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Geophysics

Impact of Modern Climate Change on Glaciers in East Georgia

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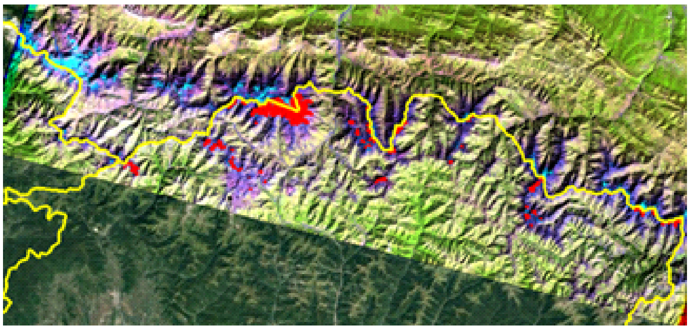
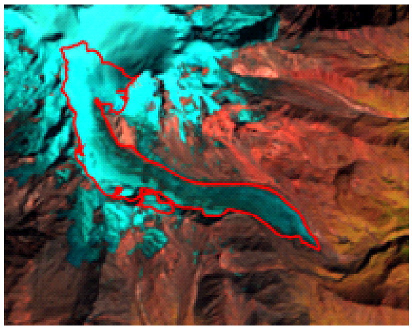
ABSTRACT. Based on the satellite Earth observations and GIS technologies the changes in the glaciers of East Georgia under the influence of regional climate change are considered. It should be noted that in the past the glacier parameters (area, length and volume) increased. It was defined that during the second half of the last century the Georgian glaciers were steadily diminishing due to the impact of global warming. M. Sylvén, et al. stated that the glaciers total area in Georgia decreased by 36% and their volume by 48%. This process is still underway and very likely will continue in the future. In the past glaciers researches were carried out mainly basing on terrestrial observations characterized by significant shortcomings: high expenses, data irregularity both in terms of space and time. Satellite Earth observation is practically free of these limitations. The impact of modern regional climate change on small glaciers melting and large glaciers retreat is researched. It is determined that over the past 40 years, approximately 70% of small glaciers of East Georgia completely or partially melted under the impact of regional climate change. Significant increase of the rate of large glaciers retreat is noted, especially for the last 15 years. Last result obviously indicates degradation of glaciers under the accelerated impact of regional climate change. *© 2016 Bull. Georg. Natl. Acad. Sci.*

Key words: climate change, satellite, Earth observation, glaciers

To manifest modern regional climate change impact the corresponding researches are carried out: investigation of the glaciers degradation on the example of small glaciers changes (number and size dynamics) and analysis of the dynamic of large glaciers retreat.

Under conditions of global warming glaciers recede and degrade, which is reflected in the related changes of glacier runoff and water balance. These processes result in the increasing number of glacial and hydrological disasters such as glacier falls, river bed blockage leading to catastrophic flash floods and mudflows. The investigation of glacial melting is important for the study of sea/ocean level changes that may carry significant risk for the residents of coastal areas. That is one of the most negative im-





(a) (b)

Fig. 1. Landsat satellite false color images representing: (**a**) small glaciers from study area circled with red; (**b**) Gergeti glacier with its contour.

pacts of modern climate change on humankind.

Glaciers variations are clear indicators of the anticipated climate change. It should be noted that in the 18th and 19th centuries glacier parameters (area, length and volume) increased [1, 2]. It was discovered that during the second half of the last century Georgian glaciers were steadily diminishing due to the impact of global warming. As a consequence, the glaciers total area in Georgia decreased by 36% and their volume - by 48%. Some glaciers melted away completely. The length of glaciers was reduced by 600 m on average. The glaciers ice thickness: in the lower part it decreased by 50-150 m; in the upper part it reduced by 20-30 m [3, 4]. This process is still underway and most likely will continue in the future.

In the past glaciers researches were carried out mainly based on the terrestrial observations. Corresponding field works were difficult to organize and were characterized by significant shortcomings: (1) high expenses, (2) data irregularity both in terms of space and time resolution, (3) uncertainties in data.

Satellite Earth observation (EO) is practically free of these limitations. Satellite EO gives possibility of (1) the complex study of all glaciers [5, 6] including indication and determination of the small ones [7, 8]; (2) determination of destructive impact of modern regional climate change [9].

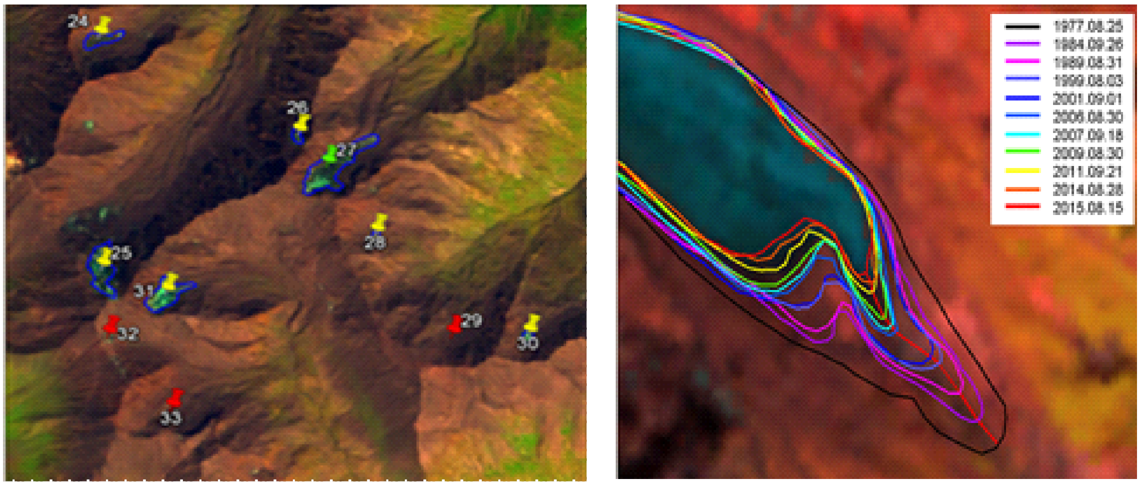
Study Area and Research Methodology

The glaciation is the phenomenon of the planetary scale. The glaciers in Georgia are represented only in the Great Caucasus range and their amount exceeds 500. The Great Caucasus represents high mountains system. Thus, Georgian glaciers are of the mountain type and display the well-developed glaciers.

The study area is located in the eastern part of the Great Caucasus on the territory of Georgia (see Fig. 1 (a)). In the present article satellite EO is applied to determine glacial contours (see Fig. 1 (b)). Quality assurance and quality control (QA/QC) procedures based on the complex use of high-resolution satellite EO together with the historic data and expert knowledge are used to validate the results [6]. Application of several GIS systems is very important as well.

The determination of a glacier's contours with high accuracy is fundamental to research the glaciers characteristics [6, 8, 10] and hence to investigate the impact of modern regional climate change on the variations of the Georgian glaciers.

In the present study the impact of modern regional climate change on small glaciers melting and large glaciers retreat is researched. In general global warming has substantial negative impact on glaciers, which is particularly evident in the case of small and large glaciers. This often leads to small glaciers fragmenting, turning them into the snowfields or their full melting (see Fig. 2 (a)) and the significant retreat of large glaciers (see Fig. 2 (b)). It should be noted that the area of small glaciers varies in the range of 0.1 to 0.5 km^2. Snowfields can be formed by the degradation of small glaciers leading to residual areas less than 0.1 km^2.



(a) (b)

Fig. 2. Landsat satellites images displaying: **(a)** small glaciers marked by green pins, snowfields represented by yellow pins and vanished glaciers shown by red pins and corresponding contours for the Pirikiti Alazani River basin; **(b)** Schematic picture of the Gergeti glacier retreat.

Results

On the Landsat satellite image (see Fig. 2 (a)) the presented area (Pirikiti Alazani River basin) corresponds to the scheme № 3 from the glacier catalog of the former Soviet Union [11-13]. The existing small glaciers are shown by green pins, the red pins mark the vanished glaciers and yellow pins represent the snowfields. Corresponding contours for small glaciers and snowfields of Pirikiti Alazani River basin are determined. The comparison of this image with the corresponding area of the scheme № 3 from the glacier catalog of the former Soviet Union give possibility to identify small and vanished glaciers and snowfields. This comparison revealed those glaciers and snowfields remained or/and originated, vanished from small glaciers (№24 - №33**)** of the Pirikiti Alazani River basin existing 40 years ago. The time period between the terrestrial observations included in the former USSR catalog and the data of the satellite EO is equal to 40 years.

Study area is covered by five more schemes of the former Soviet Union catalog [11-13]. Similar study was performed for all the remaining small glaciers from the study area of East Georgia. The received results are given in Table 1.

Table 1 shows the numbers of small glaciers registered in the schemes of the former USSR catalog and the amount of small and vanished glaciers and created snowfields calculated from the satellite EO data. Analysis of this table shows that out of 108 small glaciers registered in the former USSR catalog, only 32 are left after 40 years; 64 snowfields resulted from small glaciers degradation and 27 of small glaciers fully vanished. It can be concluded that more than 70% of the small glaciers fully or partially melted due to the impact of regional climate change.

It should be noted that 105 small glaciers were earlier researched [9], as 3 more existing small glaciers from the study area could not be identified.

In the present study the impact of modern regional climate change on large glaciers are studied on the example of the Gergeti glacier (Fig. 2 (b)). Gergeti glacier was selected because: (1) the end of this glacier is free of debris that provides easy processing and analysis of multispectral sensor observations; (2) possibility to determine the speed of glacier retreat due to modern climate change using available 11 different files of Landsat satellites data spanning the period of 1977-2015; and (3) practically for the same period availability of the corresponding terrestrial observations for QA/QC procedures and validation of the results.

Table 1. The number of small and vanished glaciers and snowfields (East Georgia) determined according to satellite EO images and the catalog of the former Soviet Union

Scheme	Number of Small Glaciers according to the catalog	Number of Small and Vanished Glaciers and Snowfields based on Satellite EO data		
		Small glaciers	Snowfields	Vanished glaciers
1	13	10	5	0
2	2	2	0	0
3	15	4	10	3
4	24	2	9	13
5	48	13	30	11
6	6	1	10	0
Total	108	32	64	27

Table 2. The coordinates of the positions of the glacier retreat contour crossing with glacier tongue, retreat distances toward previous position.

№	Date	Coordinate		Retreat toward previous position (m)	Total retreat (m)
		latitude	longitude		
1	8/25/1977	42.664006°	44.558418°	0	0
2	9/26/1984	42.664683°	44.557493°	106	106
3	8/31/1989	42.665486°	44.556670°	111	217
4	8/3/1999	42.666306°	44.555701°	122	339
5	9/1/2001	42.666503°	44.555308°	40.6	379.6
6	8/30/2006	42.667224°	44.553724°	152	531.6
7	9/18/2007	42.667407°	44.553513°	25.4	557
8	8/30/2009	42.667635°	44.553219°	38.2	595.2
9	9/21/2011	42.668386°	44.552674°	94.9	690.1
10	8/28/2014	42.668662°	44.552612°	31.7	721.8
11	8/15/2015	42.668917°	44.552400°	34.4	756.2

The satellite images were all chosen at the end of the ablation period (August-September for Georgia) and with less than 20% of cloud cover.

In Fig. 2 (b) eleven locations of the Gergeti glacier terminus with the corresponding dates to indicate its retreat due to global warming are shown. Every location is represented by a contour of a different color. Glacier retreat distances were identified along the mid-valley based on the red color line crossing the successive terminus outlines.

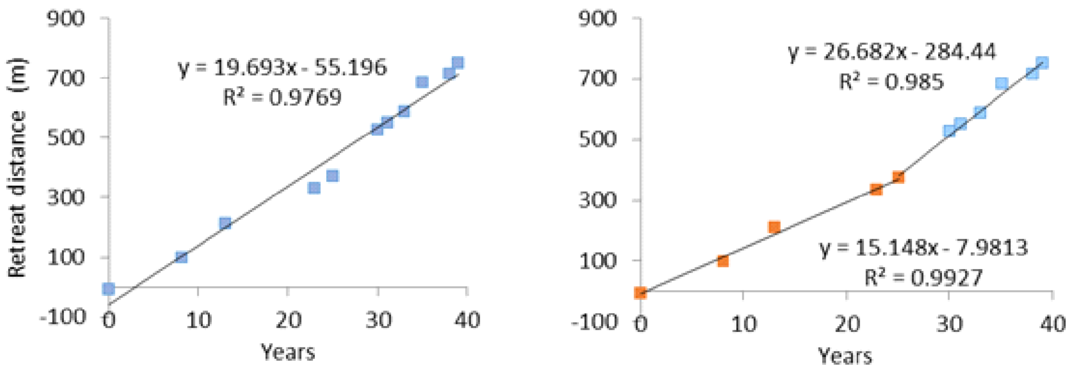
In Table 2 the coordinates of the positions of the glacier retreat contour crossing with glacier tongue, retreat distances toward previous position are presented. The satellite image since 1977 is the initial and its retreat value is considered to be equal to zero.

Based on the numerical values representing the Gergeti glacier retreat corresponding graph and relevant linear trend for the spanning period of 1977-2015 are plotted (Fig. 3 (a)).

The analysis of the whole observational period (1977-2015) shows that the average rate of the Gergeti glacier retreat rate is equal to 19.7 m per year.

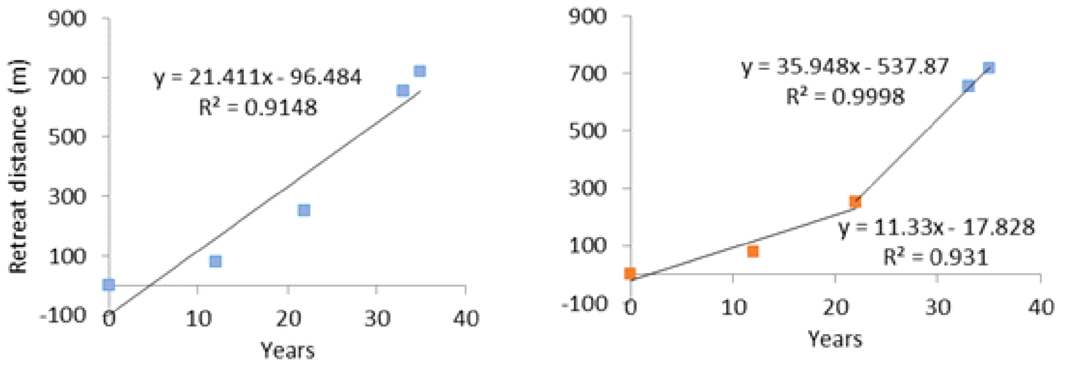
For better understanding of the impact of climate change on glacier retreat the research period of 40 years was divided into two periods: 1977-2001 and 2001-2015. Corresponding linear trends for these periods are created (see Fig. 3 (b)). The analysis carried out for the first period shows that the Gergeti glacier retreat rate was equal to 15.1 m annually and it reached 26.7 m per year for the second period. These numbers show that for the last 15 years the retreat tendency increased significantly and difference between the two periods is about 11.6 m annually.

Based on these data and the data for other glaciers not cited here it can be concluded that climate change was accelerated during the last period showing the nonlinear character of this process.



(a) (b)

Fig. 3. Gergeti glacier retreat dynamic and corresponding linear trends based on satellite EO: (**a**) for the whole period (1977-2015). Starting position refers to 1977; (**b**) For the I (1977-2001) and II (2001-2015) periods.



(a) (b)

Fig. 4. The Gergeti glacier retreat dynamic and corresponding linear trends based on the terrestrial observations: (**a**) for the whole period (1978-2013). Starting position refers to 1978; (**b)** For the I (1978-2003) and II (2003-2013) periods.

For QA/QC of satellite EO data related to Gergeti glacier, the data from terrestrial observations for the time period of 1978-2013 were used. Based on these data (five positions) Gergeti glacier retreat dynamics are shown in Fig. 4 a.

According to terrestrial observations the linear trend for the whole observational period (1978-2013) shows that the retreat rate of the Gergeti glacier is equal to 21.4 m per year on average. The results revealed a similar trend, the glacier retreated as it was documented according the satellite monitoring data. Namely, comparison of the data from terrestrial observations with those of the satellite EO shows that the retreat rate is almost the same. The difference (1.7 m/per year) is negligible and can be referred to the difference in observational periods.

For validation of the climate change impact on the Gergeti glacier retreat in dependence of time periods the similar approach was used for terrestrial observations. The research period of 35 years of terrestrial observations were divided into two periods: 1978-2000 and 2000-2013 and corresponding linear trends for these periods were created (see Fig. 4 b). Using the data of the terrestrial observations it was determined that the Gergeti glacier retreat rate is equal to 11.3 m annually during the first period and it reaches 35.9 m per year in the course of the second period. Greater difference of these data comparing with those of satellite monitoring is observed outcome. The difference is nearly 4 m annually during the first period and more than 9 m annually in the course of the second period. These differences are caused by the distinction in the observational periods for the satellite EO (40 years) and for the terrestrial observations (35 years).

Conclusions

In the present study the impact of modern regional climate change on Georgian glaciers degradation is investigated. In general global warming has substantial negative impact on glaciers, which is particularly evident in the case of small and large glaciers. This often leads to small glaciers fragmentation, turning them into the snowfields or their full melting. In case of the large glaciers their considerable retreat is determined.

The detailed study was carried out to compare the number of small glaciers registered in the former USSR catalog and the amount of small glaciers received after processing of satellite EO data for 2014. This time period between these data is at least 40 years long. The results show that out of 108 small glaciers registered in the former USSR catalog, nowadays only 32 remain; 64 snowfields resulted after small glaciers degradation and 27 small glaciers fully vanished. Based on the corresponding analysis it can be concluded that more than 70% of small glaciers fully or partially melted due to the regional climate change impact. This fact can be very likely considered as a great impact of the modern climate change on small glaciers melting.

Impact of modern regional climate change on large glaciers is mainly studied on the example of the Gergeti glacier. It was chosen because the end of this glacier is free of debris, the availability of 11 different files of Landsat satellite data spanning the period of 1977-2015 and existence of terrestrial observations for QA/QC procedures. The satellite images were chosen for the end of the ablation period and with less than 20% of cloud cover. The analysis of the Gergeti glacier retreat rate for the whole observational period (1977-2015) shows that the average rate of retreat is equal to 19.7 m per year.

For validation of the satellite EO data related to the Gergeti glacier, the available terrestrial information for the time period of 1978-2013 were used. As it is shown the retreat rate of the Gergeti glacier according to terrestrial observations is equal on average to 21.4 m per year that is a similar according to the glacier retreat rate as was documented in the data from the satellite monitoring. The difference is negligible and very likely may be referred to the distinction in observational periods. It shows the reliability of the satellite EO data, its processing and analysis.

For better understanding of the impact of climate change on glacier retreat based on the satellite EO data the research period for 40 years was divided into two periods: 1977-2001 and 2001-2015. Corresponding linear trends analysis carried out for these time periods showed that the Gergeti glacier retreat rate increased considerably, namely for the last 15 years the retreat velocity increased significantly and difference between the two periods is about 11 m annually. Based on these data and the data for other glaciers not cited here it can be concluded that climate change is accelerated during the last period showing the nonlinear character of this process.

For validation and QA/QC of satellite EO data related to Gergeti glacier, available terrestrial information for the time period of 1978-2013 were used. These data was divided into two periods. The data of the terrestrial observations for the first period (1978-2000) revealed that Gergeti glacier retreat rate is equal to 11.3 m annually and it reaches 35.9 m per year for the second period (2000-2013). A greater difference of these data comparing with those of satellite monitoring is observed outcome. The difference is nearly 4 m annually for the first period and more than 9 m annually for the second period. These differences are likely caused by the distinction in the observational periods for the satellite EO (40 years) and for the terrestrial observations (35 years).

Summarizing it can be concluded that the glaciers in East Georgia are intensively melting under the impact of regional climate change. The large glaciers are degrading and retreating, the medium glaciers are partially transformed into small glaciers, major portion of small glaciers are turning into snowfields or completely vanishing. At least 70 % of small glaciers in East Georgia are now turned into snowfields or fully melted. Analysis of large glacier retreat shows that the rate of its retreat is considerably increased. The retreat rate of the latest 15 years is significantly scaled up in comparison with previous one.

The research revealed the acceleration of regional climate change in East Georgia.

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გეოფიზიკა

თანამედროვე კლიმატის ცვლილების გავლენა აღმოსავლეთ საქართველოს მყინვარებზე

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განხილულია თანამგზავრული დისტანციური ზონდირების და GIS ტექნოლოგიების გამოყენების საფუძველზე აღმოსავლეთ საქართველოს მყინვარების ცვლილების საკითხები გლობალური დათბობის პირობებში. უნდა აღინიშნოს, რომ წარსულში მყინვარების პარამეტრები (ფართობი, სიგრძე და მოცულობა) იზრდებოდა. გასული საუკუნის მეორე ნახევრიდან საქართველოს მყინვარების მახასიათებლები მცირდებოდა გლობალური დათბობის გამო. მ. სილვენმა და სხვებმა განსაზღვრეს, რომ საქართველოს მყინვარების ფართობი შემცირდა 36 %-ით, ხოლო მოცულობა - 48 %-ით. ეს პროცესი ახლაც მიმდინარეობს და სავარაუდოა, რომ მას ადგილი ექნება მომავალშიც. წარსულში მყინვარებზე დაკვირვება, როგორც წესი, ტრადიციულად მიწისპირა დაკვირვებებით მიმდინარეობდა, რომლებიც მნიშვნელოვანი ნაკლოვანებებით ხასიათდებოდა, სახელდობრ: მაღალი ღირებულება, მონაცემთა არარეგულარული განაწილება სივრცესა და დროში. დედამიწის ზედაპირზე თანამგზავრული დაკვირვებები ამ ნაკლოვანებებისაგან ფაქტიურად თავისუფალია. ამ ტექნოლოგიის გამოყენებით შესწავლილია მცირე მყინვარების დნობა და დიდი მყინვარების უკანდახევა კლიმატის რეგიონული ზემოქმედების შედეგად. დადგინდა, რომ უკანასკნელი 50 წლის განმავლობაში ადგილი აქვს მცირე მყინვარების დაჩქარებულ დნობას. განისაზღვრა, რომ აღმოსავლეთ საქართველოს მცირე მყინვარების დაახლოებით 70% მთლიანად ან ნაწილობრივ გადნა. განსაზღვრულია დიდი მყინვარების უკან დახევის სიჩქარის საგრძნობი მატება განსაკუთრებით უკანასკნელი 15 წლის განმავლობაში. ეს შედეგები ნათლად მიუთითებს მყინვართა დეგრადაციაზე კლიმატის რეგიონული ცვლილების აჩქარების გამო.

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