

PAPER • OPEN ACCESS

Glacier area changes in Northern Eurasia

To cite this article: Tatiana Khromova *et al* 2014 *Environ. Res. Lett.* **9** 015003

View the [article online](#) for updates and enhancements.

You may also like

- [Controls on the relative melt rates of debris-covered glacier surfaces](#)
E S Miles, J F Steiner, P Buri *et al.*
- [What influences climate and glacier change in southwestern China?](#)
Teppei J Yasunari
- [Detailed quantification of glacier elevation and mass changes in South Georgia](#)
David Farías-Barahona, Christian Sommer, Tobias Sauter *et al.*



The Breath Biopsy® Guide
Fourth edition

DOWNLOAD THE FREE E-BOOK

BREATH BIOPSY

OWLSTONE MEDICAL

Glacier area changes in Northern Eurasia

Tatiana Khromova, Gennady Nosenko, Stanislav Kutuzov, Anton Muraviev and Ludmila Chernova

Institute of Geography, Russian Academy of Sciences, Staromonetny, 29, 119017, Moscow, Russia

E-mail: tkhromova@gmail.com, gnosenko@gmail.com, s.kutuzov@gmail.com, anton-yar@rambler.ru and ludmila.chernova@gmail.com

Received 15 June 2013, revised 21 November 2013

Accepted for publication 20 December 2013

Published 15 January 2014

Abstract

Glaciers are widely recognized as key indicators of climate change. Recent evidence suggests an acceleration of glacier mass loss in several key mountain regions. Glacier recession implies landscape changes in the glacial zone, the origin of new lakes and activation of natural disaster processes, catastrophic mudflows, ice avalanches, outburst floods, etc. The absence or inadequacy of such information results in financial and human losses. A more comprehensive evaluation of glacier changes is imperative to assess ice contributions to global sea level rise and the future of water resources from glacial basins. One of the urgent steps is a full inventory of all ice bodies and their changes. The first estimation of glacier state and glacier distribution on the territory of the former Soviet Union has been done in the USSR Glacier Inventory (UGI) published in 1965–1982. The UGI is based on topographic maps and air photos and reflects the status of the glaciers in the 1940s–1970s. There is information about 28 884 glaciers with an area of 7830.75 km² in the inventory. It covers 25 glacier systems in Northern Eurasia. In the 1980s the UGI has been transformed into digital form as a part of the World Glacier Inventory (WGI). Recent satellite data provide a unique opportunity to look again at these glaciers and to evaluate changes in glacier extent for the second part of the 20th century. About 15 000 glacier outlines for the Caucasus, Polar Urals, Pamir Alay, Tien Shan, Altai, Kamchatka and Russian Arctic have been derived from ASTER and Landsat imagery and can be used for glacier change evaluation. Results of the analysis indicate the steady trend in glacier shrinkage in all mountain regions for the second part of the 20th century. Glacier area loss for the studied regions varies from 13% (Tien Shan) to 22.3% (Polar Urals). The common driver, most likely, is an increase in summer air temperature. There is also a very large variability in the degree of individual glacier degradation, very much depending on the morphology and local meteorological conditions.

Keywords: Northern Eurasia, glacier systems, glacier changes, space imagery, glacier inventory

1. Introduction

The cryosphere is an integral part of the global climate system with important links and feedback generated through its influence on surface energy and atmospheric circulation. Components of the cryosphere are present at all latitudes of the globe, including the Equator (Climate and Cryosphere Project Implementation Strategy Document 2007). Glaciers, as one of the main components of the cryosphere, play a visible role

in the territory of Northern Eurasia (NEESPI Science Plan: <http://neespi.org/>). Deglaciation in the mountain systems will affect water resources and the quality of the interior areas of the continent and, thus, the global climate and society. Melting of glaciers in mountains is essential for water supply and irrigation. The lowlands can be flooded due to sea level rise because of the melting of glaciers and ice sheets.

Efforts to correctly estimate the world's ice storage are ongoing. Total inventorying of glaciers is carried out in 11 countries and some national inventories are not accessible for foreign users (Omura 2009). The World Glacier Inventory (WGI), based on the original WGI (WGMS 2008) from the World Glacier Monitoring Service (WGMS), was updated



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

in 2012 and currently contains information on just over 131 000 glaciers, approximately 77% of the total glaciation (http://nsidc.org/data/docs/noaa/g01130_glacier_inventory/). The database of the GLIMS project (www.glims.org) contains shape-file outlines plus complete metadata on approximately 68% of the world's glaciers, representing 71% of the total glacier area. The GLIMS database is being continually updated. The Randolph Glacier Inventory (RGI) (www.glims.org/RGI/randolph.html) was produced in 2012 as a more globally complete inventory of glacier outlines but with limited documentation or metadata. The last RGI update has been done in April 2013.

Observations of glacier fluctuations were carried out on the Eurasia territory since the 19th century (Dolgushin and Osipova 1989). The number of glaciers under investigation drastically increased since the end of the 1950s until the middle of the 1980s. In the 1990s, after the disintegration of the USSR, ground observations were significantly reduced. At the same time, it became possible to use space images for an estimation of glacier changes.

The current climate warming has already lasted for longer than 150 years. In the middle of the 19th century, the Little Ice Age had come to its end and everywhere mountain glaciers began to decrease (Solomina 2000). Since the end of the 1950s until the middle of the 1970s, the glaciers were in a quasi-stationary state in most of the mountain areas in Eurasia (Dyurgerov 2005). Now, the glaciers degrade in all mountain areas of Eurasia. This is reflected in the fact that small glaciers disappear, the termini retreat, the area and volume of glaciers decrease, their surfaces are covered with moraines and large spaces of dead ice are being formed. Compound glaciers are broken into simpler components. Estimations of these changes were published in a number of papers; however, the general picture of the modern Eurasian glaciers to the present moment is not complete. Permanent, regular and detailed observations of the glacier behaviors are necessary to be performed in different regions, and first of all, based on remote sensing methods. One of the urgent steps is a full inventory of all ice bodies and their changes (Barry 2006).

North Eurasia as a NEESPI (North Eurasia Earth Science Partnership Initiative) study area includes the former Soviet Union, Northern China, Mongolia, Fennoscandia, Eastern Europe and the coastal zones of these countries (<http://neespi.org/>). In this letter we give an overview of our recent results on glacier inventory and glacier changes in the territory of the former Soviet Union achieved both by surface measurements and satellite remote sensing.

2. Data and methods

The first estimation of glacier state and glacier distribution in the territory of the former Soviet Union has been done in the multivolume 'The Catalog of Glaciers of the USSR' (UGI) published in the period of 1965–1982. The inventory consisting of 69 volumes is based on topographic maps and air photos and reflects the state of glaciers in the 1940s–1970s (The Catalog of Glaciers of the USSR 1965–82). There was information about 28 702 glaciers with an area of

78 240.65 km² in the UGI. In the 1990s data from the UGI were transformed into digital format and incorporated into the World Glacier Inventory (WGI) and now available through the National Snow and Ice Data Center (NSIDC) internet site (http://nsidc.org/data/glacier_inventory/). Latitude and longitude were added for each glacier. Later 182 glaciers with total area 61.1 km², which were not mentioned among glacier systems of the Koryak, Chukchi and Kolyma highlands presented in the UGI, were added. These glaciers were discovered, visited and investigated in the 1980s–1990s by R V Sedov, a researcher from Magadan (Kotlyakov *et al* 2011). Now the UGI covers 25 glacier systems (figure 1, table 1). 70% of the glaciation is concentrated in three northern glacier systems (72°–82°N): Franz Joseph Land (995 glaciers with total area 13 740 km²), Novaya Zemlya (685 glaciers with area 23 645 km²) and Severnaya Zemlya (285 glaciers, 18 325 km²). Two southern glacier systems (36°–43°N) constitute 22% of the glaciation. They are Pamir Alay (9108 glaciers, 9808 km²) and Tien Shan (5428 glaciers, 7326 km²). The other 20 glacier systems (44°–80°N, 40°–170°E) cover 8% of the glaciation (Chernova *et al* 2011).

The present-day data on glaciers come, first of all, from remote sensing. International projects have been initiated, such as GLIMS (Global Land Ice Measurement from Space, www.glims.org) and GlobGlacier (www.globglacier.ch), which are aimed at studying glaciers by means of satellite remote sensing (Bishop 2004, Racoviteanu *et al* 2009). A system of regional centers is created in the framework of the GLIMS project (<http://glims.org/>). One of those regional centers is located at the Institute of Geography, Russian Academy of Science (<http://igras.ru/en>) and is responsible for glacial regions of the former Soviet Union, which is an essential part of Northern Eurasia glaciation. Original software has been developed in the framework of this project that makes it possible to delineate glacier boundaries from space images and to save the results of delineation in the standard form intended for storage and analysis in a special database.

Vector coverage of outlines for more than 15 000 glaciers in the Arctic, Polar Urals, Caucasus, Pamir Alay, Tien Shan, Altai and Kamchatka has been created at the Institute of Geography RAS. The images of The Enhanced Thematic Mapper Plus (Landsat ETM+, resolution 30 m) and The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER, resolution 15 m) were analyzed. Images were supplied by NASA Land Processes Distributed Active Archive Center (LP DAAC) in UTM WGS 84 projection and were orthorectified prior to the distribution (Lang and Welch 1999). All images were acquired at the very end of the ablation season when glacier tongues were free of seasonal snow and under cloud-free conditions and were suited for glacier mapping. Where glacier margins were obscured by shadows from rocks and glacier cirque walls, a contrast-stretching function was applied to the imagery using ENVI 3.5 software. The ASTER digital elevation models (DEM), obtained together with images from LP DAAC, were used to delineate the upper boundaries for complex glaciers (Kutuzov 2012, Muraviev and Nosenko 2013, Nosenko *et al* 2010, 2013, Shahgedanova *et al* 2012).

The glacier outlines for each data item were digitized manually. To do the digitization GLIMSView software was

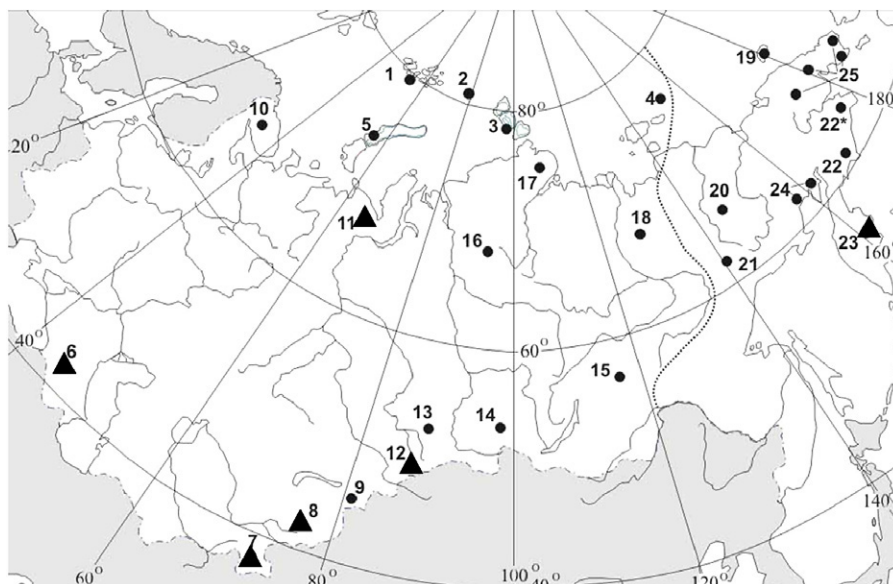


Figure 1. Glacier systems of former USSR. 1—Franz Josef Land and Victoria Island, 2—Ushakova Island, 3—Severnaya Zemlya, 4—De Long Islands, 5—Novaya Zemlya, 6—Caucasus, 7—Pamir Alay, 8—Tien Shan, 9—Dzhungarski Alatau, 10—Khibiny, 11—Urals, 12—Altai, 13—Kuznetskii Alatau, 14—Eastern Sayan, 15—Kodar Range, 16—Putorana, 17—Byrranga, 18—Orulgan, 19—Wrangel Island, 20—Cherskii Mountains, 21—Suntar_Khayata, 22—Koryak Uplands, 23—Kamchatka, 24—Kolyma Uplands, 25—Chukchi Uplands. Black triangles show the location of the glacier systems analyzed in this letter.

Table 1. Glacier systems according to the electronic version of the glacier inventory of USSR (2010 (UGI) (note: data for glacier systems 1–21 and 23 are given according to the UGI for the period 1940–1970; data for glacier systems 22, 24 and 25 are given by R V Sedov for the period 1980–1990 (Kotlyakov *et al* 2011)). (www.webgeo.ru/index.php?r=47).

Glacier system	North latitude	Longitude	All glaciers			Glacier mass, billion t. (km ³)
			Number	Area km ²	Average size, km ²	
1 Franz Josef Land and Victoria Island	79.54–81.51	E—36.7–65.25	996	13 749.7	13.80	2 100
2 Ushakova Island	80.90–80.93	E—79.82–79.83	2	325.4	162.7	48
3 Severnaya Zemlya	78.42–81.25	E—90.95–105.32	287	18 326.1	63.85	4 700
4 De Long Islands	76.63–77.12	E—148.57–158.03	15	80.6	5.37	11
5 Novaya Zemlya	72.8–76.88	E—53.15–67.62	685	23 645.4	34.52	8 100
Ice sheets	72.8–81.51	E—36.77–158.03	1985	56 127.2	28.28	14 959
6 Caucasus	39.07–43.95	E—39.90–48.00	2 080	1 427.12	0.69	75
7 Pamir Alay	36.0–39.38	E—67.47–75.2	10 995	9 828.04	0.89	970
8 Tien Shan	39.4–42.98	E—70.24–80.27	7756	7 305.36	0.94	620
9 Dzhungarski Alatau	44.5–45.5	E—79.2–81.7	1 365	999.8	0.73	50
10 Khibiny	67.8–68.0	E—33.4–33.9	4	0.1	0.02	0.0
11 Urals	64.8–68.2	E—59.7–67.0	143	28.66	0.20	0.7
12 Altai	47.0–50.4	E—83.7 0–90.15	1517	923.1	0.61	39
13 Kuznetskii Alatau	53.7–54.7	E—88.3–89.32	91	6.79	0.07	0.2
14 Eastern Sayan	51.72–56.00	E—96.68–100.62	105	30.3	0.29	0.9
15 Kodar Range	56.8–57.0	E—117.2–117.7	30	18.8	0.63	0.6
16 Putorana	69.0–70.0	E—90.0–92.3	22	2.54	0.12	0.1
17 Byrranga	75.7–76.0	E—107.4–108.0	96	30.5	0.32	0.9
18 Orulgan	67.4–69.0	E—127.8–128.9	74	18.38	0.25	0.7
19 Wrangel Island	70.98–71.3	E—178.65–179.68	101	3.46	0.03	0.1
20 Cherskii Mountains	64.9–67.7	E—138.6–149.2	372	155.4	0.42	10
21 Suntar_Khayata	61.8–62.9	E—140.6–143.2	208	201.6	0.97	12
22 Koryak Uplands	60.17–62.3	E—166.7–173.35	1451	303.46	0.59	9.2
23 Kamchatka	51.3–62.1	E—156.7–173.4	405	874.0	2.16	49
24 Kolyma Uplands	60.38–61.99	E—152.00–160.10	19	3.61	0.19	0.1
25 Chukchi Uplands	64.6–67.8	E—175.47–W—171.42	47	13.53	0.29	0.6
Mountain glaciers	36.0–76.0	E—33.4–W—171.42	26 899	22 174.55	0.82	1838.2
Total in USSR	36.0–81.51	E—33.4–W171.42	28 884	78 301.75	2.71	16 797.2

used (www.glims.org/GLIMSVIEW/). World glacier inventory IDs were added to each polygon with GLIMS ID. The method of joint statistical analysis of data derived from space images and data of the UGI and early glacier inventories was used to detect glacier area change. Accuracy of the UGI data for each studied region was validated using historical air photos (Kutuzov 2012, Muraviev and Nosenko 2013, Nosenko *et al* 2010, 2013, Shahgedanova *et al* 2012).

The images for different years were co-registered using a network of interactive ground control points (GCP) with a suitable maximum root-mean-square error ($RMSE_{x,y}$). Three types of errors resulting from co-registration, line placement and presence of debris cover on glaciers have been estimated. The error of co-registration was calculated following Granshaw and Fountain (2006). A buffer, with a width of half of the $RMSE_{x,y}$ was created along the glacier outlines and the error term was calculated as an average ratio between the original glacier areas and the areas with a buffer increment. The line placement uncertainty was estimated following Burgess and Sharp (2004). A sample of test glaciers was re-digitized ten times and the obtained line placement error was multiplied by the perimeter of each glacier in the sample. For debris-covered glaciers, this error term was increased using an additional line placement error for debris-covered segments. This was derived as a difference between outlines on test debris-covered glaciers obtained from the field measurements (Muraviev and Nosenko 2013, Nosenko *et al* 2010, 2013, Shahgedanova *et al* 2012).

The overview of our recent results received for some glacier regions of the former Soviet Union is presented below.

3. Caucasus

The Caucasus Mountains extend west-north to east-southeast between the Black Sea and the Caspian Sea. This is one of the few regions with alpine glaciers in the world. The glaciers exist in two main regions: the Big Caucasus (Bolshoi Kavkaz) and the Transcaucasia plateau (Zakavkazskoye nagorie). The main part of the glaciers is situated in the Big Caucasus (98% of number and 99.7% of area).

The Glacier Inventory by K I Podozerski (PGI) is the first information about glacier numbers and areas in the Caucasus. This inventory, based on the ordnance survey in 1887–1910, was published in 1911 in Russia (Podozerski 1911). The second inventory of the Caucasus glaciers is the result of a manual evaluation of various glacier parameters from the original aerial photographs and topographic maps (The Catalog of Glaciers of the USSR 1965–82). Both data sets contain tables with glacier parameters and do not have glacier outlines. The changes between the PGI and the UGI were analyzed by different authors (The Catalog of Glaciers of the USSR 1965–82, Panov (1993). The main result of all studies is the glacier retreat in the Caucasus. There is also widespread evidence of glacier recession in this region since the end of the LIA (Solomina 2000). Some studies declare a strong retreat trend for a few glaciers between 1972 and 1986 (Rototaeva *et al* 2006). Some studies for the Caucasus based on remote sensing methods (Stokes *et al* 2006) revealed that 94% of 113 selected glaciers have retreated between 1985 and

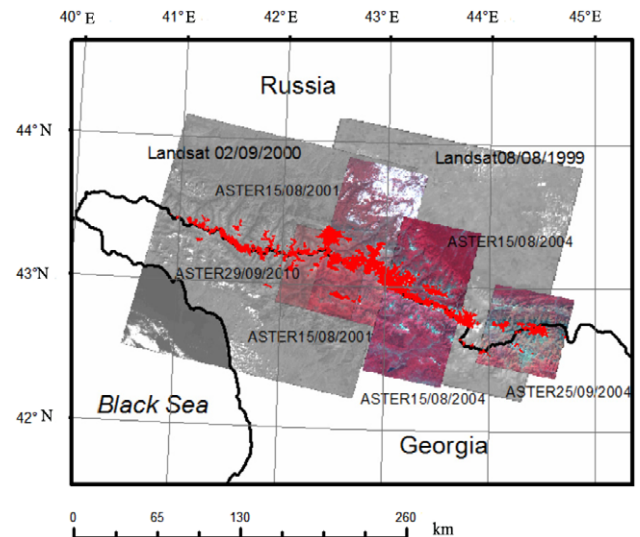


Figure 2. Caucasus glacier outlines (in red) derived from Landsat and ASTER imagery.

2000. Our analysis shows the decrease in glacier area in the Caucasus during the last 100 years.

Landsat ETM+ (12/09/2000, 8/08/1999) and ASTER (15/09/2001, 15/08/2004, 25/09/2004 and 29/09/2010) imagery, covering more than 90% of the glacierized area in the Caucasus, were obtained for the study (figure 2).

It was determined that the total area of 1100 glaciers decreased from the beginning (PGI) to the middle (UGI) of the 20th century by 24.7% and from the middle of the 20th century (UGI) to the beginning of the 21st century (space imagery) by 17%. For Elbrus glaciers we found 14.8% and 6.28%, respectively. More detailed analysis will be published in a special paper.

To estimate changes for the first decade of the 21st century, glacier outlines have been delineated from two ASTER scenes acquired on 15 September 2001 and 29 September 2010 covering the central sector of the Greater Caucasus Ridge and the Elbrus glaciated massif (Nosenko *et al* 2013). Outlines of 179 glaciers were mapped, of which 108 glaciers are located on the northern slopes of the Greater Caucasus and on Mt Elbrus in the Baksan River catchment (Russia) and 71 are located on the southern slopes in the Inguri River catchment (Georgia) (figure 3). It was found that glaciers lost 4.9% of their area between 2001 and 2010. Glacier wastage was higher in the Inguri catchment at 5.6%; in the Baksan catchment glaciers lost 4.3% of their area.

The observed shrinkage of Caucasus glaciers could be connected with increasing summer temperatures. Increase in precipitation has not compensated for an increase in temperature for the 1987–2001 and 2001–2010 periods (Nosenko *et al* 2013). The results show a strong area reduction for all studied glacier regions in the Caucasus. There is, however, some variability in the degree of reduction. The difference in the glacier retreat rates could be explained by such factors as different precipitation trends, different elevations of glacier tongues, and different sizes and morphological types of glaciers (Nosenko *et al* 2013).

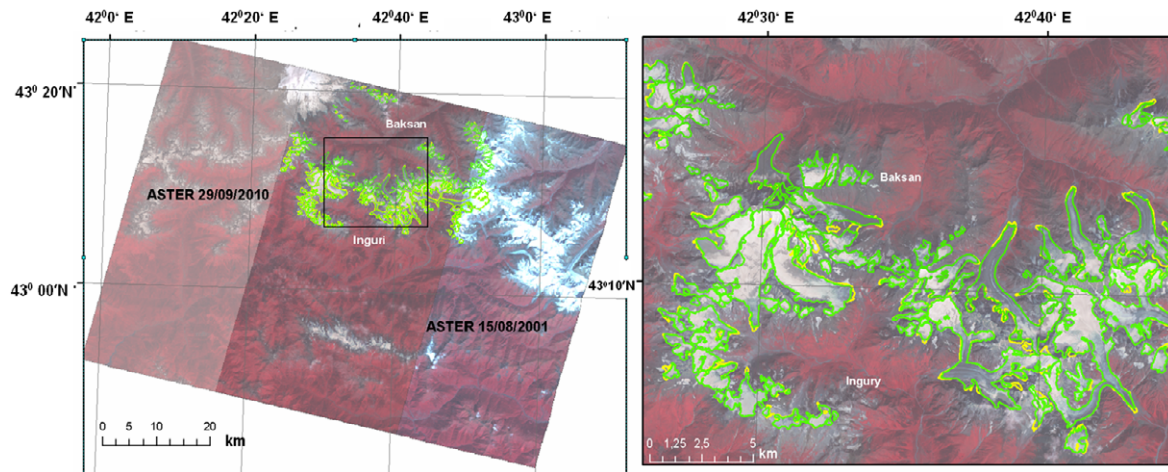


Figure 3. ASTER images and glacier outlines for 2001 (yellow) and 2010 (green). Inguri and Baksan drainage basins, Caucasus.

4. Altai

The Altai Mountains located on the junction of Russia, Kazakhstan, Mongolia and China is the highest part of the Altai–Sayan mountain system. According to the UGI there are 1517 glaciers in Altai, which cover 923.1 km² (table 1).

The data presented in the UGI are based on the analysis of aerial photographs for the 1950s and field surveys of the 1960s. Information concerning glacier change in the latter stages of the 20th century is limited. A number of investigations of changes in the areas of small samples of glaciers were conducted in the Russian Altai using terrestrial photogrammetry, GPS surveys and remote sensing (Narozhny and Nikitin 2003, Pattyn *et al* 2003, Narozhny *et al* 2006, Surazakov *et al* 2007) but an up-to-date large-scale regional assessment is lacking. Recently in the framework of the GLMS project the new coverage of 924 glacier outlines was created for the Altai region (figure 4(a)). Glacier outlines have been delineated from Landsat (four images for 2000–2002) and ASTER (17 images for 2000–2012). All images were acquired at the end of the ablation season and under cloud-free conditions.

The UGI data dating to 1952, aerial photographs from 1952, ASTER (09/10/2004) and perspective images from the International Space Station (ISS, 09/09/2006) were used to estimate the changes that took place in the 1952–2004 period on the glacier area of the North and South Chuisky ranges (Nosenko *et al* 2010). The glacier surface areas for 2004 were derived from ASTER imagery (figure 4). 256 glaciers with a combined area of 253 km² have been identified in the region in 2004. Estimation of changes in the extent of 126 glaciers with individual areas not less than 0.5 km² in 1952 revealed a 19.7% reduction. However, analysis of mapping errors (the values published in the UGI were verified by re-mapping a sample of 21 test glaciers using the available original air photographs) shows that this may be overestimated by 3.3% and that the combined glacier surface area declined by 16.4% between 1952 and 2004. One of the largest in the Russian Altai, the Bolshoi Taldurinskyi glacier had an area of 28 km² in 1952

(26 km² according to the re-mapping results) but has now separated into two glaciers with a combined area of 22.6 km² (figure 4). The observed glacier retreat is primarily driven by an increase in summer temperatures since the 1980s when air temperatures were increasing at a rate of 0.10–0.13 °C a^{−1} at the glacier tongue elevation (Narozhny and Nikitin 2003, Narozhny *et al* 2006). The detailed analysis could be found in Shahgedanova *et al* (2010).

5. Urals

The Ural Mountains, being a border between Europe and Asia, stretch from north to south over more than 2000 km, representing a great variety of natural conditions. Despite relatively low elevations there are a number of glaciers there, mainly of small size. All glaciers are located to the north from 63°50' N because of the special climate and relief features of the northern part of the Ural mountain system: widespread former glaciation topography is represented by cirques, sharp peaks, crests and troughs.

The UGI comprises data on 143 glaciers, which cover 28.66 km² (table 1). Cirque and niche glaciers prevailed in this region, due to the local topography and very intensive snow-drift which plays an important role in snow accumulation and glacier nourishment (Dolgushin 1961, Troitskiy *et al* 1966). Other types included cirque-valley and hanging glaciers.

Estimation of glacier area changes for the Polar Urals (figure 5(a)) during the second part of the 20th century has been done using ASTER images, UGI data and air photos from 1953 (Shahgedanova *et al* 2012). Analysis of the satellite imagery has shown that in 2000 there were 30 glaciers in the study region with a combined map area of 7.13 km². Overall, the Polar Urals glaciers have lost 22.3% of their UGI area, but the extent of shrinkage varies significantly, between 4% (Bolshoy Usinskiy glacier) and 46% (MGU glacier). Ten glaciers have lost not less than 25% of their area. The two largest glaciers in the region, IGAN (Institute of Geography Academy of Sciences) and MGU (Moscow State University) (figure 5(b)) exhibited the highest absolute and relative loss

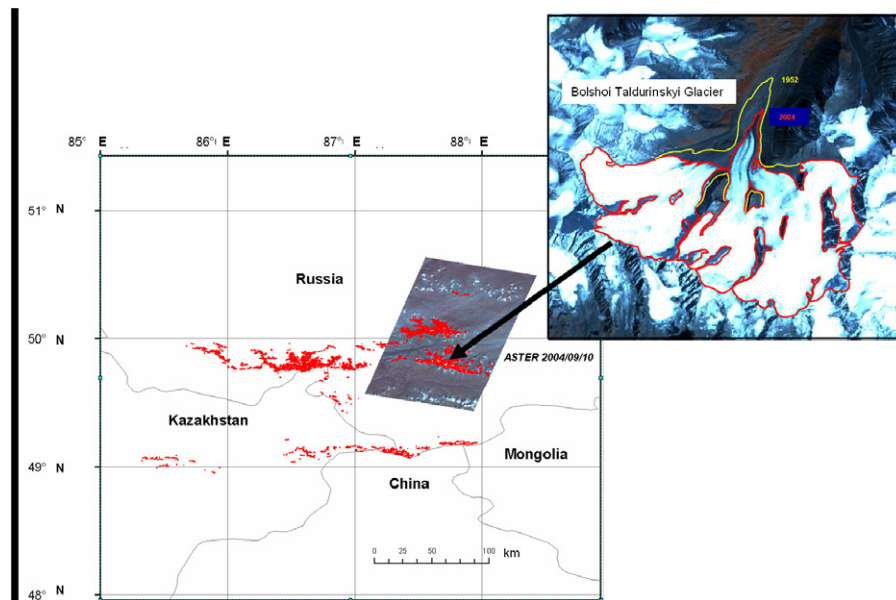


Figure 4. Altai glaciers delineated from space imagery and ASTER 09/10/2004 used for the evaluation of changes in the surface area of glaciers in the North and South Chuya Ridges in 1952–2004 (main map). Retreat of the Bolshoi Taldurinsky glacier, the South Chuya Ridge, between 1952 (air photos) and 2004 (ASTER) (inset map).

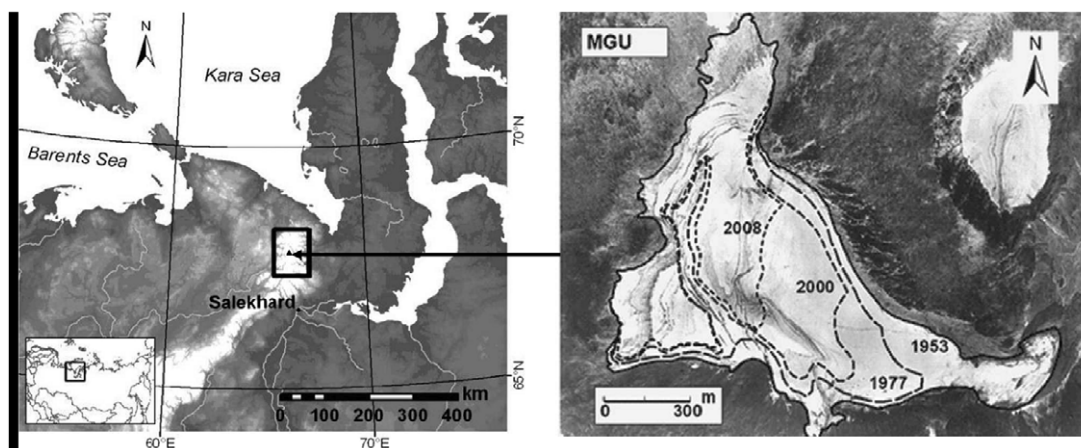


Figure 5. (a) Geographical location of the Polar Urals glaciers. Black rectangles show location of the Polar Urals (inset map) and glacierized study area (main map). (b) Changes in map area of the MGU glacier of the Polar Urals between 1953 and 2008. An aerial photograph from 1953 is used as background.

of area, averaging 34.9%. The cirque glaciers have lost 20% of their UGI area while niche glaciers have lost 14%. The difference in the rates of shrinkage of cirque and niche glaciers may reflect the topographically favorable, shaded locations of the niche glaciers. The difference between the shrinkage rates of glaciers with different aspects is small and close to the accuracy of area change measurements in this dataset. The most extensive shrinkage occurred among corrie-valley and corrie glaciers. Some glaciers completely disappeared (Shahgedanova *et al* 2012).

6. Tien Shan

The Tien Shan Mountains (approximately 40°–45°N; 67°–95°E) are among the main glaciated regions of Eurasia.

According to the UGI compiled using data from the 1950s–1970s, there were 7756 glaciers in the USSR part of Tien Shan with area of 7305.36 km² (table 1). The foothills are densely populated and with mean annual precipitation of 200–600 mm, local, predominantly agricultural economies rely on the glacier-fed rivers for irrigation. Recently about 5000 Tien Shan glaciers have been delineated from ASTER images at the beginning of the 21st century by the Institute of Geography RAS and incorporated in the GLIMS database (figure 6(a)).

Changes in the extent of glaciers and rates of glacier termini retreat in the eastern Terskey-Alatau Range, Tien Shan Mountains have been evaluated using remote sensing techniques (Kutuzov 2012). Changes in the extent of 109 glaciers between 1965, 1990 and 2003 have been estimated

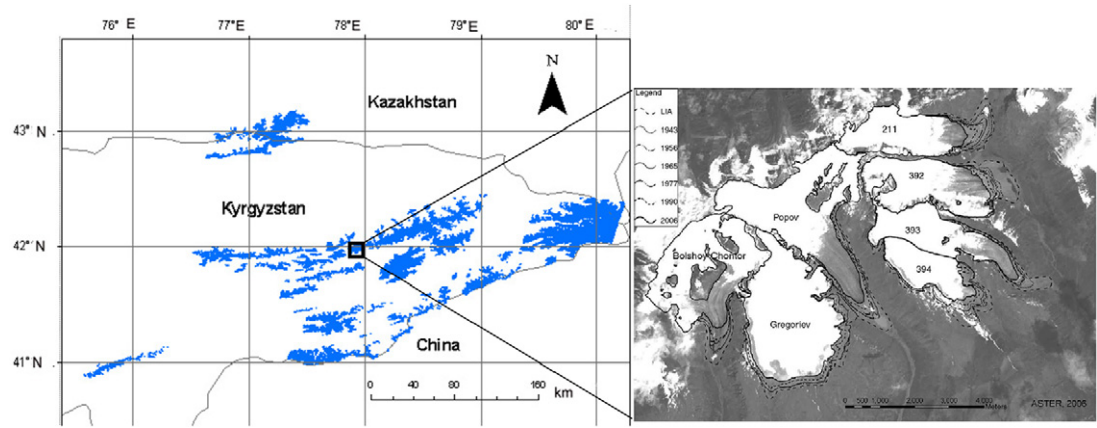


Figure 6. (a) Tien Shan glaciers delineated from space imagery (2000–2012) for the GLIMS project (<http://glims.org>). (b) Outlines of seven Tien Shan glaciers for the LIA, 1943, 1956, 1965, 1977, 1990 and 2006.

Table 2. Glacier area reduction in some glacier systems of Northern Eurasia. Data for comparable time periods are in bold.

Glacier system	All glaciers according to UGI		Number of glaciers analyzed	Period	Glacier area loss	
	Number	Area km ²			km ²	Per cent
Caucasus	2 080	1427.12	1100	1910–1965	540.5	24.7
Caucasus			1100	1965–2001	252.6	17.7
Caucasus			181	2001–2010	10.3	4.65
Pamir Alay	10 995	9828.04	5	1978–1990	3.2	7.8
Pamir Alay			5	1990–2001	5.1	11.6
Pamir Alay			5	1978–2001	8.3	19.4
Tien Shan	7 756	7305.36	109	1965–1990	9.9	8.3
Tien Shan			106	1990–2003	5.2	4.7
Tien Shan			106	1965–2003	15.1	13
Urals	143	28.66	30	1953/60–2000	2.4	22.3
Altai	1 517	923.1	126	1952–2004	56	19.7
Kamchatka	405	874.0	161	1950–2002	57.7	16.6

through delineation of glacier outlines on topographic maps, Landsat TM and ASTER imagery for 1965, 1990 and 2003, respectively. Glacier surface area has decreased by 12.6% of the 1965 value between 1965 and 2003. Detailed mapping of seven glaciers using historical maps and aerial photographs from the 1943–1977 period has enabled glacier extent variations over the 20th century to be identified with a higher temporal resolution (figure 6(b)). Glacier retreat was slow in the early 20th century but increased considerably between 1943 and 1956 and then again after 1977. The post-1990 period has been marked by the most rapid glacier retreat since the end of the LIA. The observed changes in the extent of glaciers are in line with observed climatic warming. The regional meteorological stations have revealed a strong climatic warming during the ablation season since the 1950s at a rate of 0.02–0.03 °C a^{−1} (Kutuzov and Shahgedanova 2009). The results correspond well with other estimations of glacier changes in this region which have been published previously (Kuzmichenok *et al* 2004, Khromova *et al* 2003).

7. Pamir Alay

The Pamir Alay forms part of the extensive high-mountain system of Central Asia, comprising the Pamir–Karakoram–

Hindu-Kush ranges with a glacier area of about 40 × 103 km². The entire system is characterized by similar topography: high peaks, steep slopes and deep narrow valleys.

The regional climate is dominated in winter by air masses originating in the Atlantic–Mediterranean region while in summer the South Asian monsoon has a weak influence. The climate is typical for Central Asia high-mountain regions: dry and cold. Annual precipitation at the plateau level of the Pamir Alay is about 100 mm with a maximum in May–June. The annual air temperature is about −3 °C; −18 °C in winter and 5–8 °C in summer (June–August) (Getker 1985, Glazyrin and Tadzhibayeva 2011).

The first glacier inventory for the Pamir Alay was published in 1955 by R Zabiroy (Dolgushin and Osipova 1989). The next estimation (10 995 glaciers with an area of 9828.04 km²) has been done in the UGI (table 1). Schetinnikov made a glacier inventory for this region in the 1980s (Shchetinnikov 1998). About 8000 glacier outlines have been derived from ASTER images for the first decade of the 21st century for the GLIMS database during 2000–2012 (figure 7).

Historical surveys and recent satellite imagery were used to map and assess glacier recession in the eastern Pamir Alay over the last three decades. For this study we used topographic maps of 1:100 000 scale published in 1943 and 1970; air photos

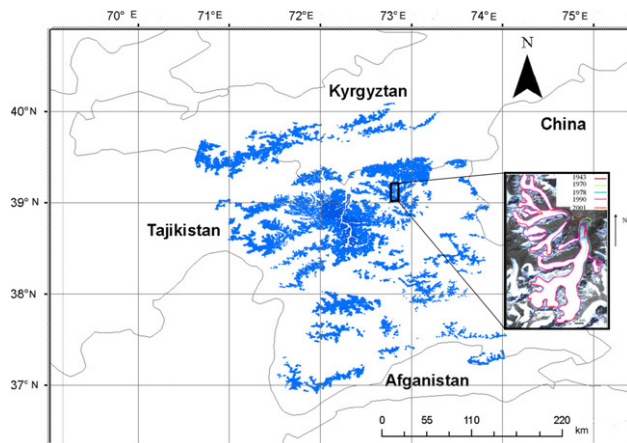


Figure 7. Pamir Alay glaciers delineated from space imagery (2000–2012) for the GLIMS project (<http://glims.org>). Black rectangle shows location of study glaciers in Zulumart Range (inset map).

from 1978 and 1990; space images: from Russian satellites in 1972, 1978, 1980 and 1990 and ASTER data for 2001. Climatic records from the ‘Fedtchenko’ glacier station (4156 m a.s.l., 38.83°N, 72.22°E) and ‘Murgab’ meteorological station (3576 m a.s.l., 38.17°N, 73.97°E) are used for analysis of the climate conditions in the region.

Changes in the area of five glaciers in the Zulumart Range, eastern Pamir Alay reveal an accelerating trend since the end of the 1970s through 2001, as a continuation of glacier wastage and retreat since, at least, the end of the Little Ice Age (figure 7). The glacier area decreased 7.8% during 1978–1990 and 11.6% in 1990–2001. Given the documented sensitivity of Pamir Alay glaciers to summer temperature (Glazyrin *et al* 2002), we consider it likely that these reductions in area were due to increases in summer air temperature. The precipitation in winter (in the humid part of the region) and in summer (in the driest part) has also shown increases, but these did not compensate for the mass loss due to ablation. Decreases in glacier area and retreat of glacier fronts, increased debris-covered area and the appearance of new lakes have been determined (Khromova *et al* 2006). These results agree with documented changes in other mountain and subpolar regions in the Northern Hemisphere and specifically in Central Asia (Vilesov and Uvarov 2001, Vilesov and Seversky 2013, Khromova *et al* 2003, Kuzmichenok *et al* 2004).

8. Kamchatka

According to the UGI, the glaciation of Kamchatka consists of 405 glaciers, with a combined area of about 874 km². Of these glaciers, 38% are located in regions of active volcanism, 44% on ancient volcanic massifs (regions of quaternary volcanism), and less than 19% in non-volcanic regions. The Kamchatka glaciation is located between 50° and 60°N, near the Pacific Ocean and the Sea of Okhotsk, which feed the glaciers with moisture from cyclones related mainly to the Aleutian Low. Within the Kamchatka Peninsula precipitation is one of the highest in Russia and shows seasonal variations, being under the influence of the monsoon (Muraviev 1999). The

temperature and precipitation regimes, other climatic factors, relief and geological structures form the modern marine-type glaciation.

Recently outlines of 529 glaciers have been delineated from Landsat and ASTER imagery for the beginning of the 21st century (figure 8). 388 glaciers have been determined for the northern part of the Middle Ridge while UGI declares 197 glaciers for this area. 190 new glaciers were not mentioned in the UGI, 59 glaciers are parts of 22 disintegrated ones and 36 glaciers from the UGI have not been found in the images.

Changes in surface area of 139 glaciers which are presented in both the UGI and the new coverage created from space images have been examined. ASTER images for 18 August 2002, the data of the UGI and air photos for 1950 have been used. The analysis shows a degradation of the total area of 139 glaciers by 16.6%. But glacier area loss varied strongly within the studied sample, from 0.5% to 60%. One of the biggest glaciers of the studied region, the Slunina Glacier, lost only 0.7% of UGI area (figure 8(b)). During 1950–2002 the average summer air temperatures were increasing and the amount of solid precipitation reduced. It could be the cause of the glacier retreat (Muraviev and Nosenko 2013).

9. Summary and conclusions

Glaciers of Northern Eurasia in the 20th century primarily retreated along with short-lasting periods of steady state or even advance (1910–1920s and 1960–1970s). In the end of the century the glacier degradation strengthened far and wide. Results of the analysis indicate the steady trend of glacier shrinkage in all mountain regions for the second part of the 20th century. Glacier area loss for the studied regions varies from 13% (Tien Shan) to 22.3% (Polar Urals) (table 2, figure 9). There is also a very large variability in the degree of individual glacier reduction, very much depending on the morphology and local meteorological conditions. The common driver, most likely, was an increase in summer air temperature. The data of the meteorological stations located close to glaciers show that the average summer air temperatures was increasing in all studied regions between the middle of the 20th century and the beginning of the 21st century (Kutuzov and Shahgedanova 2009, Shahgedanova *et al* 2010, 2012, Nosenko *et al* 2013, Muraviev and Nosenko 2013). In some regions like the Caucasus or the eastern Pamir Alay, the precipitation has shown increases, but these did not compensate for the mass loss due to ablation (Khromova *et al* 2006, Nosenko *et al* 2013).

The results of this work demonstrate the use of satellite images (table 3) for the present glaciation assessment. The analysis allowed estimating numerically the scale of area reduction for glaciers of different morphological types, aspects and elevation in different geographical regions.

The UGI, which is now available online as a part of the WGI, provides data on 28 884 glaciers of the former Soviet Union in the mid-20th century, potentially serving as an important baseline for the investigation of recent glacier changes. The quality of this information, however, is known to vary between regions and it is important to evaluate the quality

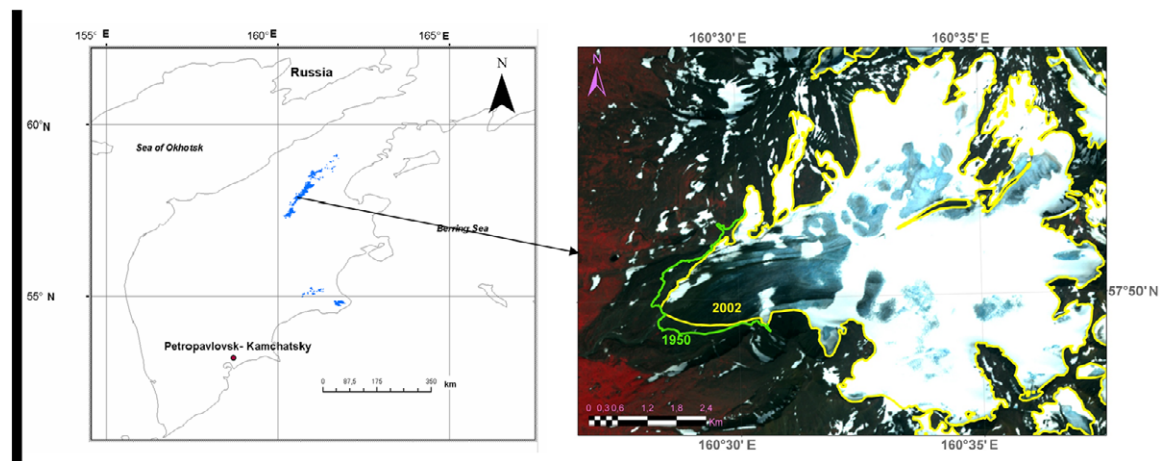


Figure 8. (a) Glaciers delineated from Landsat and ASTER imagery for the beginning of the 21th century (in blue). (b) Change of the outline position of Slunina Glacier: yellow line—ASTER 18/08/2002, green line—air photo, 1950.

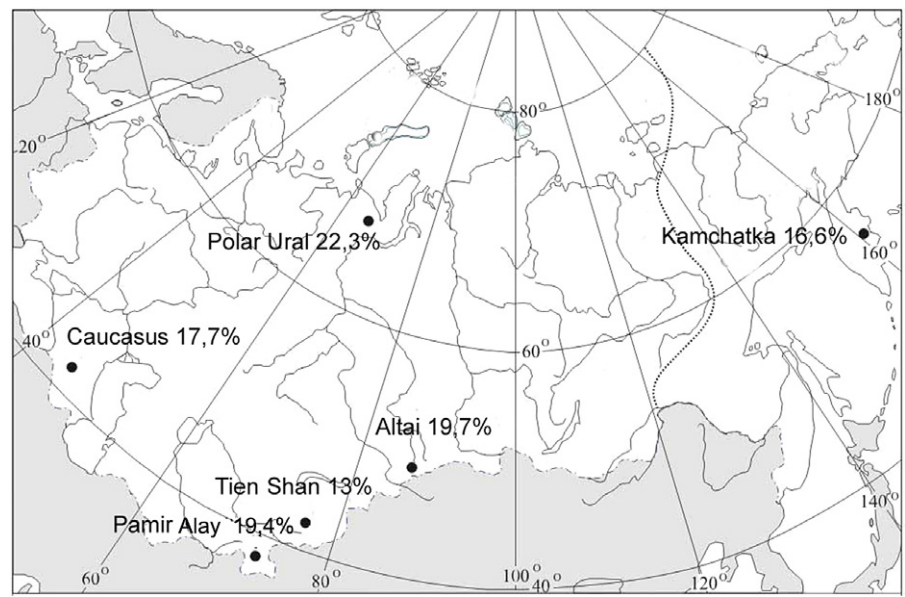


Figure 9. Glacier area shrinkage (in per cent) in the studied mountain regions of Northern Eurasia in the second part of the 20th century.

Table 3. Imagery used for the assessment of glacier area changes.

Region	Sensor	Date
Caucasus	Landsat ETM+	12/09/2000, 08/08/1999
		15/09/2001, 15/08/2004,
	ASTER	25/09/2004, 29/09/2010
		09/10/2004
Altai	ISS	09/09/2006
Polar Urals	ASTER	14/07/2000
Tien Shan	Landsat TM	31/07/1990
	ASTER	10/09/2003
Pamir Alay	ASTER	23/08/2001
Kamchatka	ASTER	18/08/2002

of the UGI before using it as benchmark data for each study area.

The results of this study—continuing glacier recession—correspond well with other studies performed in different areas

of Northern Eurasia and elsewhere. Accurate determination of these glacier changes can be used to assess regional hydrological responses. Changes in regional water supply will have important consequences for agriculture, as well as for hydroelectric plants.

Acknowledgments

This overview is based on results of our studies supported for different time periods through the EU INTAS grant No. 1000013-8593, NASA Grant NNG04GM09G for the GLIMS Core Functions, grants of the Russian Foundation for Basic Research Nos. 10-05-00242, 11-05-91159-NSFN-a and 11-07-00389-a, the Program of Presidium of Russian Academy of Sciences No 4 and the Program of Department of Earth Sciences Russian Academy of Sciences No 12. The anonymous reviewers are thanked very much for their very

useful comments. We also thank Natalia Zverkova for help with an illustration preparation.

References

- Barry R G 2006 The status of research on glaciers and global glacier recession: a review *Prog. Phys. Geogr.* **30** 285–306
- Bishop M P et al 2004 Global land ice measurements from space (GLIMS). Remote sensing and GIS investigations of the Earth's cryosphere *Geocarto Int.* **19** 57–85
- Burgess D and Sharp M 2004 Recent changes in areal extent of the Devon Ice Cap, Nunavut, Canada *Act. Antar. Alp. Res.* **36** 261–71
- Catalog of Glaciers of the USSR, 1965–82 (Katalog lednitov USSR) vol 1–69 (Leningrad: Gidrometeoizdat) (in Russian)
- Chernova L P, Khromova T E, Zverkova N M, Nosenko G A and Muraviev A J 2011 Glaciological provinces of Russia and the belt of minimal snowiness on the continent *Ice and Snow V* **2** 5–11 (in Russian)
- Climate and Cryosphere (CliC) Project Implementation Strategy Document 2007 *WCRP Informal Report No* 126 WMO/TD-No 1301 http://ipo.npolar.no/reports/archive/wcrp_inf_2007_126_rev1.pdf, www.climate-cryosphere.org/index.php/media-gallery/mediaitem/346-wcrp-inf-2007-126-rev1
- Dolgushin L D 1961 Main features of the modern glaciation of the Urals *IASH Publ* 54: *General Assembly of Helsinki—Snow and Ice* pp 335–47
- Dolgushin L D and Osipova G B 1989 *Ledniki (Glaciers)* (Moscow: Mysl Publishers) p 448 (in Russian)
- Dyrgerov M B 2005 *Glacier Mass Balance and Regime Data of Measurements and Analysis* (Boulder, CO: University of Colorado) Institute of Arctic and Alpine Research Occasional Paper No 55 (268 pp) and Supplement to Occasional Paper No 55, updated January 2005 at www.nsids.org
- Electronic version of the glacier catalogue of the USSR 2010 www.webgeo.ru/index.php?r=47
- Getker M I 1985 Snow resources in Central Asia mountains *Thesis, Doctoral degree* (Institute of Geography Russian Academy of Sciences), Moscow (in Russian)
- Glazyrin G, Braun L N and Shchettinnikov A S 2002 Sensitivity of mountain glacierization to climate changes in central Asia *Z. Gletxcherkunde Glazialgeol.* **38** 71–6
- Glazyrin G E and Tadzhibayeva U U 2011 Climate change in the high mountains of Central Asia in the late XX century *Ice and Snow V* **2** 12–6 (in Russian)
- Granshaw F D and Fountain A G 2006 Glacier change (1958–1998) in the North Cascades North Part Complex, Washington, USA *J. Glaciol.* **52** 251–6
- Khromova T E, Dyrgerov M B and Barry R G 2003 Late-twentieth century changes in glacier extent in the Ak-shirak Range, Central Asia, determined from historical data and ASTER imagery *Geophys. Res. Lett.* **30** 1863
- Khromova T E, Osipova G B, Tsvetkov D G, Dyrgerov M B and Barry R G 2006 Changes in glacier extent in the eastern Pamir, Central Asia, determined from historical data and ASTER imagery *Remote Sens. Environ.* **102** 24–32
- Kotlyakov V M, Khromova T E, Zverkova N M, Chernova L P and Nosenko G A 2011 Two new glacier systems in Northeastern Eurasia *Dokl. Earth Sci.* **437** 374–9
- Kutuzov S 2012 Glacier area and volume changes in the Terskei Ala-Tau Range for the second part of XX century *Ice and Snow V* **1** 5–15 (in Russian)
- Kutuzov S and Shahgedanova M 2009 Glacier retreat and climatic variability in the eastern Terskey-Alatau, inner Tien Shan between the middle of the 19th century and beginning of the 21st century *Glob. Planet. Change* **69** 59–70
- Kuzmichenok V, Aizen N, Surazakov A and Aizen E 2004 Assessment of glacial area and volume change in Tien Shan (Central Asia) during the last 60 years using geodetic, aerial photo, ASTER and STRM data *American Geophysical Union Trans. Eos. (Abstracts, Fall Meeting 2004 Supplement)* vol 47 p F110
- Lang H R and Welch R 1999 *ATBD-AST-08 Algorithm Theoretical Basis Document for ASTER Digital Elevation Models* (Standard Product AST14), Version 3.0 http://eospsso.gsfc.nasa.gov/eos_homepage/for_scientists/atbd/docs/ASTER/atbd-ast-14.pdf
- Muraviev A Y and Nosenko G A 2013 Glaciation change in northern part of the Middle Range on Kamchatka Peninsula in the second half of the XX century *Ice and Snow V* **2** 5–12 (in Russian)
- Muraviev Y D 1999 Present-day glaciation in Kamchatka—distribution of glaciers and snow *Cryospheric Studies in Kamchatka II* (Institute of Low Temperature Science, Hokkaido University) pp 1–7
- Narozhny Y K, Nikitin S A and Borodavko P S 2006 Glaciers of the Belukha mountain knot: Mass exchange, dynamics, and ice resource distribution *Materialy Glyatsiologicheskikh Issledovaniy (Data of Glaciological Research)* **101** 117–27 (in Russian)
- Narozhny Y K and Nikitin S A 2003 Contemporary glaciation in the Altai at the beginning of the 21st century *Materialy Glyatsiologicheskikh Issledovaniy (Data of Glaciological Research)* **95** 93–101 (in Russian)
- Nosenko G, Khromova T, Rototaeva O and Shahgedanova M 2013 Respond of glaciers in Central Caucasus to temperature and precipitations changes in 2001–2010 *Ice and Snow V* **1** 24–33 (in Russian)
- Nosenko G, Khromova T, Muravyev A, Narozhny Y and Shahgedanova M 2010 Using historical data and modern space imagery for assessment of glacier area changes in Altai mountains *Ice and Snow V* **2** 19–24 (in Russian)
- Omura A 2009 Completing the World Glacier Inventory *Ann. Glaciol.* **50** 144–8
- Pattyn F, De Smedt B, De Brabander S, Van Huele W, Agatova A, Mistrukov A and Declair H 2003 Ice dynamics and basal properties of Sofyiskiy glacier, Altai mountains, Russia, based on DGPS and radio-echo sounding surveys *Ann. Glaciol.* **37** 286–92
- Panov V D 1993 *Evolution of Modern Glaciation of Caucasus* (St. Petersburg: Gidrometeoizdat) p 430 (in Russian)
- Podozerski K 1911 *Glaciers of Caucasus (Inventory of Caucasus Glaciers* vol 29) (Tiflis: Zap. KORGO) p 200 (in Russian)
- Racoviteanu A E, Paul F, Raup B, Khalsa S J S and Armstrong R L 2009 Challenges in glacier mapping from space: recommendations from the Global Land Ice Measurements from Space (GLIMS) initiative *Ann. Glaciol.* **50** 53–70
- Rototaeva O, Nosenko G, Tarasova L and Khmelevsky I 2006 Caucasus *Oledenenie Severnoi i Tsentralnoi Evrazii v Sovremennuyu Epohu (Glaciation in Northern and Central Eurasia at Present Time)* ed V M Kotlyakov (Moscow: Nauka) pp 141–62
- Shahgedanova M, Khromova T, Nosenko G and Muravyev A 2010 Glacier shrinkage and climatic change in the Russian Altai from the mid-20th century: an assessment using remote sensing and PRECIS regional climate model *J. Geophys. Res. Atmos.* **115** D16107

- Shahgedanova M, Nosenko G, Bushueva I and Ivanov M 2012 Changes in area and geodetic mass balance of small glaciers, Polar Urals, Russia, 1950–2008 *J. Glaciol.* **58** 211
- Shchetinnikov A 1998 *Morfologiya i rezhim lednikov Pamiro-Alaya (The Morphology and Regime of Pamir-Alai Glaciers)* (Tashkent: Central Asia Hydro-Meteorological Institute) p 219 (in Russian)
- Solomina O N 2000 Retreat of mountain glaciers of northern Eurasia since the Little Ice Age maximum *Ann. Glaciol.* **31** 26–30
- Stokes C R, Gurney S D, Shahgedanova M and Popovnin V 2006 Late-20th-century changes in glacier extent in the Caucasus mountains, Russia/Georgia *J. Glaciol.* **52** 99–109
- Surazakov A B, Aizen V B, Aizen E M and Nikitin S A 2007 Glacier changes in the Siberian Altai Mountains, Ob river basin, (1952–2006) estimated with high resolution imagery *Environ. Res. Lett.* **2** 1–7
- Troitskiy L S et al 1966 *Oledenenie Urala (Glaciation of the Urals)* (Moscow: Nauka) (in Russian)
- Vilesov E N and Uvarov V N 2001 *Evolutsiya sovremennogo oledeneniya Zailiyskogo Alatau v XX veke (The Evolution of Modern Glaciation of the Zailiyskiy Alatau in the 20th Century)* (Almaty Kazakh State University) p 252 (in Russian)
- Vilesov E N and Seversky I S 2013 Degradation of glaciers in Dzungarian (Zhetisu) Alatau *Ice and Snow V* **2** 12–21 (in Russian)
- WGMS 2008 *Global Glacier Changes: Facts and Figures* ed M Zemp, I Roer, A Kääb, M Hoelzle, F Paul and W Haeberli (Zurich: UNEP, World Glacier Monitoring Service) p 88 (www.grid-unep.ch/glaciers/)