanov. August 1958.

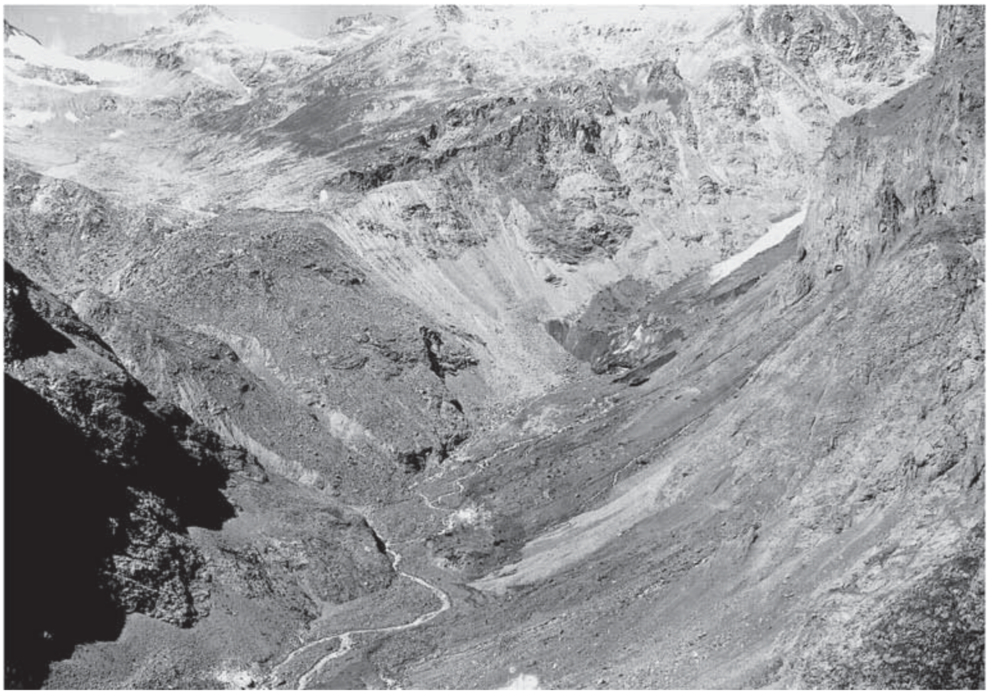

Fig. 6. The tongue of the Bolshoi Azau glacier. Phototheodolite image by Ye.A. Zolotarev. August 31, 2002.

of a surface swell wave sliding between 2600 and 2700 m elevation. According to V.P. Rengarten's communication with S.P. Soloviyev in 1913, the glacier advanced 15 m ahead compared to 1911 [Soloviev, 1933]. In 1925, V.Ya Altberg (who worked at the glacier in 1925–1928) reported that the glacier was 20 m higher than the waterfall in the canyon and was again retreating [Altberg, 1928].

We used works by Ye.P. Oreshnikova [1936] (who surveyed the glacier in 1932–1933), P.V. Kovalev [1961] (who provided data on the glacier retreat at the end of 1940s), materials of the Elbrus phototheodolite survey in 1957–1959 (Fig. 5), the survey of the glacier tongue in 1969, and our surveys of 1973, 1980, 1987, 1997, and 2002 (Fig. 6) to compile a chart of the Bolshoi Azau glacier tongue fluctuations from 1849 to 2002 (Fig. 7). The surveys were reconciled using a 1 : 5000 topographic map, which we created for a site at the Azau river using data of the 1987 phototheodilite survey when the valley was completely free of dead ice.

A distinct feature of the glacier retreat is a simultaneous formation in the valley of a large volume of dead ice that hampered the identification of its front location. Thus, for example, on the 1957–1959 map, the glacier front was 700 m above its actual end position in the valley and 40 m above its bed. This made it difficult to systematize elevations of the glacier tongue by earlier researchers [The glaciation..., 1968].

The aforementioned information may also help to explain the peak rates of the glaciers retreat in 1959–1969. During this time, the area was simply getting free of dead ice. Overall during 150 years, the glacier has retreated 2860 m, i.e., the average retreat rate was about 19 m/year. This retreat was cyclic and interrupted by short delays and small advances during its early phases and in the 1970s, with 55-years intervals between the cycles.

During special research efforts, we found a similar cycle with an insignificant time shift at a representative of the Central Caucuses

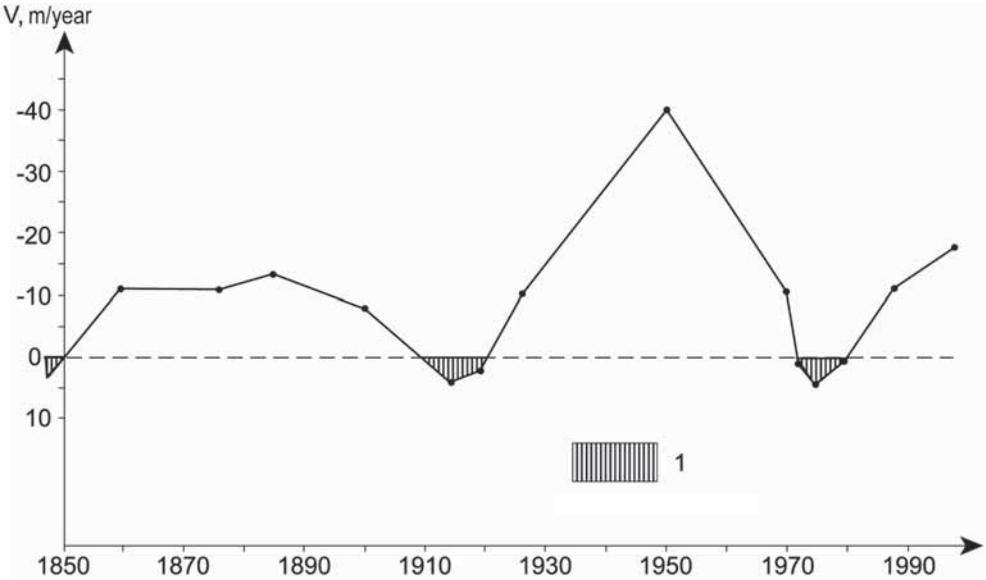

Fig. 7. Fluctuations of the Bolshoi Azau glacier from 1849 to 2002. 1 – the glacier advancement.

glaciers the Dzhankaut glacier. This fact suggests that air temperatures were the main climatic parameter that influenced the glaciers response [Zolotarev and Popovnin, 2003]. Changes in air temperatures cause changes of the ice-flow end ablation while the ice inflow stays relatively constant during a long period of time in the accumulation area of the glacier. The difference between the ice inflow and loss at the end of the ice-flow determines if the glacier retreats or advances.

ANALYSES OF CARTOGRAPHIC MATERIALS ON ELBRUS GLACIATION

Analysis of the 1887–1890, 1:42000 scale, topographic survey map. The first instrumental (plane-table) survey of the entire Elbrus glaciation was conducted by a team of the Corps of Topographical Engineers in 1887–1890. The survey was compiled into a 1:42 000 scale map. First, it had to be determined if it is possible to superimpose the modern map with the old map to obtain quantitative parameters of spatial changes of the Elbrus glaciers during 1887–1957. Analysis of the maps confirmed that it was in principle possible to make cartographic measurements on the 1887 Elbrus map. A correct superimposition of similar surfaces shown on multitemporal maps is challenging even for the modern cartographic material; there are no standard solutions for this problem. In our case, we decided to convert the map from a 1:42000 into a 1:25000 scale using the coordinate and elevation benchmark system of the more modern map. This transition was done by zones using at least three identical control points on the modern and old maps. When converting the old Russian elevation system (Russian fathom) into the metric one and drawing elevation contours, a 5 m systematic error correction was applied to all glaciers except to those located on the southern exposure slopes. This newly compiled map was refined later on; especially when the glacier boundaries were reconciled when new data became available.

Then, this and the 1957 maps were digitized and used in computer models to determine changes in the area and volume of the glaciation. It should be noted, that the 1887 map can only produce reliable estimates for the glaciers' tongues, i.e. up to approximately 4000 m elevation. The research conducted indicated that above this mark, changes in elevation may be within an error of measurements [Zolotarev, 1997]. However, special research efforts aimed at comparison of multitemporal digital models of Elbrus compiled using aerial photography of 1979 and 1997 indicated that over 90 % of volume changes are associated specifically with the area below 4000 m. Therefore, the 1887 map is also suitable for the studies of the Elbrus glaciation evolution. It should also be noted that the area of glaciation in 1887, which we measured on the newly-compiled map using digital methods (147,5 $км^2$), is approximately 1 % different from the area measured by K.I. Podozersky [1911] on the original map using measuring grid. This is consistent with the negligible error of estimates.

Modern cartographic materials on the Elbrus glaciation. During the IGY (1957–1959), scientists from the Laboratory for Aerospace Methods (at that time, the Laboratory of Aerial-Photo Methods) of the Department of Cartography and Geoinformatics of the MSU Faculty of Geography conducted a phototheodolite survey to assess the evolution of the Elbrus glaciation. They compiled a 1:10 000 scale map, which became a base map for the future cartographic-aerial-space monitoring of the Elbrus glaciation [The glaciation..., 1968].

In 1980–1983, a preliminary recognizance work for the second survey was undertaken [Knizhnikov et al., 1984]. In 1986–1987, the phototheodolite survey was repeated for the entire Elbrus glaciation. In addition in 1979–1987, its aerial photographic survey was conducted.

During the 1986–1987 phototheodolite survey, a lichenometric study of stadial moraines was accomplished. Its materials were used to determine the Elbrus glaciation area and volume in the mid XIX century. It appeared that these parameters were close to the maximal parameters of the "Little Ice Age" (XIII-mid XIX) [Solomina, 1999].

All these data together with the digital orthophtographic map compiled from the 1997 aerial photographic survey provided a unique opportunity to study tendencies in the glaciation changes, which have happened during a 100-years time-period.

RESEARCH METHODS

Lichenometrical method of determining the maximum limits of the glaciation in the last millennium and middle of the XIX century. The founder of the lichenometrical method R. Beschel [Beschel, 1961] believed that through their lives, lichen thallus grows at different speeds. In the beginning of growth, the speed is high becoming constant in the middle of the growing cycle till lichen reaches its maximal diameter for given environmental conditions, after which the growth rate decreases. Practically, this means that different annual growth values for different lichen diameters have to be used for proper age-dating. Challenges of determining such dependency for each specific region is the main reason that makes wide scale application of this method difficult. Special importance should be given to methodological research built on Beschel's ideas to establish a mathematical model that describes a maximal lichen thallus diameter as a function of age of its growth substrate. This is achieved by using lichens from different age-control sites; the age is determined using other methods, e.g., historical, cartographical, or radiochronological [Golodkovskaya, 1981]. These efforts demonstrated the influence of environmental conditions on lichen growth. Thus, data on growth obtained for the northern slope of the Central Caucuses appeared to be unacceptable for age dating of the southern slope moraines [Golodkovskaya, 1982].

In our opinion, this undoubtedly valuable work is lacking a critical evaluation of the source data accuracy resulting in an unjustifiably accurate claimed precision of age dating. It should also be considered that historical and cartographical sources provide only a time of formation of a relief form, i.e., a substrate where lichens may appear in the future and at different times. Dating errors related to older control sites may comprise several decades. In this case, one has to be especially careful to exclude inconsistencies between the age of boulder trains and the diameters of lichens that grow on them. Such inconsistencies may be a result of a limited life span of lichens growing under temperate climate (according to Beschel, 1500–2000 years). Considering all these facts, it is reasonable to conclude that there may be a decade-long dating error for the last century dating. For a thousand-year period, one can only date to a century with more or less satisfactory level of confidence despite any reliable mathematic models applied to data processing. Therefore, it is also reasonable to conclude that at the end, differences in the annual lichen growth for the sites with different environmental conditions may result in dating differences that are within the limits of these errors. Then, a simplified solution is possible, i.e., specifically, a statistical processing of the annual lichen growth data from control sites with different environmental conditions may be applied. In this case, deviations from the mean values of the annual growth of a given size can be determined. These deviations characterize a probable error in age determination. Specifically this very method was applied to study the Elbrus and Baksan river basin glaciers changes during the last century.

Along with the moraine, mudflow deposits, which compared to ice have a certain advantage of being even-aged, were widely used in our research as control sites. Overall, there were 20 mudflow basins in the valleys of Preelbrus'e within which over a hundred of 1400–2000 m elevation sites were processed.

Twenty five control sites on mudflow sediments with known descend from 1909 to 1979 were used together with 14 sites (in six glacial valleys) on the stadial moraines within the 1930s to 1850 age interval. Besides, three sites with the ancient mudflow and fluvioglacial sediments with known radiocarbon dating data [Kaplin et al. 1971; Kotlyakov et al. 1973] and our dating data "IGAN-747" were used.

The following dependencies were established through processing of these data: a) no lichens were found on the deposits younger than 10 years; b) the minimal visible size of lichens was 1 mm; c) a sharp decline in the annual lichen growth occurred during the first decades of their lives (to 50 years); and d) beginning from the diameter of about 100 mm and bigger, the annual growth has practically stabilized and was 0,15–0,11 mm/year.

Based on these data a generalized graph of the annual lichen growth was compiled for different environmental conditions [Seinova and Zolotarev, 2001]. The annual growth generalized curve was drawn using the annual growth average values for different diameters. The upper and lower enveloping curves allowed assessing real accuracy of the annual growth values. For convenience, this graph is presented in a tabular format (Table 1). The annual growth values are presented with a possible standard deviation. Also, the annual growth data are supplemented with the data on the sediments age and absolute values of the mean-root-square error (year). It was assumed that lichens inhabited the sediments not earlier than 10 years after their formation.

The values of the mean-root-square error of the sediments age and the error of the radiocarbon dating for a respective point on the graph (diameter of about 100 mm) coincide, which confirms the credibility of the results obtained.

The actual data used to obtain the annual growth values correspond to the absolute elevations in the 1800–2000 m interval. There is no clear dependency between changes in the growth rates and absolute elevations. However, in reality there is a tendency to a fast increase in the growth below 2000 m elevation noted by V.I. Turmanina [1971]. A lack of actual data does not allow one to quantitatively express this tendency. In order to date the sediments located above 2300 m (the middle of the interval of our actual data on absolute elevations) it seems feasible to use the lower enveloping curve on the growth graph (see Table 1) adding absolute values of the standard deviation to the age values.

Using data from published sources on maximal diameters of *Rhizocarpon*

Table 1. Annual growth of different sized lichen Rhizocarpon geographicum and dating of the respective deposits for the northern slope of the Central Caucasus (absolute elevations 1800–2900 m)

Lichen diameter, mm	Annual growth, mm	Age of deposits, yrs	
1	–	10	XX c.
2	–	12	
5	1,00 ± 0,10	15 ± 1	
10	0,78 ± 0,11	20 ± 2	
15	0,65 ± 0,12	30 ± 5	
20	0,55 ± 0,11	45 ± 7	
25	0,47 ± 0,10	60 ± 10	
30	0,43 ± 0,09	80 ± 12	
35	0,39 ± 0,08	100 ± 15	XIX c.
40	0,37 ± 0,07	120 ± 18	
45	0,34 ± 0,07	140 ± 23	
50	0,33 ± 0,06	160 ± 26	
55	0,31 ± 0,06	180 ± 29	
60	0,29 ± 0,05	210 ± 31	XVIII c.
65	0,27 ± 0,05	240 ± 35	
70	0,25 ± 0,04	290 ± 40	
75	0,23 ± 0,04	330 ± 45	XVII c.
80	0,22 ± 0,03	360 ± 50	
85	0,20 ± 0,03	420 ± 55	XVI c.
90	0,18 ± 0,03	500 ± 60	
95	0,16 ± 0,02	570 ± 70	XV c.
100	0,15 ± 0,01	666 ± 80	XIV c.
105	0,15	700 ± 90	XIII c.
110	0,14	760 ± 100	
112	0,14	820 ± 110	XII c.
120	0,13	900 ± 120	XI c.
130	0,13	1000 ± 130	X–IX c.
140	0,12	1200 ± 140	VIII c.
150	0,12	1360 ± 150	VII c.
160	0,11	1450	VI c.
170	0,11	1550	V c.
180	0,11	1650	IV c.
190	0,10	1900	III-II c.
200	0,10	2000	I c.

Table 2. The age of the stadial moraines of the river Baksan valley glaciers identified with the lichenometry method.

Maximal diameter of lichens (mm) on the stadial moraines in the glaciers valleys							Time of formation of the morainic ridges
Bolshoi Azau	Malyi Azau	Terskol	Irik	Yusengi	Dzhankaut	Bashkara	
		115		125			XIII c.
		85		85	90	80	First half of XV c.
	66		64				End of XVII c.
50		51	50	50			End of XVIII c.
38		40	40	40	41		Mid XIX c.
34	34	30	33	32	33	30	1880th
20	21	24		20	21	21	1910th
15	15	17			14		1930th

Fig. 8. Changes in the Elbrus glaciation from the end of the XVII century. 1 – area of ice that melted during 1700–1887; 2 – lava; 3 – glacial divides. Glacier boundaries: 4 –1987, 5 –1957, 6 –1887, 7 –stadial moraine line of the mid. XIX century.

geographicum lichen growing on the stadial moraine of several glaciers [Turmanina, 1971] supplemented with our own observations, the following representation of changes in the southern Elbrus and Baksan river glaciation was obtained (Table 2).

As shown in Table 2, the middle and end of the XIX century stadial moraines were represented most fully. They were well preserved –the fact noted previously in published literature. The moraines with lichen diameters of 115–120 mm were preserved in fragments as remnants. In the river Yusenga, this moraine towers over the frontal apron near the right valley side in 2 km to the tongue of the Becho glacial (2400 m elevation) and in the river Terskol valley –amidst the avalanche and scree deposits of the left side of the valley in 1 km to the modern tongue of the glacial (2540 m elevation).

The end moraine lines with lichen diameters of 85–90 mm were found near five out of seven studied glaciers. The end moraine lines were well visible in the relief, have the greatest relative elevation, and were apparently formed during the longest period of the stationary state of the studied glaciers. For the glaciers Djankaut and Bashkara, these moraines had been dated earlier to the mid XVII century based on the data on the annual lichen growth of 0,3 mm/year [Turmanina, 1971]. In general, the data from Table 2 suggest that a consecutive decline of the glaciation during the last two millenniums was interrupted by periodically advancing glaciers. Judging by the morphology of the end moraines and the lichen size on their surface, the glacialtion in the second millennium AD in this region of the Central Caucasus has reached its maximum in the mid of the XVII century and after some retreat, has come back to almost the same magnitude in the middle of the XIX century.

The results of the lichenometric survey of the stadial moraines allowed determining the Elbrus glaciation boundaries at the end of the XVII and middle XIX centuries (Fig. 8). Their identification was based on a large scale (1:10 000), 10 m contour topographic map of the Elbrus glaciation compiled from the 1957 survey where practically all ridges of the stadial moraines are shown with special cartographic symbols. The map was used to identify the area and volume of the glaciers during their maximum development. This was accomplished by interpolation of the contour lines from the ridges elevation for the areas occupied by the glaciers at the end of the XVII and middle of the XIX centuries.

Thus, for each glacier from its tongue to the upper level of the stadial moraine, the maps were compiled and digitized together with respective sites shown on the 1957 topographic map. Multitemporal digital models were developed from these data for each glacier. The difference in the estimates between these two models allowed determining changes in the average elevation and ice volumes of all Elbrus glaciers tongues from their ends to 4000 m elevation (Table 3).

Digital photogrammetric processing of ground and aerial photography. Until the end of the XX century, stereo-autograph processed phototheodolite surveys were commonly used to capture spatial positions of mountain glaciers. The results of the data processing served as a basis for large scale maps used in cartographic analyses and compilation of thematic maps. The aforementioned 1:10 000 scale Elbrus glacial system map serves as an example of such maps.

The modern state in cartographic research is characterized by digital photogrammetric processing of ground, aerial, and space imagery. This stage is associated with "digital imagery", that is obtained in Alpine glaciology through scanning and digital aerial or phototheodolite surveys.

Processing of digital photographic pairs is performed with the help of digital photogrammetric computer software packages (developed also for personal computers). Let us review in detail a

Table 3. Change in the area and volume of the Elbrus glaciation beginning from the mid. XIX c.

Name of glacier	Area of glaciers in horizontal projection, km^3					Volume of glaciers, km^3				
	1850	1887	1957	1979	1997	1850	1887	1957	1979	1997
Elbrus peaks (area above 5200 m elevation)	4,818	4,818	4,818	4,818	4,811	0,480	0,480	0,470	0,480	0,481
1. Ulluchiran	13,914	12,944	12,124	12,277	12,301	1,589	1,269	1,227	1,318	1,230
2. Karachaul	6,638	5,918	5,748	5,538	5,485	0,610	0,605	0,552	0,595	0,548
3. Ullu-Kol + Ullumalien-derku	6,146	5,826	5,186	4,960	4,882	0,481	0,475	0,412	0,439	0,488
4. Mikelchiran	6,014	5,564	4,834	4,670	4,604	0,613	0,607	0,479	0,503	0,460
5. Ice field Dzhikiugan-kez	34,832	31,762	29,042	27,295	25,581	4,929	4,339	3,207	3,032	2,558
6. Irichkat	3,006	2,816	1,806	1,735	1,680	0,260	0,256	0,196	0,196	0,168
7. Irik	12,605	12,425	10,995	10,763	10,671	1,425	1,405	1,174	1,233	1,067
8. Terskol	8,428	7,818	6,988	6,901	6,975	0,832	0,826	0,700	0,769	0,697
9. Garabashi	6,321	5,781	4,911	4,744	4,689	0,621	0,561	0,479	0,517	0,469
10. Malyi Azau	10,256	9,826	8,806	8,508	8,363	1,074	0,974	0,866	0,913	0,836
11. Bolshoi Azau	23,102	22,662	21,032	20,677	20,460	3,270	2,900	2,330	2,222	2,046
12. Ullukam	3,950	1,882	1,620	1,561	1,440	0,160	0,151	0,141	0,146	0,144
13. Kyukyur-tlyu	8,119	7,269	7,039	7,226	6,913	0,752	0,747	0,696	0,700	0,691
15. Bityukt-yube	2,560	2,330	2,170	1,997	2,212	0,254	0,251	0,221	0,231	0,221
Clif glaciers №№ 1–9	8,450	7,475	5,395	4,058	3,783	0,530	0,450	0,390	0,407	0,378
Total for Elbrus glaciation	159,159	147,516	132,514	127,728	124,85	17,880	16,296	13,540	13,741	12,482

cartographic digital method applied to the glaciers using a digital Elbrus map compiled from the 1997 aerial photographic data. The map was created using a digital photogrammetric software package that we developed for a personal computer, which includes the following main components: program stereocomparator for measuring coordinate points on digital images; programs for photogrammetric bundle adjustment; programs for automatic measurement of parallaxes and digital relief model point sets; stereo editor for editing stereo models and contour digitizing during visual interpretation of the stereo model from a personal computer monitor using LCD shutter glasses; and a program for building a digital elevation model (DEM) and creation of orthographic imagery. Photogrammetric processing included measuring control points, phototriangulation, measuring points for DEM, and compiling an orthophotomap. Digital imagery was obtained beforehand through scanning of original aerial photographs on a photogrammetric scanner.

The elements for relative orientation of images and computation of spatial coordinates of measured points were defined based on block photo-triangulation using a large number of control points over the entire aerial photographic area, which allowed reaching 1,5 m horizontal and vertical coordinate measurement accuracy sufficient for compilation of a 1 : 10 000 scale map.

The base elements of the content of the compiled orthographic map were the 1 m resolution orthographic images of the area; relief represented by 10 m contours, and an interpreted glacier boundary.

The relief mapping was done using the DEM data as an intermediate step. The DEM point sets were defined with the stereo-pairs on relatively oriented images. The necessity of selection of a large number of points for building a detailed elevation model dictated the usage of automated stereo-measurement methods that were applied to obtain 96 % of all DEM points. The rest of the points were selected through visual examination of the measurement results using stereo editor after automated processing of each stereo-pair. There were about 1 mln points in total for the entire territory processed. The obtained DEM was used to build contours and to perform imagery orthotransformation.

The glaciation boundaries were defined from visual interpretation and stereoscopic examination of the images enlarged with stereo-editor to approximately 1:5 000 scale, which permitted their detailed delineation. The interpretation methods developed in the Laboratory for Aerospace Methods of the Department of Cartography and Geoinformatics during the compilation of the Elbrus glaciation map [The glaciation..., 1968] were also applied. Additionally, the ends of the glaciers tongues ice that is entirely covered by the moraine mantle and not previously shown on the 1957–1959 map (as it was considered to be stagnant) were included in the boundaries (Fig. 9).

Adjustment of multitemporal data of repeated surveys. Monitoring of glaciers elevations is important for assessing their volume changes.

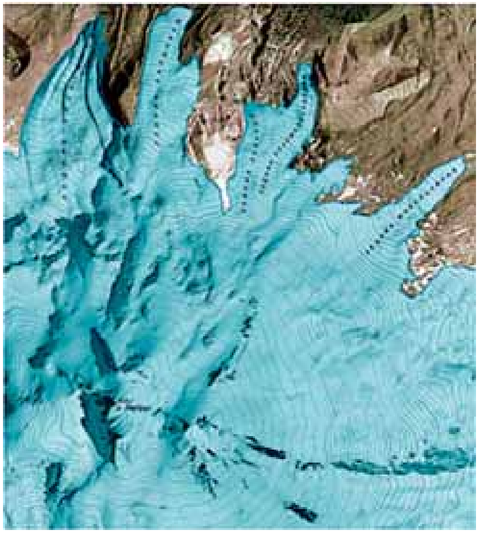

Fig. 9. Fragment of the 1 : 10 000 scale digital ortho map of Elbrus (1997) (reduced size).

Cartographic methods are traditionally used to measure elevations on multitemporal cartographic material. However, mapping of glaciers with phototheodolite data or aerial photography is time consuming. This fact together with the need to improve accuracy of measurements of changes by using raw data from repeated surveys without creation of intermediate maps required applying multitemporal data adjustment using broad-based photogrammetric instruments. Under this method, the stereo-pairs from repeated survey were oriented using maps compiled from earlier surveys. Measurements were made by pointing a coordinatograph finder device over a map contour or a node of a regular grid while simultaneously pointing a stereograph tick mark over a stereo model surface. Pointing at contours eliminates a map-based relief interpolation. Measurements based on the nodes of a regular grid, on contrary, require such interpolation, but they are preferable for the reconstruction of a continuous surface of elevation changes. Both versions of this method allow determining elevation changes more precisely than cartographic methods. Such work was conducted to identify changes in the Elbrus glaciers during 1957–1987 [Zolotarev, 1997].

This labor intensive method and its limitations associated with technical capabilities of repeated images and maps adjustments are the main factors that determined transitioning to analytical methods of imagery processing. There have been several attempts to determine changes through the comparison of the DEMs developed from multitemporal stereo pairs. It has been experimentally established that selecting points on a regular or some other arbitrary network and using structural lines or some other ways of space detalization obtained from independently measured stereo pairs, did not substantially increase the accuracy of measurements. It appears that the surface of changes obtained analytically differs substantially from the actual surface. The solution was found in conducting coordinated measurements of the stereo-pairs – at the same points with previously established planimetric coordinates [Zolotarev and Kharkovets, 1996]. In this case, the values of elevation change in a point are obtained directly without intermediate interpolations with a substantially higher accuracy provided by application of analytical methods. If necessary, the location of points may be tied to regular grid nodes within a planimetric coordinate system. The implementation of this method became possible with stereocomparators that transfer values of measured image coordinates directly to a computing system and conduct coordinates interconversion between images and real space directly during pointing of a stereoscopic tick mark on to a glacier surface under specified parameters of external orientation. Thus, the tick mark coordinates are adjusted and its position at the glacier surface in a point with necessary planimetric coordinates is reached.

ASSESSMENT OF THE ELBRUS GLACIATION VOLUME DURING DIFFERENT PERIODS OF ITS EVOLUTION

The assessment of the total volume of the Elbrus glaciation is particularly interesting because the assessment of changes in volumes during a 100-year period could provide evidence of the glaciation relative stability or, in contrast, of its substantial retreat. V.I. Kravtsova [Kravtsova, 1967] estimated the Elbrus glaciation volume at 6 km^3 using a map of the Elbrus ice thickness that was compiled during the IGY from the results of phototheodolite surveys of the ice cliffs elevations and depth of clefts, and analysis of the glaciers' valleys profiles. It was assumed that the thickness of the ice for the larger part of the firn icecap was 20–50 m and reached 100 m along the axes of the large glaciers. The average thickness of the ice for the entire Elbrus was estimated at 50 m. At the present time, it is possible to compare these assessments with the actual data for some glaciation sites.

Based on drilling and radiosounding data at the southern slope of the Elbrus (the glaciers Garabashi, Malyi Azau, and Bolshoi Azau) obtained in 1987–1989 by the North Caucasian expedition of the Institute of Geography of USSR Academy of Sciences, the average thickness of the firn icecape was 90 m, sometimes reaching 200 m [Rototaeva et al., 2003]. The ice thickness on the northern slope should be even greater. The assessment of the volume of melted ice indicated that for the Dzhikiugankez plateau, the results of assessments of the ice thickness in 1957 were underestimated by a factor of two, approximately. It means that the average ice thickness for the entire Elbrus glaciation is possibly around 100 m, and the volume of the glaciation in 1997 can be then estimated at approximately 12,5 m^3; and at 13,6 и 16,2 km^3 for 1957 and 1887, respectively. Therefore, during the last 110 years, the glaciation volume decreased by about 22 % (or 0,2 % per year). From comparison of the estimates of the glaciation volume and ice annual average losses it is reasonable to conclude that during the nearest centuries, the Elbrus glaciers are unlikely to disappear.

COMPILATION OF THE POST IGY ELBRUS GLACIATION EVOLUTION DIGITAL MAPS AND THEIR ACCURACY ASSESSMENT

The assessment of the post IGY Elbrus glaciation evolution is based on three fixed dates: 1957, 1979, and 1997, that form two approximately even time-intervals: 22 and 18 years. We digitized a 1:10 000 scale topographic map compiled by the Laboratory

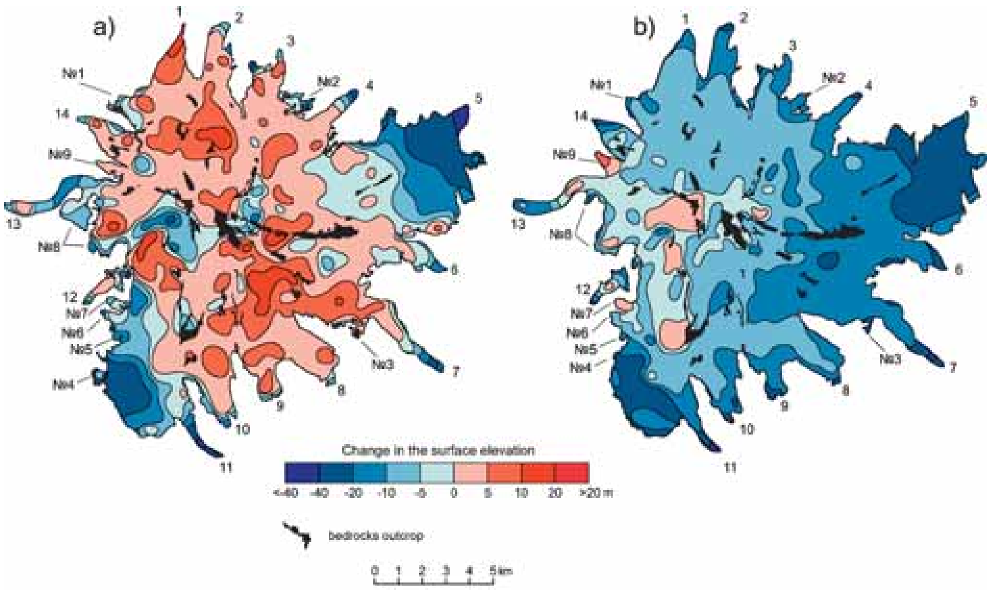

Fig. 10. Changes in the elevation of the surface of Elbrus glaciers during the intervals: a) 1957–1979 within the 1957 boundaries, b) 1979–1997 within the 1979 boundaries. Glaciers: 1 –Ulluchiran, 2 – Karachaul, 3 – Ullukol and Ullumalienderku, 4 – Mikelchiran, 5 – Dzhikiugankez, 6 – Irikchat, 7 – Irik, 8 –Terskol, 9 – Garabashi, 10 – Malyi Azau, 11 – Bolshoi Azau, 12 – Ullukam, 13 – Kyukyurtlyu, 14 – Bityuktyube.

for Aerospace Methods of the Department of Cartography and Geoinformatics of the Faculty of Geography of the MSU during the IGY. In addition, we digitally processed aerial photographic data for 1979 and 1997. As a result, for each of the dates we created digital models for the entire glaciation. The superimposition of these maps allowed measuring changes in the boundaries and elevation of the glaciation surface for each of the time-intervals. All three models were compiled using the same coordinate system and surveying control points, which substantially facilitated the models comparison. The maximal possible standard horizontal and vertical errors during the superimposition of theses multitemporal models was 2,5 m calculated from 20 contour points recognized on the maps and photographs. Because elevation measurements were conducted within the entire area of the glaciation in at least 1 mln points, the algebraic sum of errors tends to zero, as follows from the properties of random measurements errors [Reference Book..., 1966]. Therefore, a relative measurement error of changes in the glaciation surface elevations can be ignored. These theoretical discussions, in our case, were supported by the fact that the values of changes in thickness (ΔH) and volumes of the glaciers during the 1957–1997 period were obtained using two independent methods, i.e., by comparison of the digital models of 1957 and 1997 and by algebraic summation of ΔH_1 and ΔH_2 values for the corresponding periods in 1957–1979 and 1979–1997. In the ideal case, $\Delta H = \Delta H_1 + \Delta H_2$, however, due to errors associated with superimposition of multitemporal models, in reality, we had to deal with a discordance (δH) for each of the glaciers and the entire glaciation. This allowed us to define a relative measurement error for the entire glacial surface elevation at 2,6 %. A similar error of measurements for the glaciation volume was 1,8 %. Thus, the sufficiently large volume of measurements increased the end result accuracy of measurements by an order of magnitude compared to the initial estimates. It should be noted, that the 1957 topographic map, in this case, was digitized from 10 m contours. This allowed obtaining a detailed picture of changes in the surface elevation and avoiding errors in digital models based on interpolation of scattered points.

Table 4. Average annual changes in the area, elevation of the surface, and volume of the Elbrus glaciation below 4000 m elevation, for different periods

Parameter	1850–1887	1887–1957	1957–1997
Decrease in area, km^2/yr	0,310	0,210	0,190
Decrease in elevation of the surface, m/yr	0,530	0,350	0,320
Decrease in volume, km^3/yr	0,058	0,035	0,027

The compiled maps (Fig. 10) clearly show the glaciation response even for short climate change periods. In 1957–1979, despite a general decrease in the area, at almost all glaciers except for the Dzhikiugankez Plateau in its north-eastern part and Hotyu-Tau in the south-western part of the glaciation, increase in the surface prevailed reaching 40m at the northern slope of the Ulluchiran glacier. This resulted in a low positive mass balance of the entire glaciation during this period assessed at +0,94 m of water equivalent. The process was clearly a result of the total decrease in air temperatures of the Northern Hemisphere during the 1960s [Kotlyakov, 1994] when the Elbrus glaciers were advancing [Panov, 1993]. During the second period of observations (1979–1997), a universal decrease in the surface elevation took place, except for an insignificant area near the Elbrus summit. The greatest decrease was noted at the glaciers of the glaciation slope –Chungurchatchiran and Birdzhalychiran, combined under the common name the "Ice Field of the Dzhikiugankez". Here, the average value of the surface decrease for the entire glaciation area was 16,8 m reaching 40 m at the tongues.

CONCLUSIONS

In general during 40 years after the IGY (1957–1997), the Elbrus glaciation volume has decreased by 1,2 km3 which is equivalent to 1 km3 of water; 45 % of this amount falls on the two aforementioned glaciers of the

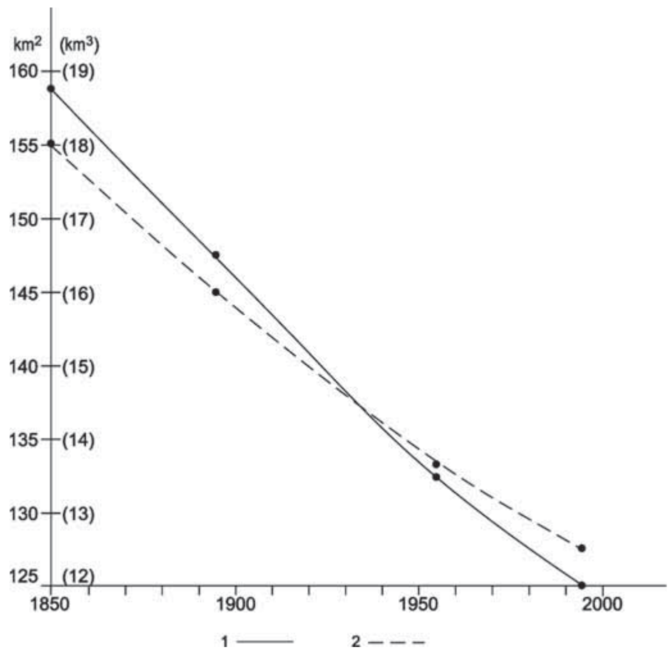

Fig. 11. Change in the area and volume of the Elbrus glaciation for 1850–1997. 1 – change in the area, km^2, 2 – change in the volume, km^3.

northeastern slope. The major portion of this volume (i.e., 98 %) is contained in the lower part of the glaciation, specifically from the ends of the tongues to the elevation of 4000 m. This fact allows tracing the rate of glaciation retreat that began in the mid XIX century because the decrease in the volume and area of the glaciation was due to melting of the glaciation tongues (Table 4).

These reasonably reliable quantitative data indicate that the greatest rate of the glaciation decrease was associated with the earlier period (1850–1887). Beginning in 1887, there has been practically even decrease in the area while volume reduction has slowed down (Fig. 11).

These data suggest that global climate change, which alternated with short periods of cooling, began in XIX century after the end of the Little Ice Age and was more likely due to natural than anthropogenic causes.

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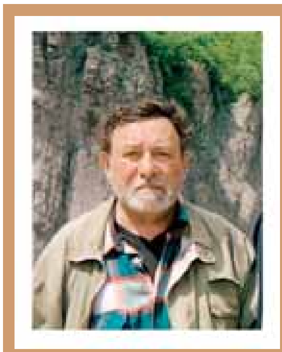

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