Monitoring and studying changes in the boundaries and area of representative glaciers Kyrgyzstan based on the results of interpretation satellite images

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To study changes in glaciers, a remote sensing method is widely used, which allows analyzing changes in the boundaries and area of glaciers based on satellite images throughout the territory of Kyrgyzstan. As a result, it is possible to fairly objectively assess the general long-term trend in the spatial change of glaciers and carry out their inventory.

In this aspect, over a long period, an analysis of satellite images and the results of aerial photography using an unmanned aerial vehicle (UAV) was carried out for representative glaciers of Kyrgyzstan, which in this article are represented by the glaciers: Abramova, Golubina, Petrova, Karabatkak, Zapadny Suek, No. 354, No. 185, No. 120, No. 122, No. 282, No. 66 (Fig. 1), the numbers of these glaciers are given according to the Catalogue of glaciers of Kyrgyzstan [1].

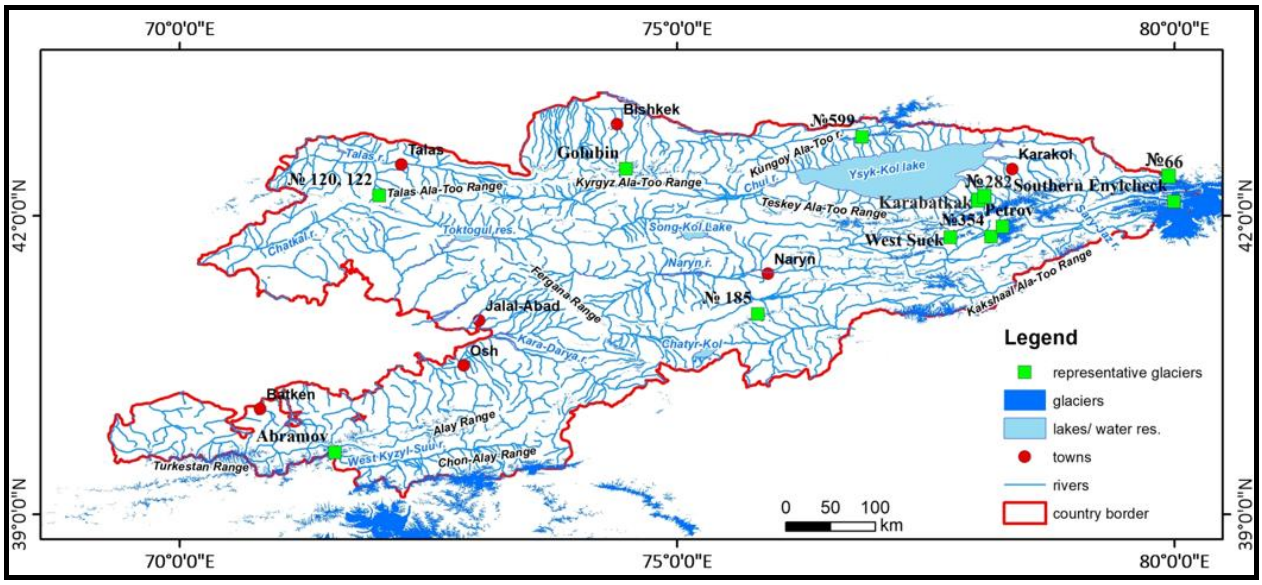

Fig. 1 Location of representative glaciers in Kyrgyzstan.

To analyze changes in glacier boundaries, mainly, optical images from the «Landsat 8.9», «Hexagon KH9», «CORONA KH-4B» (USGS EROS Archive), «Sentinel 2A,2B» (ESA, Copernicus Data Space Ecosystem), and «PlanetScope» (Planet Labs, Inc.) satellites were used with a resolution of 15; 6–9; 1.8; 10; 3 m/pixel, respectively. Most of the images have standard georeferencing and correction, including radiometric calibration, geometric correction and orthorectification from the manufacturer, in particular, the products "L1T" "Landsat 8,9" and "L1C, L2A" "Sentinel 2A,2B". Various combinations of spectral channels of the images were used to improve interpretation. The accuracy of interpretation mainly depends on the resolution of satellite images, for satellites «Sentinel 2A, 2B», «Landsat 8,9» it is, respectively, a maximum of 10 and 15 m, and the accuracy of georeferencing is in the range of 10 - 30 m. For satellite images without initial georeferencing («Hexagon», «CORONA»), geolocation was performed by coregistration by georeferenced images, by characteristic, stable reference points of the relief. The frequency of shooting, for the region under consideration, satellites «Landsat 8,9» - 16 days, with a shift relative to each other - 8 days, «Sentinel 2A, 2B» - 10 days, with a shift of 5 days.

Interpretation was performed using GIS «MapInfo», «ArcGIS», «GlobalMapper» and other programs.

The change in the Abramov glacier, located on the northern slope of the Alai Range, for the period from 1850 to 2014 was previously considered in the publication [2], where it was found that the average rate of glacier area reduction over 164 years was 0,02 km^2/year, with a total reduction of 3,65 km^2, or 14%. Over the same period of time, the length of the glacier decreased by approximately 2950 m, with an average rate of about 18.1 m/year (Fig. 2).

Analysis of changes in the Abramov glacier for the period 2013-2023 were made based on the interpretation of images from « PlanetScope» satellites, dated 13/08/2018, 18/07/2022, «Sentinel 2», dated 13/08/2019, 15/09/2020, 25/07/2021, 21/08/2023, «Landsat 8», dated 12/09/2013, 30/08/2014, 17/08/2015, 3/08/2016, 9/07/2017, 25/08/2018, with a resolution of 3, 10, 15 m/pixel, respectively. The boundaries of the glacier in Figure 2 are drawn at intervals of 1 year. The interpretation error and georeferencing was about 10-15 m. The glacier tongue boundary was refined in 2013 using ground-based GPS survey. Also, glacier tongue boundary was refined on 08/23/2022 based on aerial photography with a resolution of 0,05 m/pixel using a UAV and constructing a digital elevation model (DEM) of the glacier tongue end. Analysis of changes in the area of the Abramov glacier for the period from 2013 to 2023 showed that the area of the Abramov glacier tongue decreased by 0,177 km^2, and the average rate of reduction was 0,017 km^2/year. The maximum uneven linear reduction in the glacier length was about 230 m, at a rate of 23 m/year.

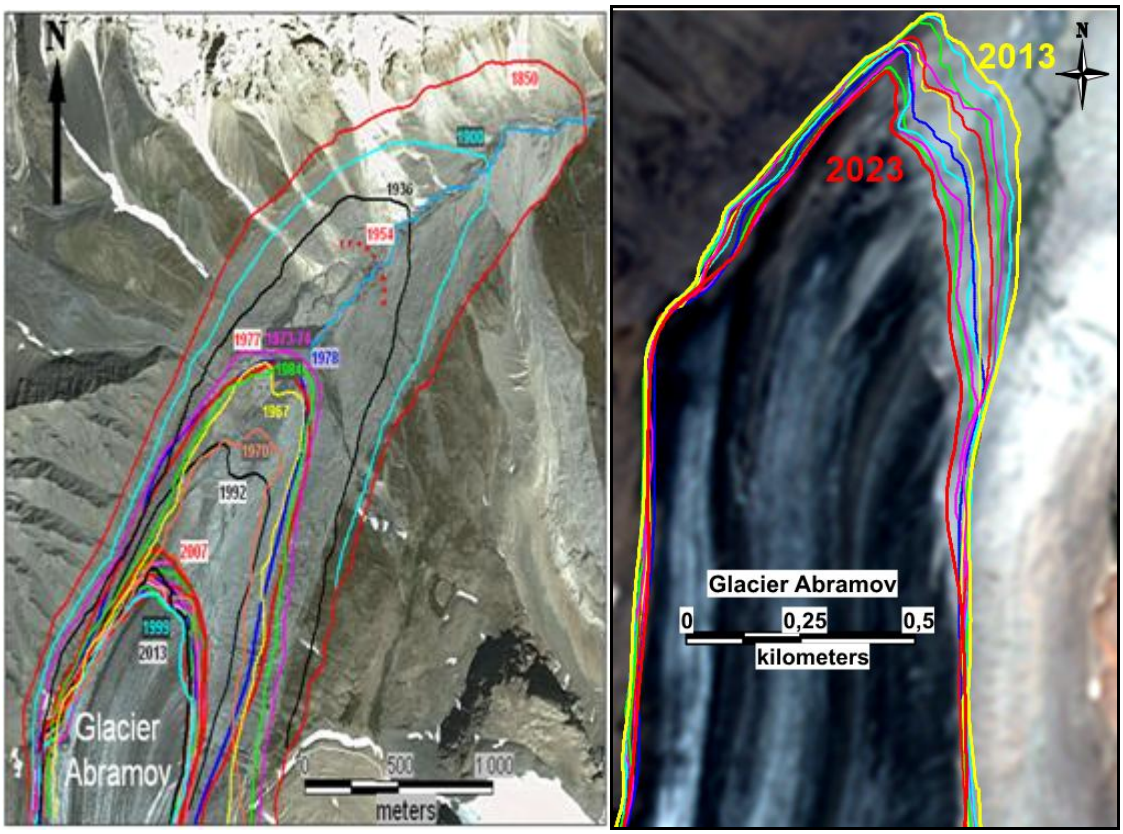

Fig. 2. Boundaries of the Abramov glacier tongue from 1850 to 2023.
The background of figures is 2007 «Geo Eye 1» satellite image on the left and 2023 «Sentinel 2» image on the right.

Thus, the rate of Abramov glacier shrinkage for the period 2013-2023 is close to the previously obtained estimate for the period from 1850 to 2013. The total shrinkage of the glacier from 1850 to 2023 was 14.5%. Currently, the degradation of the Abramov glacier continues without significant deviations from the average rate of glacier shrinkage. Over the past decade, on glacier has not observed of advances (surges), similar to those that occurred previously in 1972-1973 and 2001-2005.

The analysis of changes in the Petrov glacier, located in the Ak-Shiyrak massif, was performed using the data of V.A. Kuzmichenok [3], as well as on the basis of interpretation of images from satellites: «Hexagon KH9», dated 08/21/1980, with a resolution of 6-9 m/pixel, «Quick Bird», dated 10/4/2002, «Spot 5», dated 08/22/2007, «Landsat 8», dated 2013, with resolutions of 2, 3, 15 m/pixel, respectively, «PlanetScope», dated -/08/2018, with a resolution of 3 m/pixel and «Sentinel 2», dated 08/15/2023, with a resolution of 10 m / pixel and with an interpretation and georeferencing error about 15 m. Figure 3 shows the boundaries of the Petrov glacier tongue from 1869 to 2023.

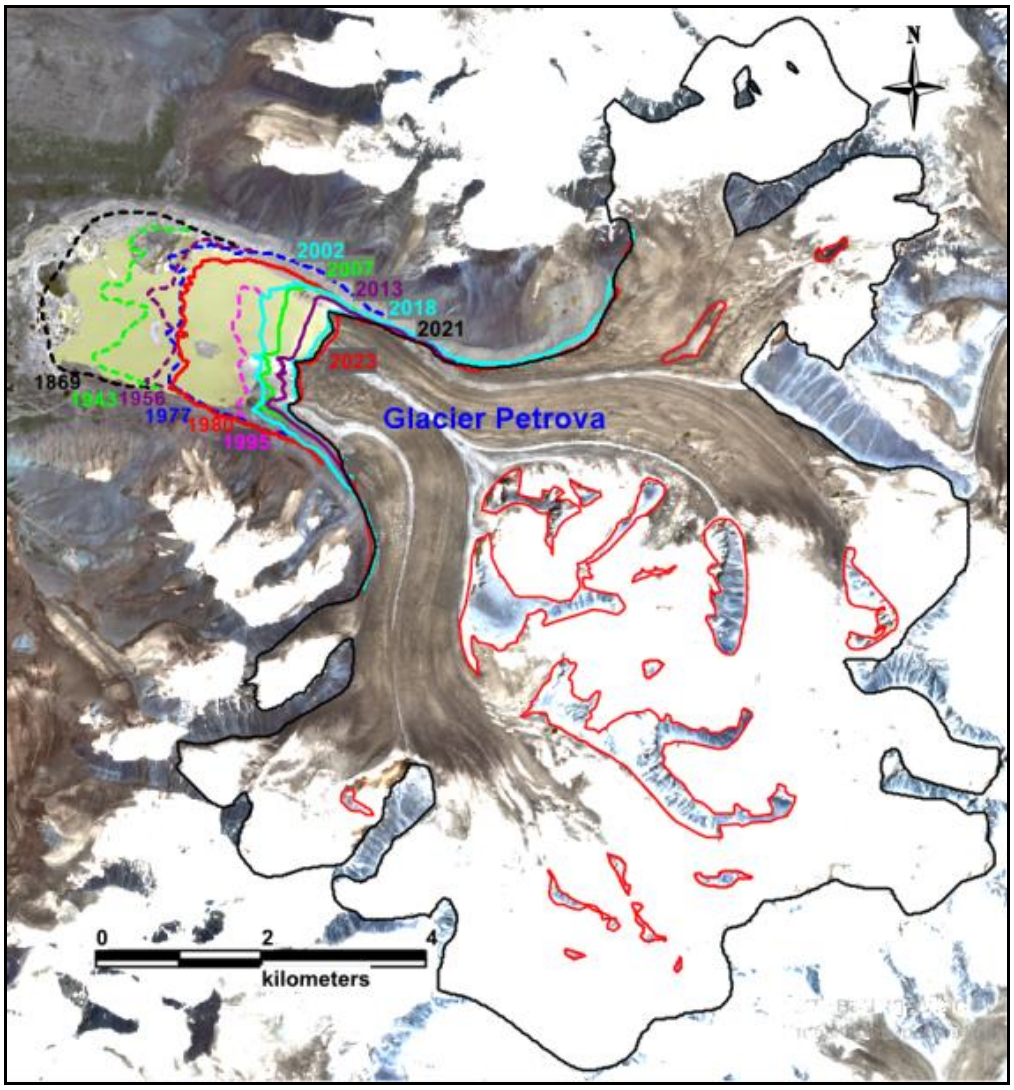

Fig. 3. Boundaries of the Petrov glacier from 1869 to 2023. Dotted boundaries - according to Kuzmichenok V.A., solid boundaries were obtained by interpreting satellite images. The boundaries of the outcrop of rocks on the surface (red contours) on the glacier are shown as of 2023. The background is a «Sentinel 2» satellite image from 2023.

The area has shrunk by 6,86 km^2, or 10,2% over 154 years, the rate of area reduction is 0,045 km^2/year. The maximum linear retreat is 3300 m, at a rate of 21,4 m / year. A feature of the Petrov glacier is the discharge of the northern ice flow directly into the eponymous periglacial lake, which contributes to the acceleration of flow ice movement. As with all glaciers, for the Petrov glacier, the main reduction in area occurs at the end of the glacier tongue and, to a lesser extent, in the lateral parts of the tongue, within the ablation zone. In the accumulation zone, the lateral boundaries remain virtually constant for decades.

The analysis of the change in the boundaries of glaciers No. 120 and No. 122 (Fig. 4), located in the Talas Range, was performed using a satellite image from 18/08/1968, the «CORONA satellite system, mission KH-4B», with a resolution of about 1.8 m / pixel, «Sentinel 2» satellite image from 21/08/2023 with a resolution of 10 m / pixel, as well as «GeoEye-1» satellite image from 15/08/2015 with a resolution of 1,65 m / pixel. The interpretation and georeferencing error was about 10 m. The change in the area of glaciers No. 120, 122 over a period of 55 years is shown in Table 1. As can be seen from the table, the rate of reduction in the area of glaciers in question for the period from 1968 to 2023 is in the range of 0,003-0,012 km^2 / year.

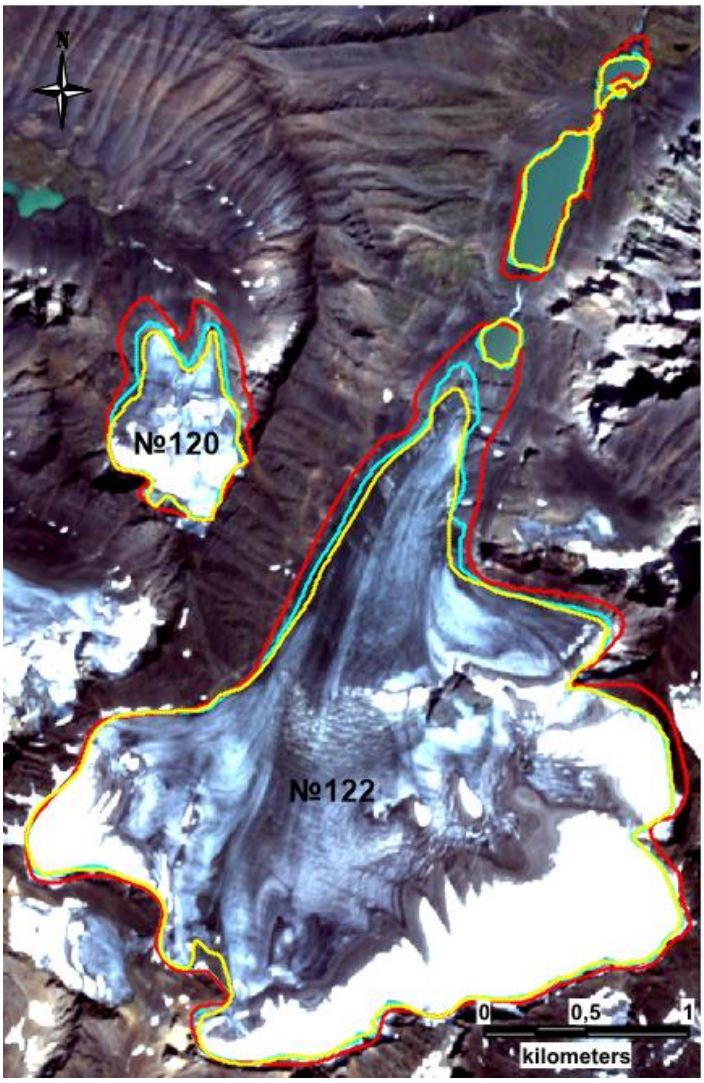

Fig. 4. Boundaries of glaciers No. 120 and No. 122 in 1968 (red), in 2015 (blue), in 2023 (yellow) and boundaries of periglacial lakes in the same years, according to satellite images. The background of the figure is «Sentinel 2» satellite image from 2023.

In this case, attention is drawn to the relatively small absolute rate of glaciers area reduction and the dependence of the relative value of area reduction, expressed as a percentage, on the size of the glacier. The maximum linear retreat from 1968 to 2023 was about 170 m for glacier No. 120, and about 410 m for No. 122 at rates of 3,1 and 7,5 m/year, respectively.

Table 1

№ glacier	Area glacier (km^2)			Reduction of area, km^2 1968-2023y.	Rate of area reduction km^2/year	% area reduction
	1968y.	2015y.	2023y.			
120	0,56	0,42	0,38	0,18	0,003	32
122	5,9	5,42	5,26	0,64	0,012	11

The largest glacial lake, located north of glacier No. 122, with an area of 0,19 km^2, has had a virtually constant area since 1968. A small lake, located to the south, closer to the end of the glacier tongue, with an area of about 0,034 km^2, was formed during the retreat of the glacier edge after 1968. It also has a stable area due to the formation of a lake basin and a lake dam on rocky outcrops.

The result of the analysis of changes in the area of glacier No. 185, located on the northern slope of the At-Bashi Range, for the period from 1968 to 2023 is shown in Figure 5. The boundaries of the glacier were determined by interpreting images of the «CORONA KH-4B» satellites, dated 19/08/1968, «QuickBird», dated 21/09/2002, «Pleades», dated 27/07/2013 and «Sentinel 2», dated 13/08/2023 with a resolution of 1.8; 0.6; 0.7; 10 m/pixel, respectively. The interpretation and georeferencing error was about 10 m. Based on the results of the analysis of satellite images, it was determined that the area of glacier No. 185 in 1968 was 0,44 km^2, and in 2023 decreased by 0,1 km^2 to 0,34 km^2, or by 23%, and the rate of area reduction over 55 years was about 0,002 km^2/year, with a linear retreat of the end of the glacier tongue by a distance of about 200 m at a rate of 3,6 m/year. In this case, the rate of area reduction is close to that of the above-discussed glacier No. 120, located in the Talas Range and having a similar total glacier area. The glacial lake formed during the retreat of the glacier tongue has had a relatively stable area of about 0,03 km^2 in the years following 2002.

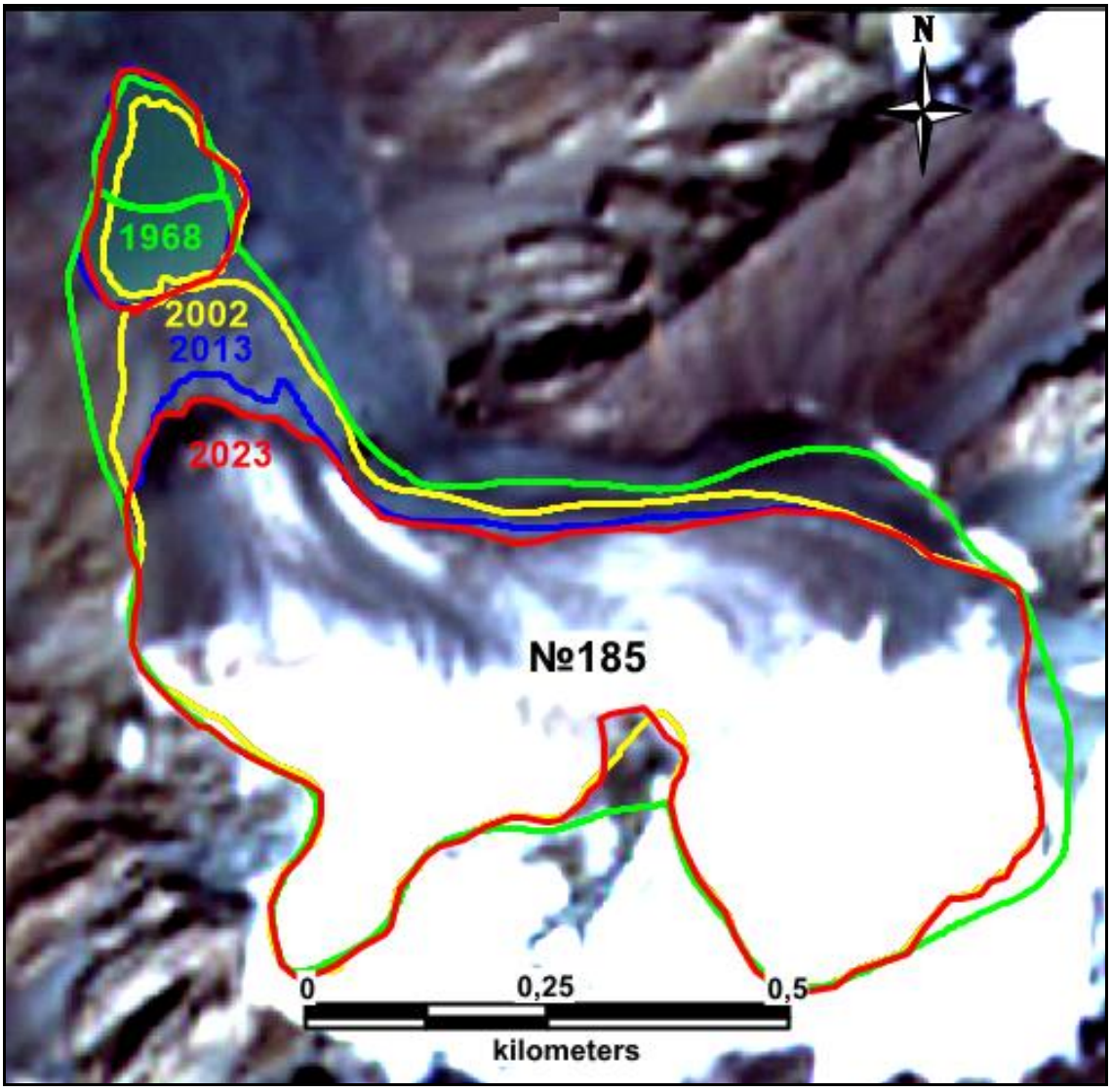

Fig. 5 Change in the area of glacier No. 185 from 1968 to 2023. The background of the figure is «Sentinel 2» satellite image from 2023.

The change in the area of the Golubin glacier, located on the northern slope of the Kyrgyz Range, for the period from 1861 to 2023 is shown in Figure 6. In this case, the boundaries of the glacier tongue in 1861, 1949 and 1963 are shown according to the information from the article by Aizen V.B. et al. [3], other boundaries were obtained by interpreting images: «Quick Bird» satellites, dated 24/07/2006 with resolution of about 1 m/pixel, «Landsat 8», dated 07/10/2013 with resolution of 15 m/pixel, «Planet Scope», dated 15/07/2022 with resolution of 3 m/pixel and «Sentinel 2», dated 10/09/2023 with resolution of 10 m/pixel. The boundary of the end of the glacier tongue in 2013 was refined during field studies by tracing with GPS receiver. The maximum accuracy of interpretation and georeferencing is about 15 m. With a total area of the glacier in 1861 equal to 6,05 km^2, the area reduction in 2023 was 0,485 km^2 or 8%, the average rate of area reduction over 162 years is estimated at 0,003 km^2 /year. For the period from 2013 to 2023, the area decreased by 0,03 km^2 at a reduction rate of 0,003 km^2 /year. The linear reduction of the glacier tongue from 1861 to 2023 was 839 m, at a rate of 5,2 m /year.

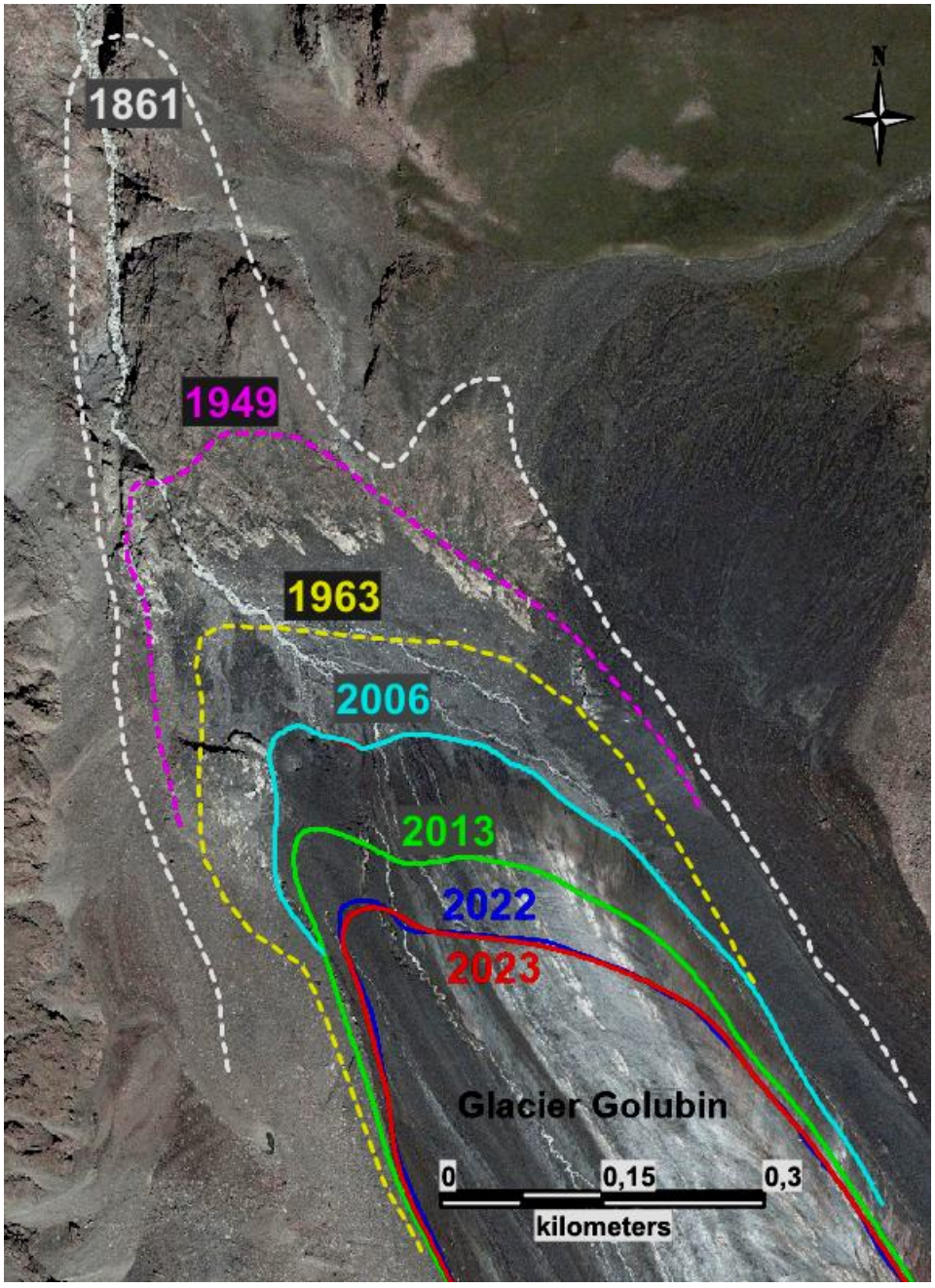

Fig. 6 Changes in boundary of Golubin glacier tongue for 1861-2023.
The background is «Quick Bird» satellite image from 24/07/2006.

The change in the Zapadny Suek glacier (No. 419), located on the northern slope of the Suek ridge, based on the analysis of satellite images, is shown in Figure 7. Here, the boundaries of the Zapadny Suek glacier, from 1980 to 2023, are determined based on the data of the «Hexagon KH9» satellites from 1980, with a resolution of 4 m / pixel and «Sentinel 2» from 11/08/2019, 14/09/2020, 24/09/2021, 04/09/2022 and 15/08/2023, with a resolution of 10 m / pixel, in a combination of spectral channels B11, B8A, B02. The accuracy of image geolocation, as well as deciphering and tracing the boundaries of glaciers is about 10-20 meters. In this case, the glacier area reduction from 1980 to 2023 was 0,26 km^2, and the rate of glacier area reduction was 0,006 km^2/year. The maximum linear retreat of the glacier tongue end over the same period was 340 m at an average rate of about 8 m/year. In general, the reduction in the area of the Zapadny Suek (No. 419) glacier from 1980 to 2023 was 19%. Thus, in 2023, uneven retreat continues, mainly in the ablation zone, of the edge of the Zapadny Suek (No. 419) glacier tongue.

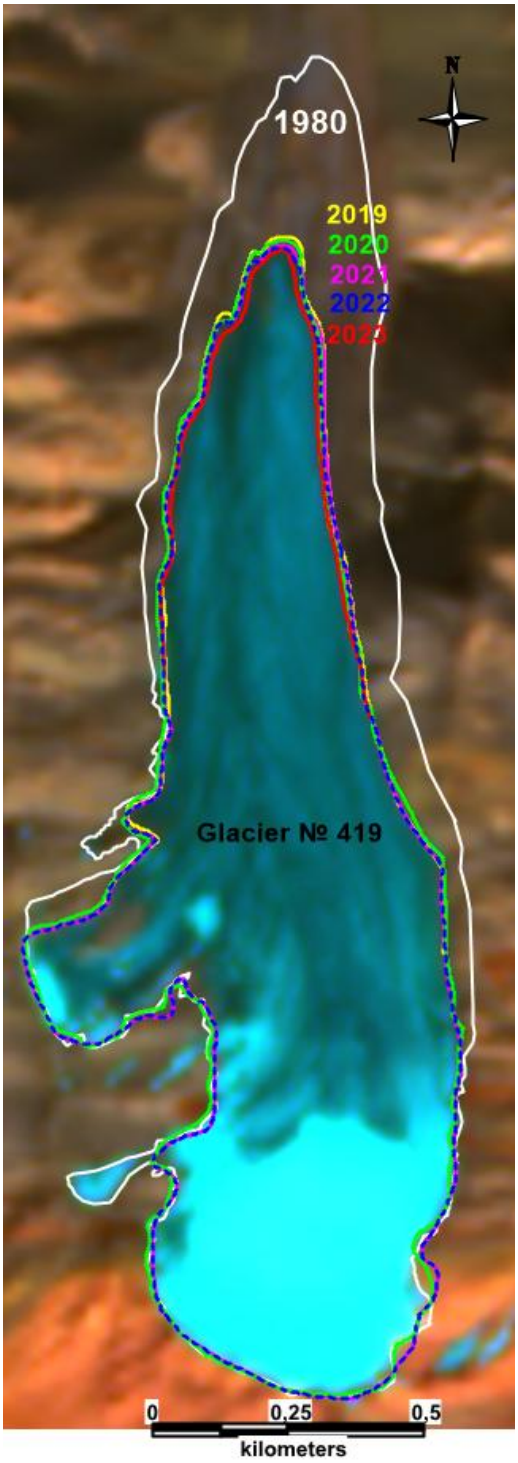

Fig. 7. The position of boundaries of glacier Zapadny Suek (No. 419) in period from 1980 to 2023, based on «Sentinel 2» satellite images obtained in 2019-2023 and «Hexagon KH9» satellite data from 1980. The background is «Sentinel 2» satellite image from 2023.

The analysis of the change in the boundaries of glacier No. 354, located in the Ak-Shiyrak massif, was carried out similarly. Figure 8 shows the position of the glacier boundaries from 1980 to 2023 based on the results of decoding the images of the «Hexagon KH9» satellite from 1980, with a resolution of 4 m / pixel and «Sentinel 2» from 11/08/2019, 21/07/2020, 19/09/2021, 26/07/2022, 15/08/2023, with a resolution of 10 m / pixel. The error in geolocation of images and determination of the glacier boundaries is about 10-20 meters. The reduction in glacier area from 1980 to 2023 was 0,59 km^2 or 8,7%, the average rate of glacier area reduction in the period under consideration was about 0,01 km^2/year, with a total linear retreat of 585 m and average retreat rate 13,6 m/year.

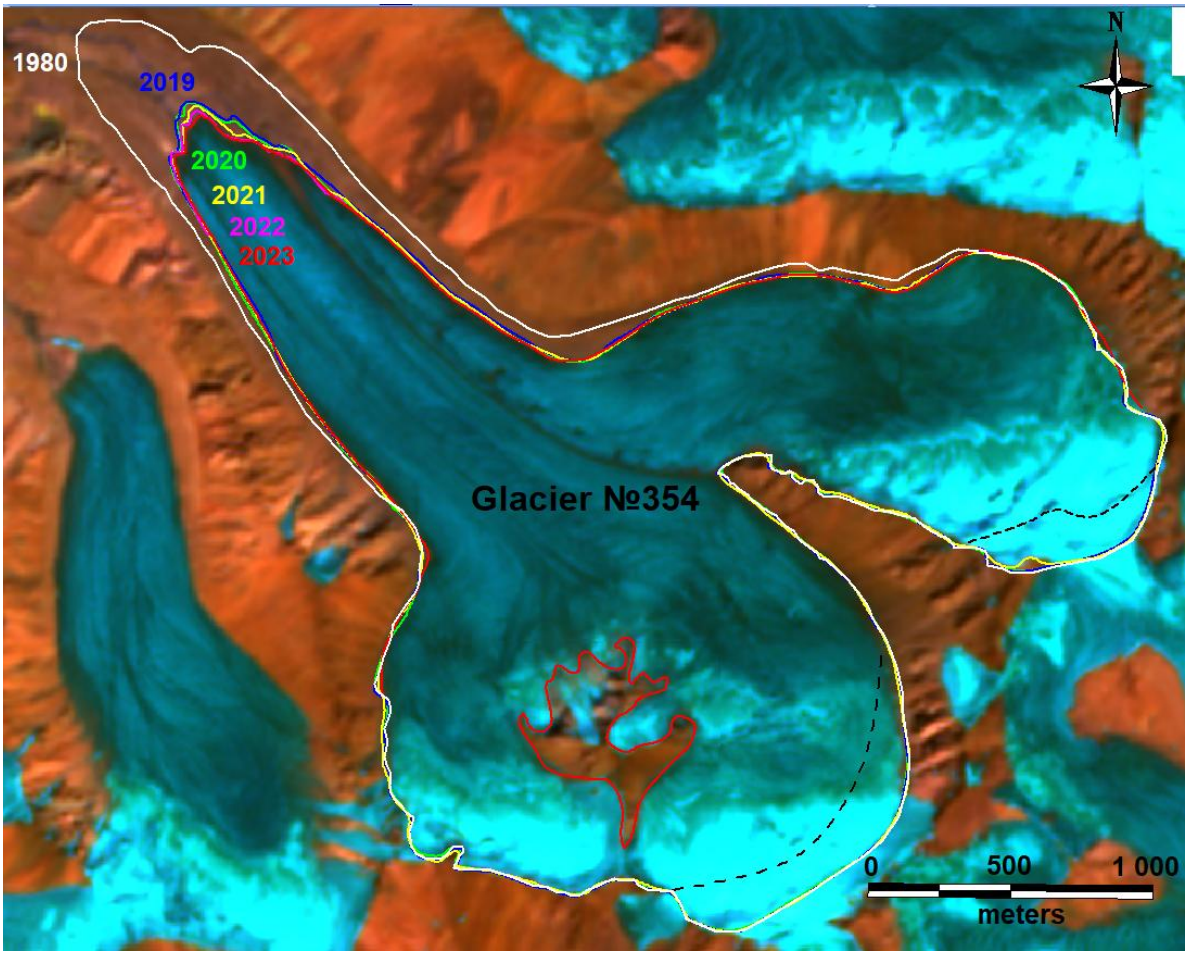

Fig. 8 Boundaries of glacier No.354 from 1980 to 2023. The black dotted line is the bergschrund. The boundary of rock outcrop on glacier (red outline) is shown as of 2023. The background is «Sentinel 2» satellite image from 2023.

Observations of changes in the Karabatkak glacier have a long history and individual moments of change in its boundary are shown in Figure 9. Here, in particular, the boundary of the glacier in 1947 is shown based on the results of a phototheodolite survey at a scale of 1:10000, carried out by the North-Kyrgyz Expedition of the Institute of Geography of the USSR Academy of Sciences. As can be seen in the figure, the glacier in 1947 occupied a significant area, which subsequently decreased as the lower and lateral boundaries of the glacier tongue retreated. Figure 9 shows that, based on the results of decoding the satellite images of the «Quick Bird» satellites, dated 4/10/2002, the «Pleiades» satellites, dated 25/09/2013 and 07/11/2016, with resolution of 0.5 m/pixel, as well as the «PlanetScope» satellite images, dated 09/2018 and the «Sentinel 2» satellite images, dated 05/08/2023 with resolution of 3 and 10 m/pixel, respectively, with an error in georeferencing the images and determining the glacier boundaries of about 10 meters, a continuation of the long-term trend of a decrease in the area of the Karabatkak glacier is observed. A specific feature of this glacier is the presence, in addition to its central part, free of moraine cover, of large areas of the glacier covered with lateral moraines that do not allow determining the lateral boundaries of the glacier tongue. For this reason, in this case, only a linear change in the tongue of the Karabatkak glacier was determined. Thus, from 1947 to 2023, the length of the glacier tongue decreased by 970 m, and the rate of linear reduction over 76 years was 12,7 m/year. Over the period from 2002 to 2023, the reduction reached 200 m and over 21 years, the average rate of reduction was 9,5 m/year.

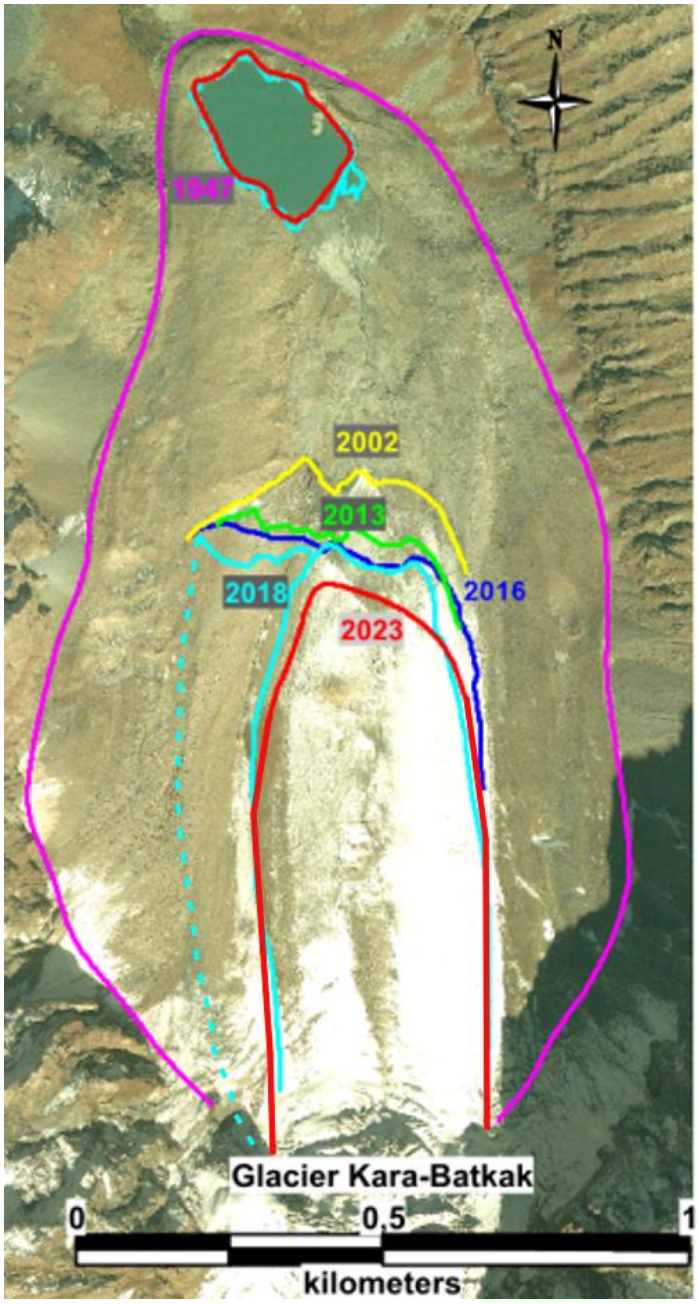

Fig.9 Change in the position of edge of the Karabatkak glacier tongue from 1947 to 2023.
The dotted line shows probable western boundary of glacier.
The background is «Quick Bird» satellite image from 2002.

In order to clarify of glaciers changes in the Karabatkak glacier area, glacier No. 282 (Fig. 10) was used. It is also located on the northern slope of the Terskey Range, 7,4 km east of the Karabatkak glacier. It was chosen as an analogue of the latter, since it is more convenient for remote sensing of changes due to the glacier tongue being free of moraine deposits, in contrast to the Karabatkak glacier, which is largely covered by moraine deposits, making it difficult to determine the boundaries of its tongue. The boundaries of glacier No. 282 were determined by interpreting images from the «CORONA, KH-4B» satellites, dated 23/09/1971, «Pleiades», dated 25/09/2013 and «Sentinel 2», dated 10/08/2023 with resolution of 1,8; 0,5, and 10 m/pixel, at an error in geo-positioning of images and determination of glacier boundaries of about 10 meters. With the total area of glacier No. 282 in 1971 equal to 3,75 km^2, the reduction in area by 2023, over 52 years, was 0,35 km^2 or 9,3%, with an average area reduction rate of 0,007 km^2/year. The linear reduction of the glacier tongue over the same period was 870 m, with a linear reduction rate of 16,7 m/year.

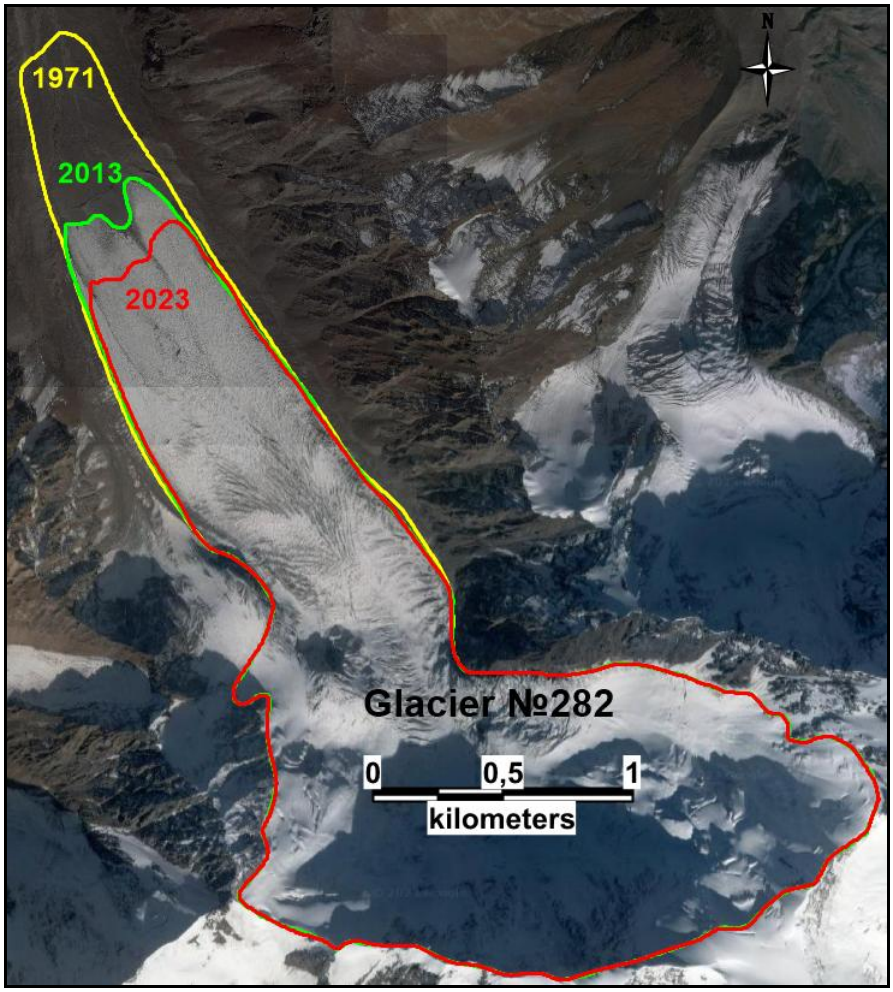

Fig.10 Changes in the boundaries of tongue of glacier No. 282 from 1971 to 2023. The background is 2013 «Pleiades» satellite image.

Glacier No. 66 is located in the eastern part of Kyrgyzstan, on the northern slope of the Adyrtor Mountains, along the southern edge of the Sary-Dzhaz River valley. The analysis of its changes was performed for the period 1984-2023. For interpretation, images of the satellites «Hexagon2 KH-9», dated 17/08/1984, «QuickBird 2», dated 11/09/2005, «Landsat 8», dated 25/09/2013, 01/09/2016, «Landsat 9», dated 22/10/2023 were used with a resolution of 1,2; 0,6 and 15 m/pixel, respectively, with an error in image geolocation and determining the boundaries of the glacier of about 15 meters. With a total area of glacier No. 66 in 1984. equal to 8,46 km^2, the reduction in area by 2023, for 39 years, was 0,59 km^2 or 7%, with an average area reduction rate of 0,015 km^2/year. The linear reduction of the glacier tongue over the same period was 630 m, with a linear reduction rate of 16,2 m/year. Table 2 shows some of the main parameters of the glaciers considered. In general, the rate of area reduction of the glaciers considered above over a long-term period is in two ranges: 0,002 – 0,007 km^2/year and an order of magnitude greater 0,01-0,045 km^2/year. The maximum reduction rates, with other similar parameters, are typical for glaciers with a large glacier area. In addition, variations in the rate of glacier area reduction depend on the exposure, relief features at their location that provide the nature and degree of shading, glacier surface slope, absolute elevation of the tongue end, degree of moraine coverage, the nature of atmospheric precipitation supply, and ablation intensity. For the Karabatkak glacier, for which only the linear rate of tongue reduction was considered, the latter is close to the rate of tongue reduction of all other glaciers considered, which indicates the similarity of the process of glacier reduction in Kyrgyzstan, with the presence of individual features.

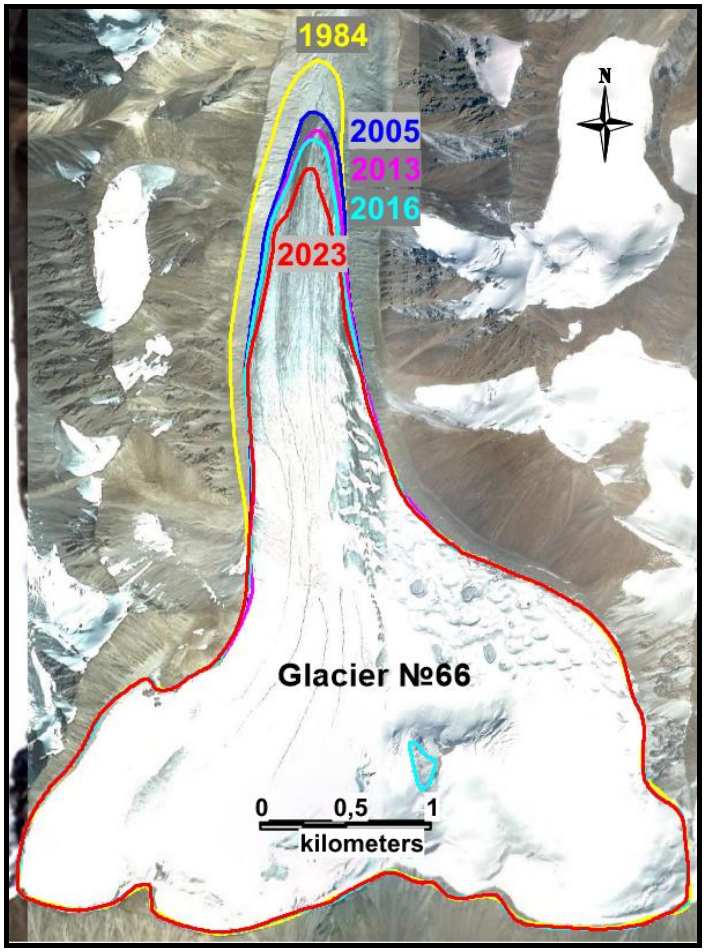

Fig. 11 Changes in the boundaries of tongue glacier No. 66 from 1984 to 2023.
The background is 2005 «QuickBird 2» satellite image.

Table 2

№ glacier, name	Expo-sition	Altitude of end tongue on 2023 y (m)	Glacier area on 2023 y (km^2)	Reduction of glacier area (km^2)	Rate of glacier shrinkage (km^2/y)	Linear glacier shrinkage rate (m/y)	% Reductions in area	Period of reduction (years)
№40, Abramova	C	~3690	22,6	3,81	0,02	~18,3	14,5	1850-2023
№368 Petrova	C-3	~3840	60.4	6,86	0.045	~21,4	10,2	1869-2023
№120	C	~3520-3550	0,38	0,18	0,003	~3,1	32	1968-2023
№122	C-B	~3290	5,26	0,64	0,01	~7,5	11	1968-2023
№185	C-3	~3880	0,44	0,1	0,002	~3,6	23	1968-2023
№250 Golubina	C-3	~3400	5,57	0,49	0,003	~5,2	8	1861-2023
№419 Zapadny Suek	C	~4005	1,37	0,26	0,006	~8,0	19	1980-2023
№354	C-3	~3870	6,78	0,59	0,01	~13,6	8,7	1980-2023
№265 Karabatkak	C	~3385	2,3? on clear ice	-	-	~12,7	-	1947-2023
№282	C-3	~3500	3,4	0,35	0,007	~16,7	9,3	1971-2023
№66	C	~3670	7,87	0,59	0,015	~16,2	7	1984-2023

The similarity of the process area reduction of different glaciers Kyrgyzstan is evident in the example of glaciers No. 120 and 185, as well as No. 354 and 66, which have similar parameters and are located at a considerable distance from each other. At the same time, the rate of area reduction of small glaciers is less than that of large ones. An approximate version of this dependence, according to the data from Table 2, is shown in Figure 12.

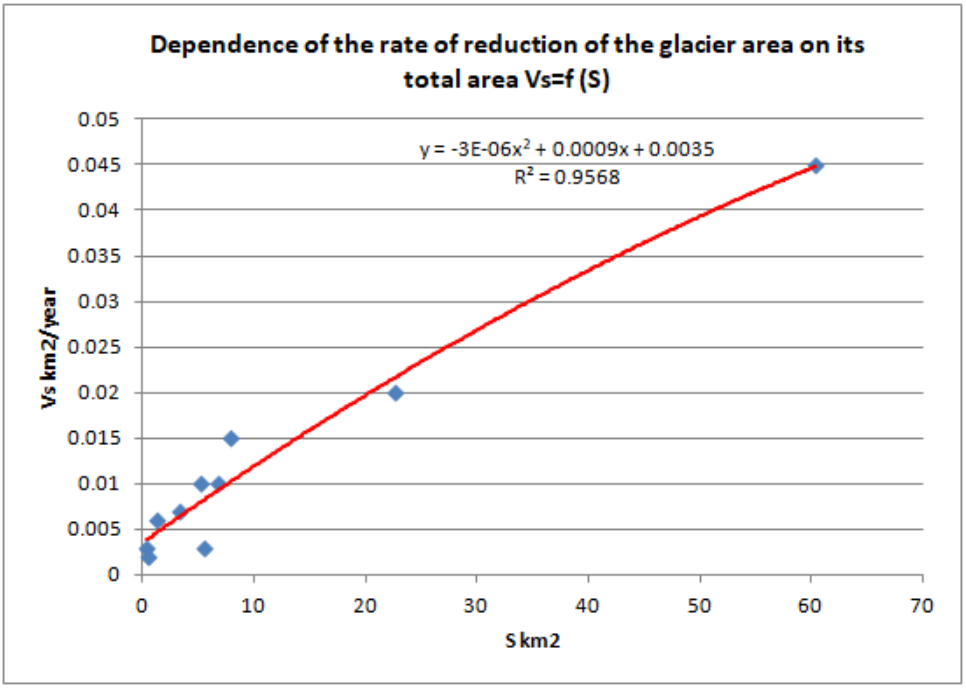

Fig. 12

It should be noted that the assessment of glacier reduction by the linear retreat of the end of the glacier, in the cases considered above, is approximate and gives only a general idea of the scale of glacier retreat. This is due to the unevenness of the retreat of the edge of glacier tongues along its perimeter both in the frontal part and in the lateral parts. For this reason, the most objective characteristic of the retreat is given by the assessment of the change in the area of the glacier tongue, taking into account all the features of its configuration. Using the parameter of the rate of change in the area of the glacier allows us to objectively compare not only glaciers of different areas, but also their changes over different periods of time. Regarding the percentage assessment of the change, it is necessary to take into account that the comparison of these values for different glaciers is incorrect in the case of a difference in their total areas and different values of time intervals used to assess the change in the area of glaciers. This is evident from the dependence of the percentage assessment of the reduction on the size of the glacier area, as can be seen from Table 2, it is always smaller for large glaciers and larger for small glaciers.

The results of decoding satellite images of the glaciers discussed above show that in 2023 their uneven retreat continues due to variations in the intensity of melting, mainly in the ablation zone, within the end of the glacier tongue. This trend is observed in all glaciers of Kyrgyzstan without exception, due to ongoing global warming and an increase in the average annual zero air isotherm since the beginning of the 20th century by approximately 100-150 m. According to the estimate of the rate of reduction of the total area of all glaciers given in the publication [1], about 0.2% / year, or approximately 16 km^2 / year, the reduction in the area of glaciers in Kyrgyzstan, if the current warming trend continues, may reach about 30% by 2100.

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