Satellite remote sensing outputs of the certain glaciers on the territory of East Georgia

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Abstract The variations in glaciers are the important indicators of regional climate change. The glaciers play an important role in the regulation of water balance. In the conditions of global warming they recede and degrade that is expressed in the related changes in glacier runoff. The research of glacier melting is important for studies of sea/ocean level changes. The Caucasian glacial dimensions (area, volume, length) have been changed over the centuries.

The scientific study of glaciers in the Caucasus was started during the first half of 18th century. In the last century the terrestrial observations on glaciers were carried out. Due to the difficulties of organization and conducting of field works the received observational data sets consists from different series of various temporal duration characteristics of glaciers. The data received contain uncertainties. From another hand carrying out of such field works are expensive.

With the launch of the Earth’s satellites it was determined that satellite remote sensing is the best technology allowing to receive data with needed regularity in terms of both time and space resolution. Some uncertainties remain in the data as the observational tool is too far away from the Earth’s surface. So, the necessity for the strong quality assessment/quality control (QA/QC) remains. A lot of studies showed that the best method for investigation of glaciers is application of satellite remote sensing combined with terrestrial observations and expert knowledge of separate glaciers.

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1. Introduction

It is obvious that variations of glaciers are clear indicators of regional climate change. Recent interest in the study of glaciers is motivated by their clear reaction to climate changes. As glaciers cover so many climate regions worldwide, from the tropics to poles, their study enables a survey of significant aspects of global and regional Climate Change. As many of their features are detectable from the space, such investigations are well adapted for the methods of remote sensing. The glaciers play an important role in the regulation of water balance in certain regions. Under the global warming glaciers recede and degrade, which is reflected in the related changes of glacier

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runoff. These processes result in glacial and hydrological disasters such as ice blocks falling from the glaciers accompanied with the debris, followed by the river bed blockage and natural dam formation, with consequent break and pass of catastrophic flash floods and/or mudflows (Kääb et al., 2006).

The investigation of glacier melting is important for studies of sea/ocean level changes that also may have a significant risk for the residents of coastal areas. That is one of the most negative impacts of modern climate change on mankind. The abovementioned put into agenda the necessity for detailed study of the glaciers.

The scientific study of glaciers in the Caucasus was started during the first half of 18th century. In the last century the terrestrial observations on glaciers were carried out. Due to the difficulties of organization and conducting the field works the terrestrial observation data resulted in different series of various temporal duration characteristics of glaciers. The data received contain uncertainties. From another hand carrying out of field works are expensive and data gathered have no sufficient spatial and temporal resolution.

With launch of the Earth’s satellites it was determined that satellite remote sensing is the best technology allowing to receive data with needed regularity in terms of both time and space resolution. Some uncertainties remain in the data as the observational tool is too far away from the Earth’s surface. So, the necessity for the strong quality assessment/quality control (QA/QC) remains. A lot of studies showed that the best method for investigation of glaciers is application of satellite remote sensing combined with terrestrial observations and expert knowledge of separate glaciers.

2. Research area & glaciers survey

Georgia is a transcontinental country, located in the South Caucasus, between the Black Sea to the West and the Caucasus mountains to the North. Georgia is bordered by Russian Federation from the North; it is sided from the South by Turkey and Armenia and it is bordered from the South-east by Azerbaijan. The territory of the country is divided by Likhi Range into two parts: West Georgia and East Georgia. This division is corroborated by the difference in physical and geographical conditions between them as well. The glaciers are located in North part of the country in the Caucasus Mountains. The main glaciers from the Caucasus Mountains in the territory of East Georgia are researched in the present study. Below are listed the important glaciers to be studied based on the satellite remote sensing. The main objective of the research is the adjustment of characteristics of Mayly, Chachy, Devdoraki, Abano, Gergety, Mna, East Suatisi, Middle Suatisi, West Suatisi, SU4G08011072, SU4G08011061, SU4G08011056, SU4G08011059 and SU4G08011058 glaciers. The last 5 glaciers have no names and they are registered in World data base as mentioned above i.e. SU4G08011072, SU4G08011061, SU4G08011056, SU4G08011059 and SU4G08011058.

In Fig. 1 as an example Aster DEM and Landsat satellite images are presented for Kazbegi glacial mountain array.

In Fig. 2 the 3D visualization of Landsat images and Aster DEM (left) and Google Earth image (right) of Kazbegi glacial mountain array are presented.

The satellite remote sensing gives possibility of universal, systematic and complex research of glaciers properties and changes. This is due to the fact that satellite remote sensing allows to cover efficiently the interesting regions and to study dynamically such important parameters, as the glacier area, terminus positions at the end of its location, firm line elevation, accumulation area, the hypsometry (Pellikka and Gareth, 2010). In turn these parameters allow calculation of glacier mass balance.

In Georgia the glacial parameters (area, volume, length) have been changed over the centuries. It is determined that from the second half of the last century the characteristics of the Georgian glaciers are steadily diminishing. The process is still underway and will likely continue in the future. The elevation of the lower boundary of the glaciers increases.

During the last century the area of the Georgian glaciers decreased by 36% and the volume reduced by 48%. Some glaciers melted away but the glacier melting process causes increase of glacier number due the fragmentation of large glaciers into small ones. Hence, the total number of glaciers increased. The length of glaciers was reduced by 600 m in average. In the lower part of glaciers ice thickness decreased by 50–150 m and in the upper part it was reduced by 20–30 m consequently. During the last decades (1970–2000) glacial conditions in Georgia have changed on the background of rainfall and temperature increase by 10–15% and 1 °C respectively.

Figure 1  Aster DEM and false colour Landsat images.
During the same period the glacier area decreased by 12%, the ice volume by 15%, while the number of glaciers increased by 2.4% (Stokes et al., 2006).

Recent studies proved sustainable recession of the Georgian glaciers. For example, in the summer of 2010 the Gergeti glacier tongue amounted up to 8.5 km. From 2004 up to 2010 it decreased by 123 m in average of about 20 m per year (Keggenhoff et al., 2011). During the period of 1810–2011 the melting dynamics of the glacier Tviberi is as follows: in 1810 its area was 47.5 km², and in 1889 – 47.1 km². Simple analysis shows that glacier area during 79 years decreased by 1%. In 1965 its area amounted to 41.6 km², i.e. the glacier area decreased by 12% compared to 1889 and in 2011 it was reduced by 35% compared to 1889 and was equal to 30.9 km². A similar case occurs with glacier Chalaati. In 1965 its area was 14.4 km² and in 2011 – 11.8 km², i.e. the glacier area decreased by 16% for the last 46 years (Shengelia et al., 2012).

3. Research methods

The following actions are performed for specifying the contours of the glaciers according to the developed methodology:

- The Google software products are used. Namely, the Google Earth satellite images and the satellite sensor ASTER data based on the generated Digital Terrain
Model (Aster DEM) are applied. GIS systems: Google Earth, BEAM Visat and Quantum GIS Lisboa are used for satellite data processing. It would be noted that the spatial resolution of satellite Aster DEM is 30 m (Bolch and Kamp, 2005);

- Various glacier characteristics stored in the GLIMS database: glaciers contours and numerical characteristics of glaciers are used for the glacier identification. GLIMS-database protected contours are generated based on the Aster sensor data (Raup et al., 2007);

- Soviet topographic maps (1: 50,000) as well as the terrestrial observations data are used for glacier contour validation. It is clear that such data exist only for the certain glaciers and for some years;

- Expert knowledge is also effectively used for the investigation of these glaciers.

Changes in glacier area and terminus positions have been widely used as the indicator of a glacier response to climate impact. These two parameters are relatively easy to determine.
from multispectral satellite images. Glacier outlines combined with a digital elevation model (DEM) give possibility to determine such glacier parameters as hypsometry, minimum, maximum and mean elevations, firn line altitude.

Delineation of glacier outlines is possible both manually and automatically based on the corresponding software by the band combination techniques. Human interpretation remains the best tool for extracting high level information from satellite imagery. Tedious, manual digitalization of glacier boundaries by an operator with good knowledge of the region can produce glacier boundary contours of high quality and accuracy. Automatic delineation of glacier relies on different spectral properties of glacial ice and snow in the visible and IR part of electromagnetic spectrum. The greatest difficulty in glacier mapping from remote sensing is the presence of debris cover on glaciers. In such cases higher resolution satellite images and DEM are used as well as the data of the terrestrial observations and expert knowledge of separate glaciers.

4. Results

For 3D visualization of Kazbegi Glacier’s array Landsat TM image (path: 170, row: 30, level L1T) from 26 September of 1984 year and ASTER DEM edition images are used. Landsat data were downloaded from USGS Earth explorer webpage, consequently ASTER DEM – from ASTER webpage of NASA JPL website. Both of them may be downloaded free of charge, in GeoTIFF format and used in any GIS 3D visualization of glaciers from study area. Kazbegi glaciers as well as all researched glaciers on the territory of East Georgia are performed by generating the Landsat false colour composite images (band 5 as red, 4 as green and 3 as blue) and wrapping over the ASTER DEM.

The boundaries of glacier array were adjusted using the high spatial resolution satellite images, e.g. for the Kazbegi glaciers based on the satellite image dated September 1, 2010, provided by Google Earth software package. That allows high accuracy digitalization of the contours of all the glaciers. Digitalization of glacier contours is performed manually on the basis of expert knowledge. Corresponding shapefiles are created. Results are compared with GLIMS database contours. These contours are derived from processing of Aster satellite images (e.g. for the Kazbegi glaciation based on the satellite image dated September 25, 2004, DEM spatial resolution – 15 m) by scientists of the Institute of Geography of Russian Academy of Sciences.

Further, Gergeti glacier will be considered as an example for the simplicity.

In Fig. 3 contours of Gergeti glacier are presented. Blue contour corresponds to the Gergeti glacier contour from GLIMS database. By red one is shown Gergeti glacier adjusted contour using satellite remote sensing. As it is revealed in Fig. 3 the difference between these contours is significant, especially in the Northern part. The reason of this difference is detected based on DEM analysis. In GLIMS data base (see Fig. 3) the whole field of the northern slope of the Kazbegi mountain is assigned to the Gergeti glacier. Manual digitalization of Gergeti glacier contour, is based on Digital Globe high resolution satellite image, as well as applying ASTER DEM data. Using the Quantum GIS software package elevation isolines with 30, 10 and 5 m resolution are generated based on ASTER DEM. The outputs are plotted, as additional layer to the Google Earth. As a result glacier contours are adjusted taking into account the watershed on the North-west slope of Gergeti glacier. The analysis shows that the plateau part from the adjusted red line till the blue line from the GLIMS data base should be attributed to Devdoraki glacier.

Fig. 4 illustrates distribution of DEM pixel numbers for Gergeti glacier according to the elevation. For determination of hypsometric curve adjusted outlines of Kazbegi glaciers and ASTER DEM data BEAM-VISAT are used.

The firn line elevation was determined according to the Hefer method (Tsomaa and Drobishev, 1977) and ablation...
The glacier research is significant due to the fact that the glaciers occupy approximately 11% (16 million square kilometres) of the earth’s land area. The glaciers contain a large number of fresh-water (30 million km$^3$), which is the 2/3 of the earth’s fresh water supply. Georgia possesses more than 600 glaciers and their detailed study is important from several points of view. In present research satellite remote sensing research is done for the main glaciers located on the territory of East Georgia.

The scientific study of glaciers in the Caucasus was started during the first half of 18th century. In the last century the terrestrial observations on glaciers were carried out. Due to the difficulties of organization and conducting the field works the terrestrial observations data resulted in different series of various temporal duration characteristics of glaciers. The data received contain uncertainties. From another hand carrying out of field works are expensive and data gathered have no sufficient spatial and temporal resolution.

According to the Hefer method the elevation of the firn line is the average of the firn line basin height and the elevation of the glacier tongue. The average of the values of the highest peak elevation (two or more peaks) around the glacier basin is determined and the value of the elevation of glacier tongue is added. Finally value of the firn line elevation is the average of these two values.

Glacier accumulation area can be determined using hypsometric curve. Glacier accumulation area is the value of one pixel area multiplied by the total number of pixels on hypsometric curve from the firn line elevation till the highest height of the glacier. Glacier ablation area is the value of one pixel area multiplied by the total number of pixels on hypsometric curve from the firn line elevation till the lowest height of the glacier. The sum of the glacier accumulation and ablation areas makes a total glacier area.

In Fig. 5 the 3D visualization of Gergeti glacier is shown. Blue contour corresponds to the Gergeti glacier contour from GLIMS database. By red one is shown Gergeti glacier adjusted contour using satellite remote sensing. The green line shows the areas free of debris. It is natural that green line differs from the blue line in the lower part of the glacier as the upper part is free of debris.

The comparison of Gergeti glacier contours received from the satellite remote sensing with Soviet topographic map (1:50,000) is presented in Fig 6. Comparison of topographic map with contours (Fig. 6) shows the changes of contour of Gergeti glacier.

These data are compared with the glacier relevant information from the USSR glaciers catalogue (Tsonaya and Drobishev, 1977).

In Table 1 the glacier parameters, such as length, area, minimum elevation, firn line elevation, ablation area of the listed glaciers of East Georgia calculated from the satellite remote sensing data (columns marked by (1)) and from the USSR glaciers catalogue (columns marked by (2)) are presented. This table allows comparison of the data received from satellite remote sensing with the data from USSR glaciers catalogue.
With launch of the Earth’s satellites it was determined that satellite remote sensing is the best technology allowing to receive data with needed regularity in terms of both time and space resolution. Some uncertainties remain in the data as the observational tool is too far away from the Earth’s surface. So, the necessity for the strong quality assessment/quality control (QA/QC) remains. A lot of studies showed that the best method for investigation of glaciers is application of satellite remote sensing combined with terrestrial observations and expert knowledge of separate glaciers.

In cases whenever the terrestrial observations are not available and expert knowledge is absent, validation is not possible. In our research maximum length, area, minimum elevation are not determined for some glaciers, namely: SU4G08011056, SU4G08011057, SU4G08011058 and SU4G08011059. Accordingly only some information about those glaciers is presented but the detailed conclusions about them is not possible to make at that stage.

Based on the detailed comparison of the output data received using the satellite remote sensing provided with the QA/QC with the similar data from the glaciers catalogue it can be concluded that during the last 50 years all the characteristics of the main glaciers from the East Georgia are changing as follows:

- The minimum elevation and equilibrium line altitude are increasing;
- The length and area as well as the ablation area are decreasing.

The carried researches define that impact of modern climate change is well expressed in East Georgian glaciers retreat due to modern warming.

It would be noted that the complex research of the glaciers using different sources’ data such as satellite remote sensing, terrestrial observations and expert knowledge is effective for better accurate determination of glaciers’ main characteristics.

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