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Glacier area and mass changes since 1964 in the Ala Archa Valley, Kyrgyz Ala-Too, northern Tien Shan

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Изменение площади и массы ледников в долине Ала-Арча в Киргизском хребте на Северном Тянь-Шане с 1964 г.

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Геодезический баланс массы, изменения ледников, спутник Corona, Тянь-Шань, цифровая модель поверхности (DTM), ASTER.

Glaciers are an important source of fresh water for Central Asia as they release water during the summer months when precipitation is low and water demand highest. Many studies address glacier area changes but only changes in glacier mass can be directly linked to climate and runoff. Despite the importance, investigations of glacier mass changes have been restricted to only a few glaciers in the Tien Shan until now. Geodetic mass balance measurements are suitable to complement and extend existing in-situ measurements. In this study, both area and mass changes of the ~40 km^2 glacier ice in the Ala Archa Valley, Kyrgyz Tien Shan, were investigated using 1964 and 1971 stereo Corona, 2012 stereo ASTER, the SRTM digital terrain model and other optical data such as Landsat ETM+ or Rapid Eye. In addition, ice thickness was modeled taking the basal shear stress and the glacier surface topography into account. The results indicate an area loss of 18.3±5.0% from 1964 until 2010 with continuous shrinkage in all investigated periods. The glacier's mass balance was −0.45±0.27 m w.e. a^{-1} for the period 1964–1999 and −0.42±0.66 m w.e. a^{-1} for 1999–2012. Golubin Glacier showed a possible slight mass gain for 1964–1971 and a decelerated mass loss for the 1999–2012 period. This is in good agreement with existing in-situ measurements exiting from 1962 until 1994 and since 2010. The overall ice volume was estimated to be 1.56±0.47 km^3 of ice in the year 2000. Hence, the entire ice would be lost by 2100 if the mass loss would continue at the same rate.

Дана оценка изменения площади и массы ледников в долине Ала-Арча в Киргизском Тянь-Шане с помощью стереоснимков спутника Corona 1964 и 1971 гг., стереоснимков ASTER 2012 г., цифровой модели земной поверхности SRTM и других оптических данных. С 1964 по 2010 г. ледники непрерывно сокращались и потеряли 18,3±5,0% общей площади. Масса ледника Голубина в 1964–1971 гг. незначительно росла; в 1999–2012 гг. его сокращение замедлилось.

Introduction

The Tien Shan and its cryosphere is the origin of the large rivers Amu-Darya, Syr-Darya, Chu, Ili or Tarim which contribute to huge endorheic lakes like Aral Sea or Lake Balkhash or terminate in the steppe or desert. These rivers are the artery for the region and, in addition, many large cities like Urumchi/Xinjiang, China, Tahskent/Uzbekistan, Almaty/Kazakhstan or Bishkek, the capital of Kyrgyzstan are located on the foothills of this mountain range and directly depend on the runoff from nearby mountains. Runoff from glaciers is especially important in summer and early autumn when the water demand is high and the seasonal snow of the mountains melted. No certain numbers about the share of glacier melt to the overall runoff exist but estimates show an average annual contribution of less than 10% for Syr-Darya and about 40% for the Tarim River [47]. Modelling results of glacier runoff in different basins of the Tien Shan show first an increase of runoff with temperature increase followed by a reduction with the continued glacier shrinkage even with continuous temperature rise [29]. It is therefore of high importance to study the ice storage of the glaciers and their past and possible future evolution.

The temperature increased on average since the 1950s accompanied by a slight but not significant increase in precipitation in most parts of the Tien Shan [2, 6, 11]. Concomitantly, glaciers of the Tien Shan shrank like in many other parts of the world since the little ice age [46] with a pronounced recession in the last decades [2, 3, 7, 11, 20, 31]. The detected area loss since the 1950s is higher in the more humid areas in northern Tien Shan than in the more arid regions of the central and eastern Tien Shan [34, 47]. Declassified imagery from the 1960s and 1970s were found to be suitable to extend the analysis back in time and to evaluate glacier outlines based on topographic maps [10, 14, 35, 36].

Area changes show an indirect signal to climate while the glacier mass balance can more directly be related to climate and hydrology. Existing mass balance measurements in the Tien Shan indicate a pronounced mass loss since the mid-1970s which is highest at Tuyuksu Glacier situated in Ile Alatau (also: Zailijskij Alatau) at the northern margin of the Tien Shan [17, 50]. However, mass balance measurements exist just for a few glaciers and only Tuyuksu Glacier and Urumchi Glacier No. 1 in eastern Tien Shan were measured continuously. Several other measurements, such as at Abramov Glacier (Pamir Alay, southern Kyrgyzstan) and Karabatkak Glacier (Terskey Alatau) were interrupted since the collapse of the Soviet Union. Between 1968 and 1994 in-situ measurements were also performed at Golubin Glacier in Ala Archa Valley/ Kyrgyz Alatau [1, 50]. The mass balance was found to be predominantly negative. Mass balance measurements at Golubin Glacier were re-established in 2010 and showed a slightly positive value for 2010/2011 [50]. However, no mass balance information exists between 1994 and 2010.

Geodetic mass balance estimations are suitable to evaluate, complement and extend existing in-situ measurements [15, 51]. National digital elevation models (DEMs), the near global SRTM3 DEM, as well as DEMs derived from optical stereo data such as SPOT, ASTER or Corona were found to be suitable for this task [9, 15, 41]. However, careful co-registration and an estimation of the penetration of the SRTM C-band radar beam into snow and ice are required to reduce uncertainties [12, 24, 37, 42].

A prerequisite for hydrologic and glaciological modelling purposes is not only the knowledge about the change in volume but also about the glacier volume and its distribution over the glaciers. The glacier thickness can be measured in the field e.g. using ground penetrating radar (GPR). This is, however, only feasible for a small numbers of glaciers. Simple models are required to estimate the current and future glaciers volume for a large number of glaciers simultaneously. Promising approaches to model the glacier bed topography based on the surface topography, glacier outlines and possibly additional information about glacier mass turnover and the mass balance gradient [22, 33].

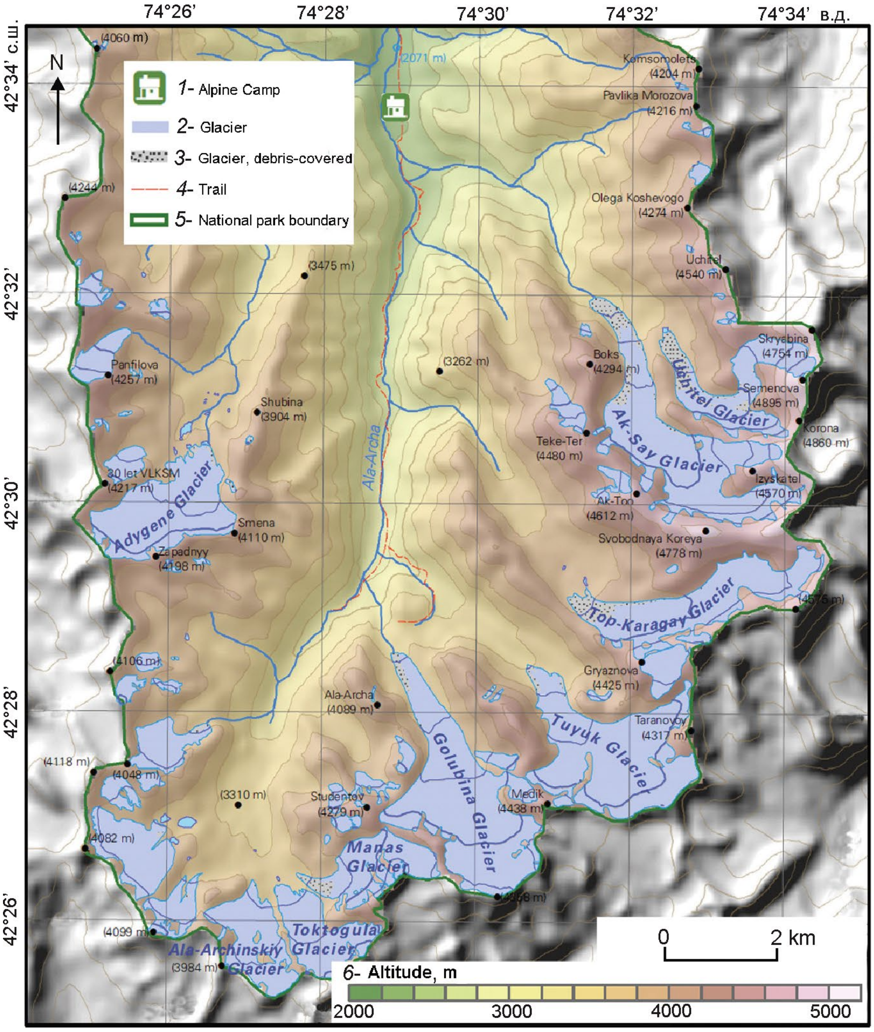
The aim of this study is (1) to reassess and extend in time the presented data about area changes in Ala Archa Valley [7] and (2) present estimations about the absolute glacier volume and glacier mass changes for different periods between 1964 and 2012 using remote-sensing derived information.

Study area

The *Kyrgyz Ala-Too* (*Kyrgyz Range)* represents the north-western part of Tien Shan with an east-west extent of over 400 km [5]. The water released at the northern slope drains into the river Chu which is the main artery for the (semi-) arid lowlands in Kyrgyzstan and Kazakhstan including Bishkek, the capital of Kyrgyzstan. At its northern slope, 40 km south of Bishkek, the study area of this work can be found: the *Ala Archa National Park* (74°24' E – 74°34' E; 42°24' N – 42°36' N, Fig. 1). This nature reserve was established in 1976 and constitutes a total area of 194 km² and extends along the Ala-Archa river basin and the surrounding with altitudes ranging from 1,500 m at its entrance up to 4,895 m at Semenova-Tyan-Shanskogo Peak. Glaciers cover an area of ~33.3 km² and extend over an altitude range of 3,310–4,760 m (2010). The annual precipitation increases from less than 400 mm, measured at Bishkek station at an elevation of 771 m asl., to about 700 mm at the glaciers [1]. The maximum precipitation occurs in late spring to early summer (see Fig. 1).

Data and methods

Declassified stereo Corona KH-4A and KH-4B images were used to obtain the glacier area and surface elevation for the years 1964 and 1971 (Table 1). Corona was a spy satellite mission operating from 1960 until the mid-1970s and was mainly designed to acquire images of the former USSR and other communist countries, such as China [34]. The images have a relatively high resolution of ~7 m (KH-4) and up to 2 m (KH-4B). The main disadvantages are the panoramic distortion and unstable acquisition parameters [19]. The utilized images were acquired at the end of the ablation season and had suitable sow conditions. Few clouds occurred at the 1964 images but all glaciers were cloud free except Golubin Glacier where the very distal part of the tongue was hidden. The 1971 data only cover a smaller part of the study region and only Golubin Glacier was investigated with the 1971 DTM data. Further data used are the widespread Landsat images which are freely available in an orthorectified level (www.usgs.gov). The most recent glacier extents were delineated from 2010 Rapid Eye data which has



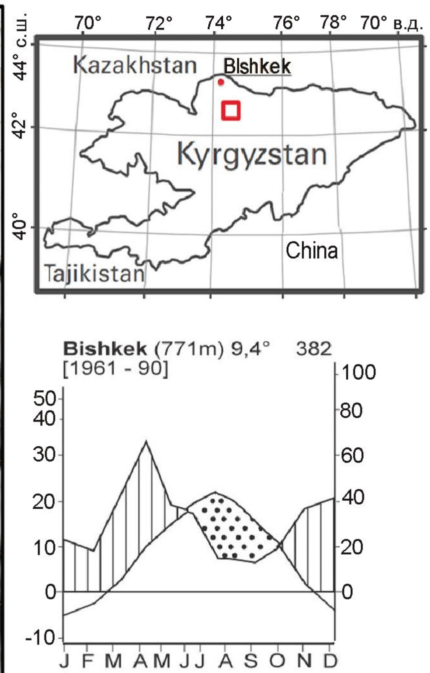


Fig. 1. Map of the study area (source: [21]), climate diagram of Bishkek

Рис. 1. Карта района исследований [21], климатическая диаграмма г. Бишкек.

1 – альплагерь; *2* – ледники; *3* – поверхностная морена; *4* – тропа; *5* – границы Национального парка

Table 1. **Utilized data**

Date	Satellite/Sensor/Product	Resolution, m	Spectral characteristics	Usage
20.09.1964	Corona KH-4	~7	Pan	Glacier delineation, DEM generation
16.09.1971	Corona KH-4B	~3	Pan	Glacier delineation, DEM generation
15.07.1994	Landsat TM	30	VNIR, SWIR, TIR	Glacier delineation
February 2000	SRTM C-Band (original)	90	–	Glacier surface elevation
February 2000	SRTM C-Band (void-filled)	90	–	Ice thickness
08.06.2001	Landsat ETM+	30/15	VNIR, SWIR, TIR, Pan	Reference, Glacier delineation
01.08.2003 17.08.2003	Terra ASTER	15	VNIR, SWIR, TIR	Glacier delineation
06.09.2010	Rapid Eye	6.5	VNIR	Glacier delineation
2012	Terra ASTER	15	VNIR, SWIR, TIR	Glacier surface elevation

a ground resolution of 6.5 m. Stereo ASTER from 2012 and the original SRTM-C band DTM data with a resolution of 90 metre was used to estimate the mass changes in addition to the Corona data. All data were co-registered to the 2001 pan-sharpened ETM+ scene. For the estimation of the glacier volume and the bed topography the void filled version of the SRTM DTM by the Consultative Group for International Agriculture Research Consortium for Spatial Information (CGIAR-CSI), version 4, was used.

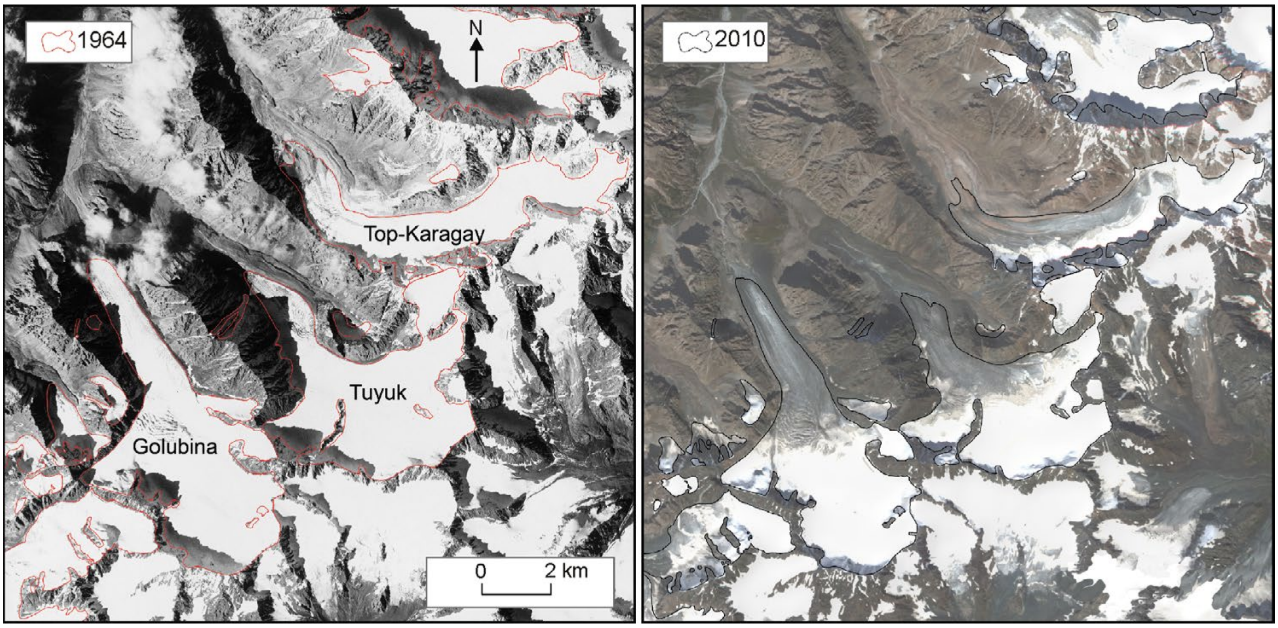


Fig. 2. Golubin, Tuyuk and Top-Karagay glaciers in 1964 (Corona KH-4A) and 2010 (Rapid Eye)
Рис. 2. Ледники Голубина, Туюк и Топ-Карагай в 1964 г. (Corona KH-4A) и 2010 г. (Rapid Eye)

Glaciers were delineated manually as most of the available scenes were panchromatic (Corona) or had no short-wave-infrared channel (RapidEye) which is needed for automation. A few glaciers had some debris cover at their tongues which made the correct identification not straight forward. Glacier melt water streams, the shaded relief, and a 2007 ALOS PALSAR coherence image [cf. 25], the difference image of the digital terrain models (DTMs) and the high resolution of the utilized imagery helped to identify the margin correctly (Fig. 2). We estimated the uncertainty based on the buffer method [cf. 13] choosing a buffer size of half a pixel for the well registered Landsat and Rapid Eye data and one pixel size for the Corona data. The resultant uncertainties vary between 2.2% for Corona KH-4B and 8.2% for the Landsat TM data. This is within the range of previously reported uncertainties of semi-automated methods [13, 39, 40] and manual delineation [38].

The SRTM DTM was chosen as the master DTM for assessing volume changes as it was proven to be of suitable accuracy [23] and has been applied for many studies assessing glacier volume changes [e.g. 9, 42]. The original non-void filled version was used as no information about the data used for void filling was available. Most glaciers were not or only slightly affected by the data voids with the maximum of less than 30% voids in the upper accumulation area of one glacier. A DTM based on 2012 stereo ASTER data was automatically generated using PCI Geomatica to assess the recent mass changes. DTMs from stereo Corona data were generated using the Remote Sensing Software Package Graz (RSG) which has been proven to provide good results for Corona data [15, 42]. About 20 ground control points (GCPs) based on the 2001 Landsat scene were selected for each Corona scene. The automatically identified tie points (TPs) required for image matching were visually checked and manually improved if necessary. The final x, y residuals of the GCPs varied between ~15 to 20 m and the z-residual was ~50 m for each scene [21]. These values are acceptable given the uncertain image acquisition parameters and the large panoramic distortion of the Corona images. Small data gaps occurred due clouds, cast shadow and snow cover in the accumulation regions of few glaciers but also in small areas in the ablation of Golubin and Ak-Say glaciers. Overall more than 80% of the glaciated terrain was covered by the 1964 DTM while the 1971 DTM had almost no gaps.

All DTMs need to be carefully co-registered in order to minimize biases. First, tilts were eliminated based on calculated trend surfaces using stable terrain [12, 42]. Thereafter the DTM were horizontally and vertically co-registered following [37]. Values ±60 m (which is similar to 3σ of the DTM differences of the stable terrain) were omitted assuming that larger deviations are unrealistic for glaciers [cf. 15, 26]. Data voids were filled with the

Table 2. **Change in glacier area 1964–2010**

Показатели	1964	1971	1994	2003	2010
Area, km²	40.9±1.8	39.9±0.9	35.8±3.2	34.6±1.7	33.4±0.8
Da/period, km²	–	−1.0±2.0	−4.1±3.3	−1.2±3.6	−1.2±1.9
Δa/yr rel, %	–	−0.27±0.68	−0.45±0.37	−0.37±1.0	−0.49±0.77
Δa (rel.) since 1964, %	–	−2.4±6.3	−12.5±9.0	−15.4±6.0	−18.3±5.0

mean value of the surrounding pixels in the ablation region and no vertical changes were assumed for the voids in the upper accumulation area. The uncertainty was estimated based on the Normalized Median Absolute Deviation (NMAD) of the non-glacierized terrain with a slope less than 25° [12, 43]. Higher slopes were omitted as it is known that the uncertainty strongly increases for steep slopes. The NMAD is more robust and less influenced by outliers than the typically used standard deviation and also proven to be a suitable measure of the uncertainty for volumetric change assessments. Glacier volume changes were converted to mass using a density of 850±60 kg m^{-3} [cf. 30].

In order to estimate the glacier volume and the thickness distribution the glacier bed topography was calculated following the approach by [33] which needs as an input a DTM and digital branch lines only. The approach is based on the shallow ice approximation [18]. The glacier thickness is mainly dependent on the glacier slope (α) and the basal shear stress (τ) and can be calculated as follows:

$$d = \tau/(\rho g f \sin\alpha)$$

with ρ being the ice density (900 kg m^{-3}), g the gravitational acceleration (9.81 m s^{-2}). The variable f is the glacier shape factor and was set to 0.8 which is typical for valley glaciers. The basal shear stress was calculated following [28] based on the vertical distance of a glacier with a maximum stress of 150 hPa. The glacier volume was only calculated for the glaciers larger than 0.5 km² as the uncertainty especially for the very small glaciers is high. However, these glaciers have usually a thickness of few a metres only and contribute, hence, only very little to the overall ice volume which is well within the estimated uncertainty of 30% [33].

Results

Glacier characteristics and area change. Fifty-one glaciers larger than 0.02 km² with an overall area of 40.9±1.8 km² were identified on the 1964 Corona KH-4A image. Glaciers smaller than 0.5 km² comprise 80% of the glacier number but only ~13% of the total ice cover (Table 2). In contrast, the three largest glaciers with an area > 5 km² cover ~43%. Overall, the glaciers in Ala Archa Valley vacated an area of 7.5±2.0 km² (18.3±5.0%) during the period 1964–2010 (Table 3). The number of glaciers increased from 51 to 62 due to disintegration of several glaciers. The glaciers shrank during all investigated sub-periods with the lowest shrinkage rates measured between 1964 and 1971 (see Fig. 2). Until 2010, the small glaciers lost on average almost 50% (~1.1% a^{-1}) of their initial area while the large glaciers shrank only ~13% (~0.3% a^{-1}). These are typical glacier characteristics and can also be found in other parts of Northern Tien Shan (Ile and Kungöy Alatau [2, 11]) and many other mountain ranges on Earth [e.g. 13, 40]. However, the rates of change vary (Fig. 3).

Table 3. **Glacier area change with respect to the size classes**

Size class	Glaciers 1964		Area, km²		% of total area	Area change	
	count	% of total	1964	2010	2010	km²	%
< 0.2	31	62	2.1	1.1	3.2	−1.0	−48.6
0.2–< 0.5	10	8	3.6	1.7	4.9	−1.6	−49.4
0.5–< 1.0	2	4	1.5	1.3	3.8	−0.3	−17.4
1.0–< 5.0	5	10	16.4	14.1	42.4	−2.3	−13.9
5.0	3	6	17.3	15.2	45.7	−2.1	−12.1
Total	51	100	40.5	33.3	100	−6.5	−18.3

Glacier volume and mass changes. Glaciers in Ala Archa Valley contained 1.56±0.47 km³ of ice in the year 2000 which leads to an average thickness of about 46 metres. Ak-Say (0.35±0.10 km³) and Golubin (0.32±0.09 km³) are the glaciers with the largest ice volume. Ak-Say, Golubin, Tuyuk and Top-Karagay glaciers have likely a maximum thicknesses of around 200 m and above (Fig. 4).

The glaciers in Ala Archa Valley showed a clear volume and mass loss during the 1964–2012 period (Table 4, Fig. 5). Overall, the glaciers lost a vol-

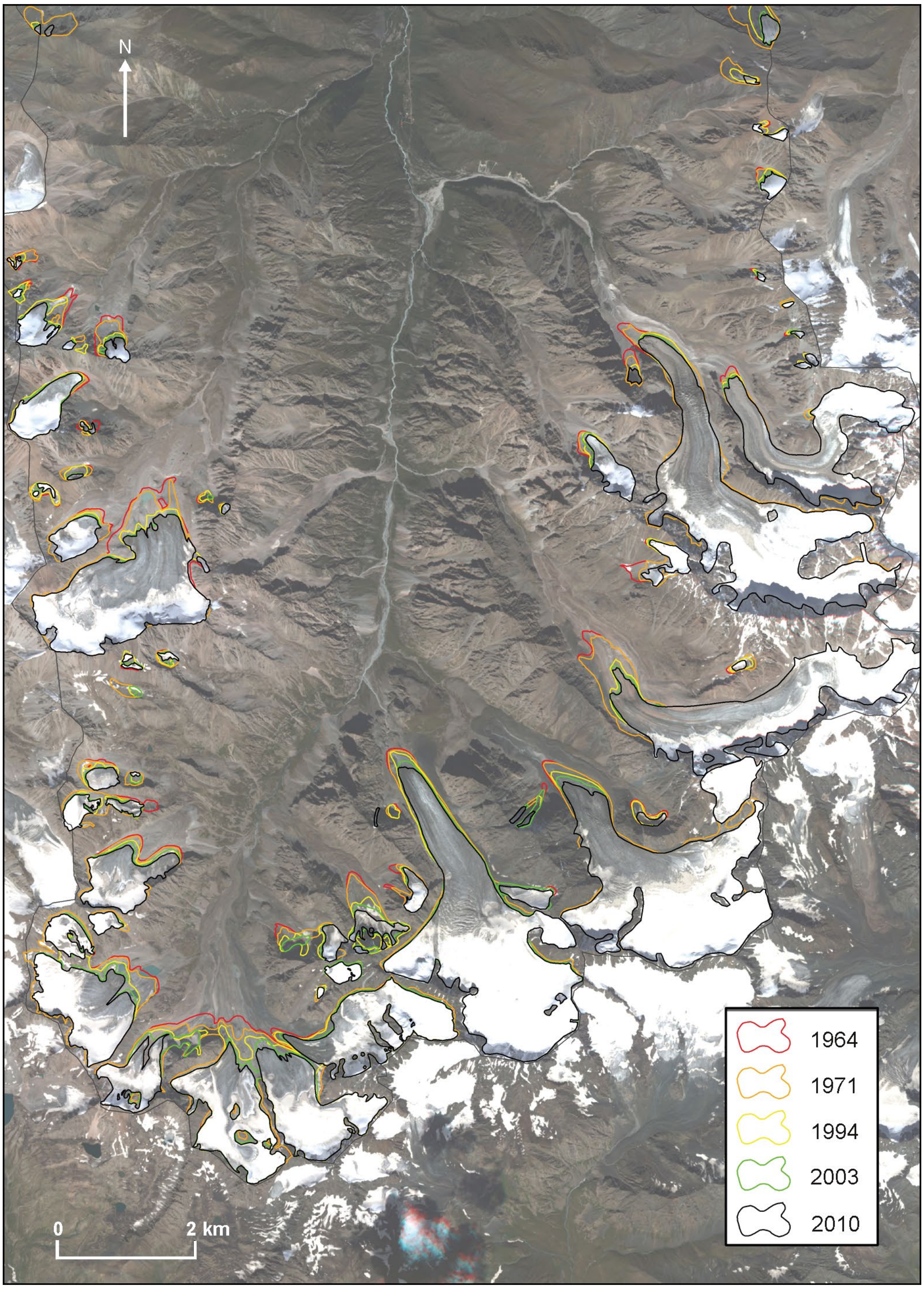


Fig. 3. Changes in glacier area 1964–2010. Background: Rapid Eye image from 2010 in natural colours

Рис. 3. Изменения площади ледников в 1964–2010 гг. В качестве фона использован снимок Rapid Eye 2010 г. в естественных цветах

ume of 0.98±0.56 km³ in the last approximately 50 years. This is almost two thirds of the estimated volume in 2000. The average mass balance was ~−0.45 m w.e. a^{-1} since 1964. The mass loss of especially Golubin Glacier and most of the other glaciers was likely less in in the 1999–2012 period than before. However, the differences are not significant considering the uncertainty (see Table 4). A possible slight mass gain (~+0.05 m w.e. a^{-1}) was found between 1964 and 1971 for Golubina Glacier (Fig. 6) but the uncertainty is here much larger than the signal. Adygyne Glacier showed the highest mass loss of the investigated larger glaciers for both investigated periods (~0.66 m w.e. a^{-1}).

Discussion and conclusions. The presented results on area and area changes (−18.3±5.0% or

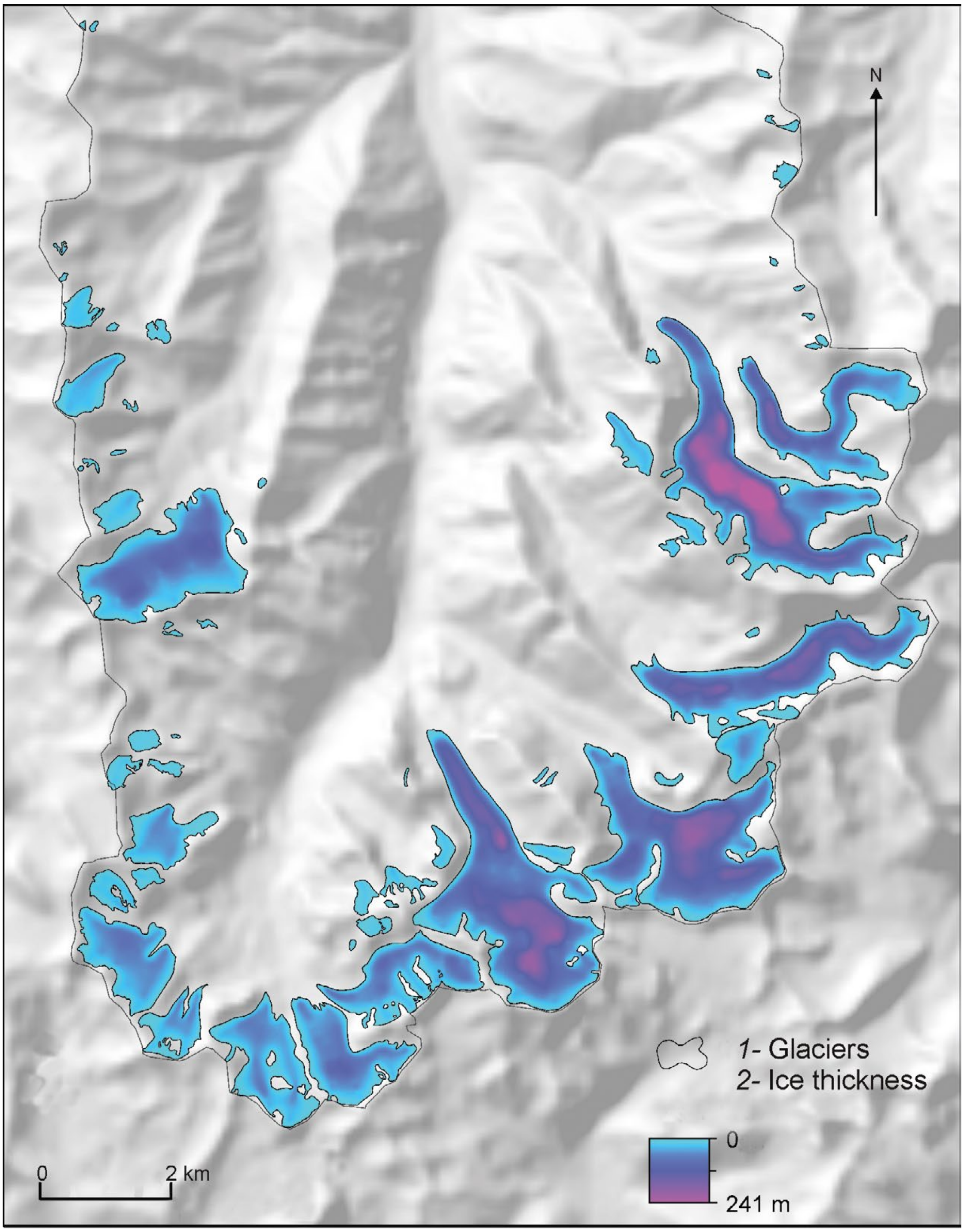


Fig. 4. Modelled glacier thickness
Рис. 4. Толщина ледников, рассчитанная по модели:
1 – границы ледников; *2* – толщина льда, м

−0.40±0.11% a^{-1} for 1964 to 2010) is slightly higher than the previously published data based on aerial images and ASTER data: Aizen et al. [7] report glacier shrinkage from 42.8 km^2 in 1963 to 36.3 km^2 in 2003 (~15.1%). In contrast to [7] we only found two disappearing glaciers while [7] report a disappearance of nine. The reason for this difference could not be investigated. It might be the case that [7] mapped very small glaciers in 1963 which could not be identified on the Corona images due to snow conditions. In contrast, [7] missed to include the debris-covered parts of Top-Karagay-glacier which we could identify using high-resolution imagery, DEM differencing results and the ALOS PALSAR coherence image.

Glacier shrinkage was similar (~16%) in Ile and Kungöy Ala-Too, which form the eastern part of the northern Tien Shan, for the period 1970–2007 based on similar high resolution data (Corona and

Table 4. **Glacier volume, elevation changes and mass balance of the glaciers > 0.5 km² for the periods 1964–1999 and 1999–2012**

Glacier	Periode 1964–1999			Periode 1999–2012			
	Initial area, km²	dh, m	GMB, m w.e. a^{-1}	Initial area, km²	Mean thickness, m	dh, m	GMB, m w.e. a^{-1}
Aydgyne	3.5	−29.9±12.2	−0.68±0.28	3.0	−39.5	−8.0±8.0	−0.65±0.65
Golubin	5.6	−23.1±12.2	−0.46±0.24	5.1	−63.4	−2.3±8.0	−0.28±0.97
Tuyuk	5.2	−21.9±12.2	−0.48±0.27	5.0	−56.3	−5.5±8.0	−0.49±0.71
Top-Karagay*	3.7	−23.3±12.2	−0.40±0.21	3.3	−53.6	−7.2±8.0	−0.42±0.47
Ak-Say	4.8	−22.4±12.2	−0.58±0.32	4.5	−76.7	−3.3±8.0	−0.35±0.85
Uchitel	2.2	−15.3±12.2	−0.38±0.30	2.0	−40.9	−8.2±8.0	−0.60±0.59
All	39.2	−20.5±12.2	−0.45±0.27	34.5	−45.6	−5.1±8.0	−0.42±0.66

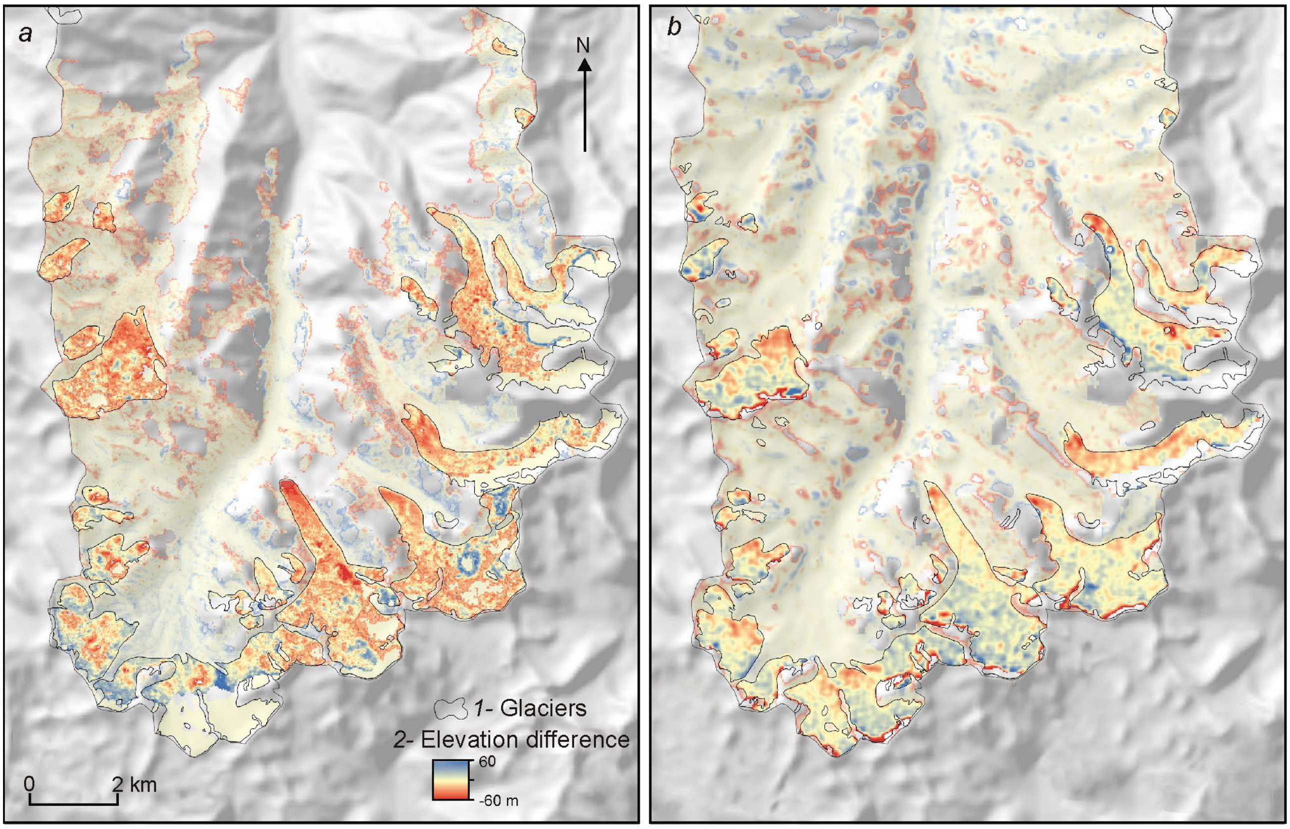


Fig. 5. DTM differences for the study area 1964–1999 (*a*), 1999–2012 (*в*)
Рис. 5. Разница ЦМР (цифровых моделей рельефа) для района исследования в 1964–1999 (*а*) и 1999–2012 гг. (*в*): *1* – границы ледников; *2* – разница высоты поверхности, м

ALOS) [35]. The glacier shrinkage is less than the reported 28.1% for the neighbouring Sokuluk watershed in the Kyrgyz Range for the period 1963 to 2000 [36]. The discrepancy can likely be explained by the overall significant smaller glacier size of the Sokuluk glaciers (0.41 km² on average to 0.81 km² in Ala Archa Valley). The glacier area loss is less in the dryer inner and central ranges of the Tien Shan with predominant summer precipitation where reported area loss varies between 0.30% a^{-1} for 1965 to 2003 [31] and less than 0.1% for parts of Central Tien Shan [38].

This study shows the suitability of stereo Corona to generate DTMs and to assess glacier mass changes since the 1960s after careful co-registration. The terrain features are in general well represented and the glacier tongues can well be identified in the DTM difference image. Hence, stereo Corona has a high

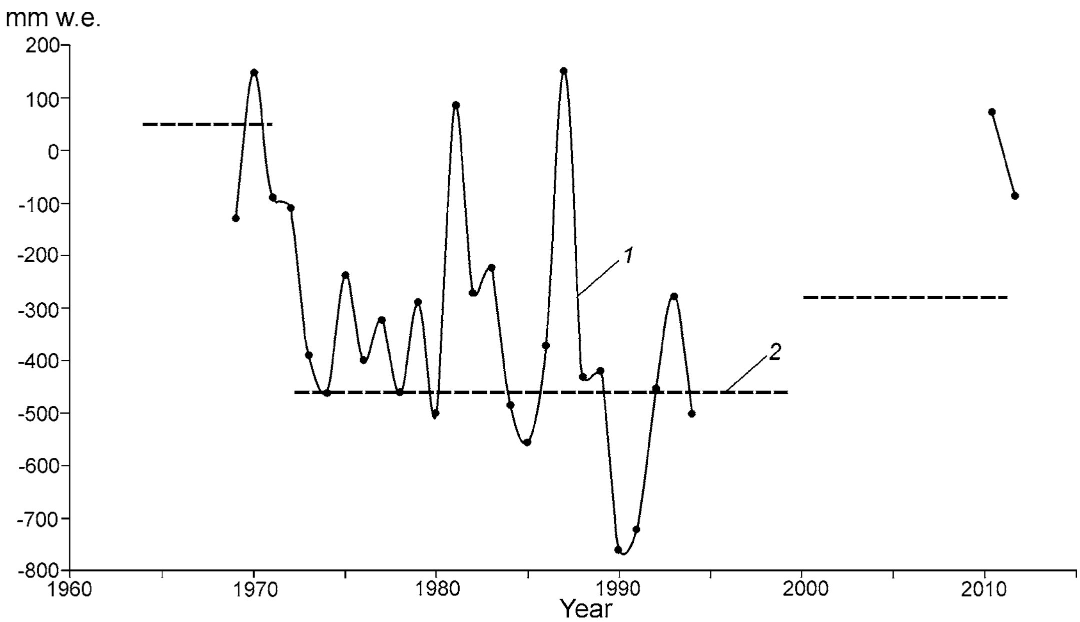


Fig. 6. Comparison of existing in-situ data (source: WGMS and CAIAG) (*1*) to the obtained geodetic mass balances of Golubin Glacier (*2*)

Рис. 6. Сравнение данных прямых измерений (источник: WGMS и ЦАИИЗ) (*1*) и полученного геодезического баланса массы ледника Голубина (*2*)

potential to significantly improve the knowledge of glacier mass changes during the last decades. While few studies use Corona to assess glacier length and area changes in Asia [e.g. 10, 35, 44] the application to volume changes since the publication of the pilot study by [12] is still very limited or restricted to small glacier parts [e.g. 32]. Similar, stereo declassified Hexagon data, which has a larger footprint, a resolution well below 10 m and is available since the mid 1970s, has huge potential especially of the territory of the former USSR, China and adjacent regions [48]. However, its application is also limited to a handful of publications with respect to glaciology [e.g. 14, 27, 43]. Soviet topographic maps have also been successfully applied to assess past glacier volume changes [3, 7]. DTM can also be generated from topographic maps to DTM generation using ASTER data is well established but the typical accuracy in mountainous terrain is ±15 m or even worse [49]. However, careful co-registration and bias correction can improve the accuracy [37] making the ASTER DTMs not only suitable to detect significant volume changes for larger glaciers with a strong signal. The theoretical uncertainty as calculated based on the NMAD is especially for the comparison of the ASTER and SRTM DTM larger than the signal. However, the volume loss of the glacier tongues can be well identified from the surrounding stable terrain. This is similar also for the Corona DTMs and gives along with the general good agreement to the existing field measurements [1, 50] confidence about the reliability of the presented results.

The revealed mass loss of 0.46±0.24 m w.e.$^{-1}$ is slightly higher than the existing mass balance measurements with a mean value of – 0.33 m w.e.$^{-1}$ for 1969 to 1994 [1, 50] but agrees well within the uncertainty. The reconstructed mass balance showed on average a slight mass gain from the late 1950s until 1970 [1] which is also in agreement with the results from the geodetic investigations despite the large uncertainty. For the period 1999 until 2012, a reduced mass loss was found which was likely due to increased accumulation identified in an elevation gain in the upper reaches of the glacier. Higher accumulation led also to a slight mass gain as measured for the mass balance year 2011 [50]. A slightly less negative mass balance in the first decade of the 21st century than the decades before were also measured at Tuyuksu Glacier [50] in Ile Alatau, reported for the Central Tien Shan based on geodetic measurements [43, 45] and is also likely for other High Asian mountain ranges such as the Himalaya [16].

One important uncertainty is the unknown penetration of the c-band radar beam used for the SRTM

DTM into snow and ice. I assumed a penetration of 2 metres which is in the range of the values estimated for the Himalaya and adjacent regions [26]. Comparing SRTM-C band with the X-band DTM (x-band has a much shorter wavelength than the c-band and, hence, only little penetration into snow and ice) for the same time revealed values of below 2 m in the ablation regions but values up to 5 m in the accumulation region [45]. An average penetration of 4 m instead of 2 m would lead to 0.13 mm w.e.$^{-1}$ higher mass loss for 1999–2012 and a lower loss for the earlier period.

The applied method to estimate the glacier volume has likely similar uncertainties than the widely used area-volume scaling method [4, 8] in case the glacier outlines are of good quality. Unfortunately, in situ measurements were not available for the study region for calibration and validation. However, results of the same model applied for the Swiss Alps are in good agreement with measured thickness data [33]. Further advantages of the applied method are that it is physically based and variations of glaciers with the same size are captured. Ak-Say Glacier has likely a higher volume (0.35±0.10 km³) than Tuyuk Glacier (0.28±0.08 km³) although it is 0.5 km² smaller (see Table 4). In addition, the distribution of the glacier thickness and overdeepenings can be identified. This is important for modelling the glacier recession and identifying possible future hazards [33]. Almost all glaciers show these overdeepenings which potentially could be filled by water with further glacier recession and hence, new potentially dangerous lakes could develop. Assuming similar mass loss rates of ~0.45 m w.e. a^{-1} for the future, the glaciers might disappear within the next 100 years.

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Изменение площади и массы ледников в долине Ала-Арча в Киргизском хребте на Северном Тянь-Шане с 1964 г.

Ледники – важный источник пресной воды в Средней Азии, поскольку максимальный ледниковый сток отмечается в летние месяцы, когда количество осадков минимально, а потребности в воде – максимальны. Многие исследования посвящены изменению площади ледников Тянь-Шаня, однако для оценки речного стока и влияния климатических изменений необходимы данные об изменении массы льда. Несмотря на важность таких исследований, до сих пор подобные работы выполнены лишь на небольшом числе ледников. Оценки баланса массы геодезическими методами могут дополнить и продлить существующие ряды прямых измерений на ледниках. В данной работе оценены изменения площади и массы ледников, расположенных в долине Ала-Арча в Киргизском Тянь-Шане, с помощью стереоснимков спутника Corona 1964 и 1971 гг., стереоснимков ASTER 2012 г., цифровой модели земной поверхности SRTM, а также других оптических данных, среди которых – LANDSAT ETM+ или RapidEye. Дополнительно было выполнено моделирование толщины льда исходя из напряжения сдвига на ложе и рельефа поверхности ледников. Результаты показали, что с 1964 по 2010 г. ледники непрерывно сокращались и потеряли 18,3±5,0% общей площади. Средний баланс массы составлял −0,45±0,27 м в.э. в год для периода с 1964 по 1999 г. и −0,42±0,66 м в.э. в год в 1999–2012 гг. Для ледника Голубина зарегистрировано незначительное накопление массы в 1964–1971 гг. и замедление сокращения массы в 1999–2012 гг. Эти результаты согласуются с существующими данными прямых измерений баланса массы, проводившихся с 1962 по 1994 г. и с 2010 г. По состоянию на 2000 г. общий объём льда составлял 1,56±0,47 км^3. Таким образом, если масса льда будет сокращаться с такой же скоростью, то к 2100 г. ледники в районе исследования полностью растают.