Dynamics of changes in the Abramov Glacier from 1850 to 2014 according to remote sensing data, ground measurements and published data.

A. Mandychev, R. Usubaliev, E. Azisov
Central Asian Institute for Applied Geosciences (CAIAG)

Introduction

The purpose of this study was to determine the nature and the rate of the glacier change for a quite long period, based on data obtained in the past and present. The Abramov Glacier, which location in the Alay Range of Kyrgyzstan is shown in Figure 1, was studied in the most detailed way from 1967 to 1994 on the basis of the *Abramov Glacier* station, installed by the Central Asian Regional Research Institute. In recent years, glacier research was been performed sporadically within various projects. The Central Asian Institute for Applied Geosciences (CAIAG), Bishkek, Kyrgyzstan, in the framework of the Water in Central Asia and CATCOS projects, together with the German Research Center for Geosciences (Potsdam, Germany), the University of Fribourg (Switzerland), conducted field research of the glacier from 2011. In the course of these works, measurements are taken to determine the balance of the glacier mass and geodetic measurements to determine the boundary and morphological characteristics of the glacier. In addition, near to the former destroyed weather station, in 2011 an automatic weather station was installed and still operates. Within the framework of these studies, in order to obtain a more complete picture of the glacier change manner, the interpretation and analysis of space images, aerial photographs, topographic maps, results of geodetic measurements and published results of past studies were carried out.

Fig.1

Methodology of research

The methodology for determining the position of the boundaries of the Abramov Glacier at different times included the interpretation and analysis of aerial photographs and space images from various satellites. The main characteristics of the images are shown in Table 1. In addition to the results of image interpretation, the boundaries of the glacier tongue, determined in the field by GPS devices, as well as topographic maps and published results of past measurements of the position of the glacier boundary made by different authors, were used. The main method for assessing the correctness of the relative position of the glacier boundaries, based on photographs and other data obtained at different times, was the comparison the position of the boundaries of stable relief elements (the boundaries of ancient moraines, local depressions, stream channels, ridges and ridges peaks, rocks) located mainly on a relatively shallow relief, in close proximity to the glacier tongue. In addition, the positioning of images and charts used a criterion such as time stability of the glacier lateral boundaries located above the end of the tongue, outside of the intense lateral ablation zone.

In the process of interpreting, the glacier boundaries were determined from the images synthesized by several spectral channels in the "ENVI" program, by the border pixels most corresponding to the spectral characteristics of the glacier body and the moraine covering it, and, similarly, by the pixels of the near infrared channels (channels 6.7), corresponding to the most cooled surfaces of open ice and moraines under which the ice lies. When interpreting the images, the definition of the border position was, largely, based on an expert assessment that took into account the features of the structure of the glacier body, its structure, nature and location of surface moraines. The formal approach in this case is not effective, since the spectral characteristics of the glacier surface both in visible and infrared ranges, especially in the presence of moraines often coincide with the spectral characteristics of wet ground outside the glacier body. The main attention was focused on the boundary of the glacier tongue located in the ablation region, as on the most variable part of the glacier. The boundary of the glacier in the accumulation area, with this accuracy of study, is considered to be practically unchanged throughout the observation period, which is largely due to the prevailing negative temperature preventing the reduction of the glacier area, as well as steep slopes in the glacier feeding area and ice divide that limits the significant increase of the area.

The largest number of satellite images used to determine the boundary of the Abramov Glacier are the images of various “Landsat” satellites. These images, as well as the pictures under the “Corona” program, were obtained from the “Earth Explorer” Internet service, USGS. “Landsat” satellite images, as can be seen from the Table 1, have a resolution, mostly 15-30 m/p and less often 60 m/p, with a processing level of L1T. This level provides a certain accuracy of geopositioning based on the use of ground control points and a digital model of the Earth's surface. This accuracy is represented by the circular error of geopositioning (RMSE), with the corresponding confidence probability (CP). This error for “Landsat” satellites images (L) is, respectively, L 1-5 MSS <60 m at 88% CP, L 4-5 <30 m at 99.5% CP, L 7 <30 m at 99.7% CP, and L 8 <30m at 99.6% CP. For the rest of the reference data used in interpreting, there is no similar accuracy estimation of geopositioning. The minimum interpretation error of all the images used corresponds to the image resolution value. For results interpretation, the evaluation of the relative spatial positioning accuracy, which was performed by measuring the difference in the position of the boundaries of stable relief forms on the compared reference image and another image and another kind of data geo referenced from the reference image, is of primary importance. The reference pictures, in our case, were an image of the “GeoEye1” satellite with the maximum resolution and initial georeference and images of the “Landsat” satellites. When co-registering images that do not have original georeference (aerial photographs, “Corona” images), the reference points were chosen near the glacier tongue, on stable, relatively gentle forms of relief. In this case, geometric distortions of the image are minimized due to the angle of survey and the inclination of the relief surface. The minimum time interval used to estimate the glacier’s change rate is approximately one year. This is due to the fact that significant part of the information on glacier change, used in this paper, does not have a more detailed time characteristic. At the same time, most of the space images used for analysis were obtained from July to October. That is, the maximum error of the time interval between the compared images is ± 4 months.

Table 1. Space images and aerial photographs used to determine the boundaries of the Abramov Glacier

Date of image taken	Satellite, air craft	Sensor	Images resolution m/p	Processing level, projection, frame of reference
19/10/1964	“CORONA” KH-4A	Photo camera	3	Georeferencing, UTM, WGS 84
22/11/1973, 20/08/1980	“CORONA” KH-9	Photo camera	6	Georeferencing UTM, WGS 84
12/07/1975, 04/08/1981, 18/07/1986	Aerial photograph	Photo camera	1,8;1; 1,6	Georeferencing, UTM, WGS 84
28/09/1977, 14/07/1978	“Landsat – 2”	MSS	60(57x79)	L1T
20/10/1992, 02/08/1998	“Landsat – 5”	TM	30	L1T?
29/08/1999,16/09/2000, 02/08/2001, 22/09/2002,24/08/2003, 27/04/2004, 14/09/2005, 17/09/2006	“Landsat – 7”	ETM	15-30	L1T
19/07/2007	“Geo Eye 1”	Optic electronic	1,2	Orthorectification, UTM,WGS 84
20/09/2007, 05/08/2008, 08/08/2009,	“Landsat – 7”	ETM	15-30	L1T
04/09/2010, 07/09/2011	“Landsat – 5”	TM	30	L1T
03/10/2012	“Landsat – 7”	ETM	15-30	L1T
12/09/2013, 27/06/2014	“Landsat – 8”	OLI_TIRS	15-30	L1T

Research results and discussion

As a result of the interpretation of the Landsat satellite images using the “ENVI 4.7” program and subsequent processing in the “MapInfo 10” program, the boundaries of the Abramov Glacier were obtained in different years. The overall picture of the position of the boundaries of the Abramov Glacier from 1977 to 2013 from the images of the “Landsat 2, 5,7,8” satellite is shown in Figure 2. As can be seen in this figure, the most stable are the lateral east and west borders. The total range of the revealed boundaries discrepancy is, in general, about 60 m/pix, and the errors in determining the individual boundaries in different times are less than 60 meters. The relative accuracy of the boundaries position increases while transiting to the “Landsat - 7.8” images, due to the presence of panchromatic channel with a resolution of 15 m/pix.

The boundaries of the Abramov Glacier in 1977 and 1978 were obtained from the “Landsat-2” satellite images with a resolution of 60 m/pix. In general, due to the relatively low resolution of the images and defects in the form of bands on the original image of 1977, the position of the boundaries is determined with an error of about 60 meters. The discrepancy between the boundaries of reference relief points located near the glacier is also about 60 meters.

The boundaries of the glacier from 1992 to 2014 were obtained from the “Landsat 5,7,8” satellite images, by TM, ETM, OLI_TIRS sensors with a resolution of 30 m/pix, on seven spectral channels, including the thermal one (band 6) and with a resolution of 15 m/pix over a panchromatic channel (band 8). In this case, also the synthesized images were obtained, by which, with various combinations of channels, the glacier boundaries were determined.

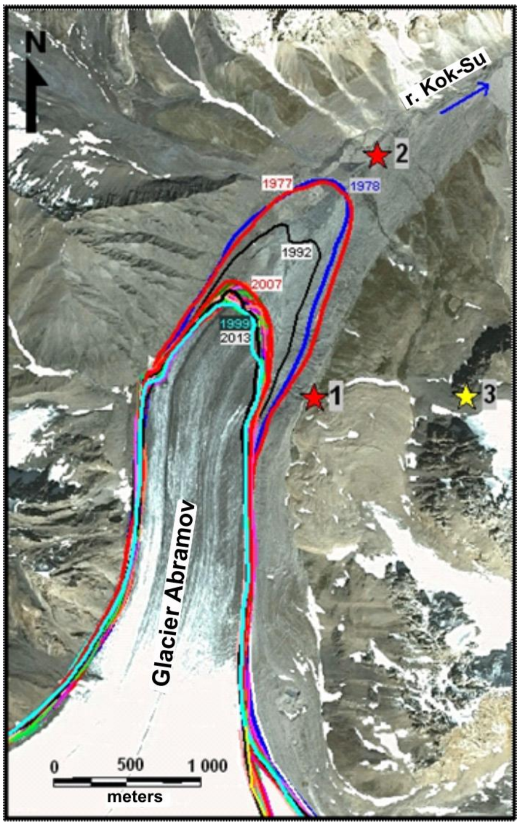


Fig.2 Boundaries of the Abramov Glacier’s tongue from 1977 to 2013
According to the “Landsat 2, 5,7,8” images. 1, 2 – location of the station and *Abramov Glacier* hydro gauge station correspondingly, 3- the location of the CAIAG’s automatic weather station.

As it is visible in Figure 2, the borders discrepancy of 1977-1978 in the frontal part of the tongue by 15-25 meters with the lower position of the boarder of 1978 with respect to the 1977 boarder is not identified with the advance of the glacier, as this difference is within the limits of a possible positioning error and interpretation. In general, it can be stated that the average boarder of the glacier's frontier during the period 1977-1978 was determined quite accurately, which is confirmed by a small discrepancy in the annual boundaries in the frontal part of the tongue, despite the fact that the "Landsat" images of this time have worse resolution, comparing to the later photographs. In addition, Figure 2 shows that the glacier recession occurred from 1978 to 1992, to a distance of about 380 m with a linear velocity of 26 m/year relative to the most advanced down the relief parts of the borders. From 1992 to 1998 and 1999, glacier recession continued to the distances of 600 and 680 meters, respectively, while the average rate increased significantly to about 86 m/year.

After that, as the Figure 3 shows, from 1999 to 2001, there was a relative stabilization of the tongue boundary, manifested in recession slowdown and in close grouping of the boundaries of this period of time in the frontal part, in the range of about 20 m. In this case, the accuracy of determining the position of individual annual boundaries in interpretation is not sufficient for a reliable determination of the relative direction of their motion and the magnitude of the displacement. Therefore, linear velocities are defined approximately: from 1999 to 2000 - recession at a speed of 20 m/year and from 2000 to 2001, possible advancing at a speed of 10 m/year.

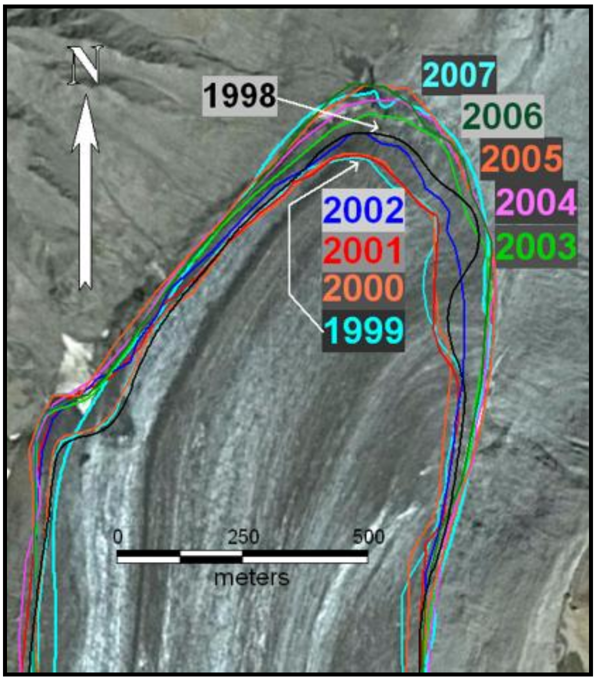


Fig.3 Borders of the Abramov Glacier from 1998 to 2007
according to the "Geo Eye 1" and "Landsat 5, 7" satellites images

Since 2001, the apparent advance of the glacier began with an increase in its area (see Fig. 3), which lasted until 2005. The maximum linear advance of the boundary of the glacier tongue was about 150-160 m in 2001-2005, that is, the average speed of the advance was about 30-40 m/year. Thus, we quite confidently fixed continuous in time, significant in the extent and area of the Abramov Glacier tongue's advance in the period 2001-2005. In this case, (see Figure 3) a "Geo Eye 1" image from 19/07/2007, from the "Google Earth" service, having a resolution of about 1.2 m/pix, is used as the background image. The position of the glacier boundary in 2007 was determined based on this picture. This boundary diverges in the frontal part by ± 10 - 15 m from the boundary determined from the "Landsat 7" image from 20/09/2007. Subsequently, from 2005 to 2007, there was a relative stabilization of the glacier's boundary with a tendency to recession along its individual fragments in the range of up to 40 meters. Starting from 2007 to 2011, as can be seen in Figure 4, the apparent recession of the glacier tongue began, maximum to 160 meters, at an average rate of 40 m/year, determined from the "Landsat-8" images. The change in the boundary of the glacier's tongue from 2011 to 2014 by the "Landsat-8" image is shown in Figure 5. As the figure shows, the change in the position of individual annual boundaries during this period is insignificant and is within the maximum resolution of 15 m/pix. For this reason, it is difficult to unambiguously determine the direction of the change of individual borders, in particular, the advancing nature of the border position in 2012 in its frontal part, relatively to the border in 2011 requires additional confirmation. However, according to Figure 6, the tendency of the recession from 2012 to 2014 with a linear rate of about 20 m/year is confidently determined, along the boundaries, the position of which is obtained by instrumental measurements with GPS instrument, with the positioning accuracy up to 10 m. A segment of the tongue separated from the main body along the western boundary, is preserved from melting due to the presence of moraine. On the same boundaries, the linear recession rate from 2007 to 2014 is about 23 m/year. During the same period, as Figures 5 and 6 show, the width of the glacier's tongue near its end part is reduced by retreating to the west of its eastern boundary by 70-80 m, with a gradual decrease in this width reduction in the south.

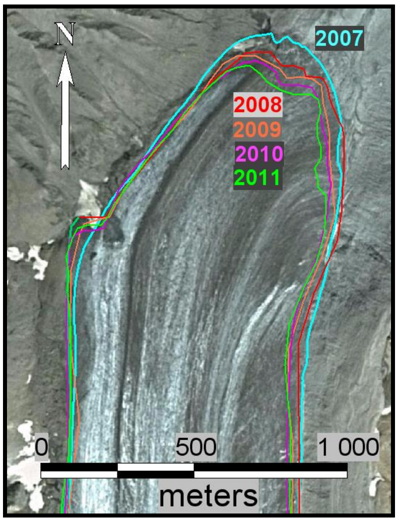


Fig.4 The boundaries of the Abramov Glacier from the images of the "Geo Eye 1" and "Landsat 8" images from 2007 to 2011

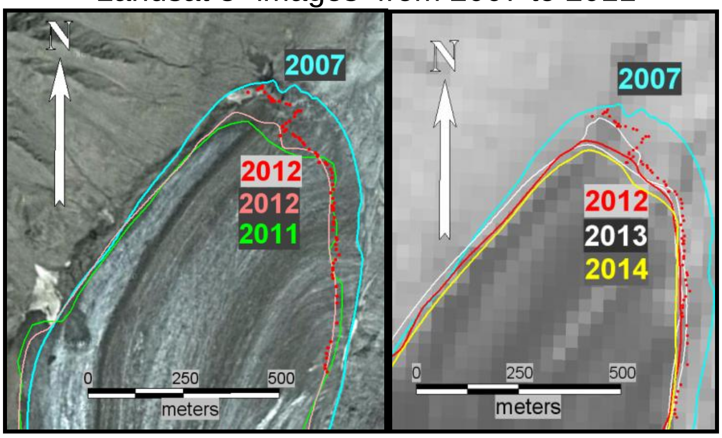


Fig.5 Borders of the Abramov Glacier from 2007 to 2014 from the "Geo Eye 1" and "Landsat 8" images, including in the infrared range (2014) and field measurements by GPS devices with an accuracy of 10 m (dotted lines).

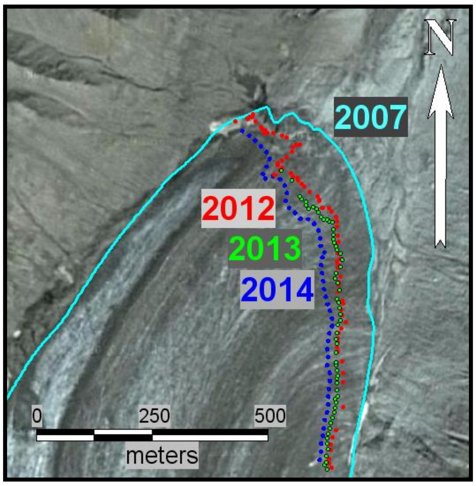
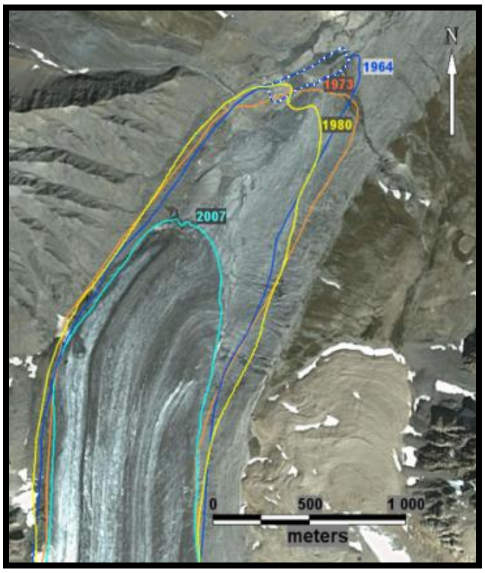


Fig. 6 The boundaries of the Abramov Glacier from 2007 to 2014 from the “Geo Eye 1”image and field measurements taken by GPS devices with an accuracy up to 10 m (dotted lines).

In order to detail the boundaries of the Abramov Glacier at different times, in addition to the “Landsat” satellite images, the “Corona” satellite images taken by the US satellites from August 1960 to May 1972 and from March 1973 to October 1980 were used. They are also obtained from the “Earth Explorer” Internet service, USGS, in the section: Declass 1 (1996), 2 (2002). The characteristics of these images are given in Table 1. Georeferencing of these images was carried out according to “Geo Eye 1” image from 19/07/2007 from the “Google Earth” service by characteristic ground control points located near the Abramov Glacier’s tongue. Interpretation of the glacier boundaries from these images allowed to supplement the picture of their changes in those years, for which there are no “Landsat” images. The boundaries of the glacier from these images are shown in Fig. 7. Correction of the glacier boundaries location, obtained from the “Corona” image, included its transformation in the form of a horizontal displacement and rotation of the vector layer containing the glacier boundary. Criteria for the transformation correctness were the boundaries of the stable forms of relief and lateral boundaries of the glacier. In this case, the error in interpretation of the boundaries due to the non-orthogonality of the image, the deformation of the film, and the inaccuracy of the geopositioning, do not exceed 50-100 meters. As a result, the boundaries of the glacier were obtained in 1964, 1973 and 1980. In this case, an interesting fact, shown in figure 8, is the discovery of the area of destruction (in the photo of the “Corona” from 1964), apparently by a temporary watercourse, possibly a mudflow (blue arrow), in the western part of the glacier tongue (red contour), the length is about 440 m and a width is up to 100 m. This phenomenon must be taken into account when analyzing the rate of glaciers’ change and the history of their development.



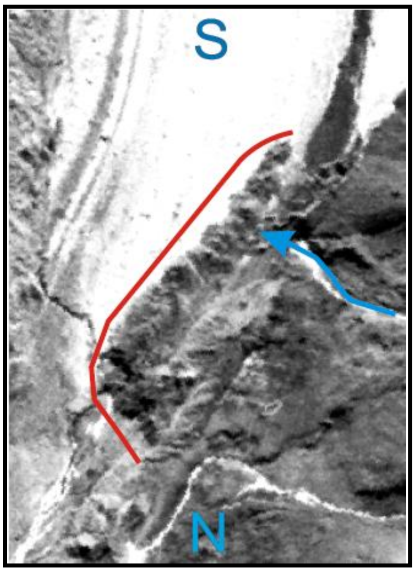


Fig.7 (left), Fig.8 (right) The boundaries of the Abramov Glacier from the satellite images of the “Corona” program in 1964, 1973, 1980. The dotted line in Fig. 7 indicates the boundary of the destroyed segment of the tongue

In addition, the position of the tongue of the Abramov Glacier in 1981 was determined from an aerial photograph from 04/08/1981 (Table 1). Its georeference is performed in the same way as the aforementioned “Corona” images. The correctness of the reference and the relative linear error are determined by the characteristic stable elements of the relief, the latter is estimated in the same range as for the “Corona” images. The glacier’s contour from the “Corona” images and the mentioned aerial photo of the glacier on the background of the “Geo Eye 1” satellite from 2007 is shown in Fig. 9. By comparing the borders of the 1980 and 1981, they have a divergence in the frontal part of the tongue, in the north about 55 meters and a sequence typical for the advance regime, with a lower boundary position in 1981, relative to the boundary of 1980. This situation is not interpreted as an advance, since a boundary error is possible. However, accounting the conformity of these boundaries and different sources, we can confidently state that the average position of the boundaries of the glacier during the period 1980-1981 is determined objectively with an error of not more than 60 m. The same figure shows the boundaries of 1973,1977,1978, obtained from the “Corona” and “Landsat-2” images. Their position indicates that together with the 1980-1981 borders they form a fairly compact group in the total range of displacements up to 100 m and reflect a relative stabilization of the perennial movement of the glacier from the end of 1973 to 1981.

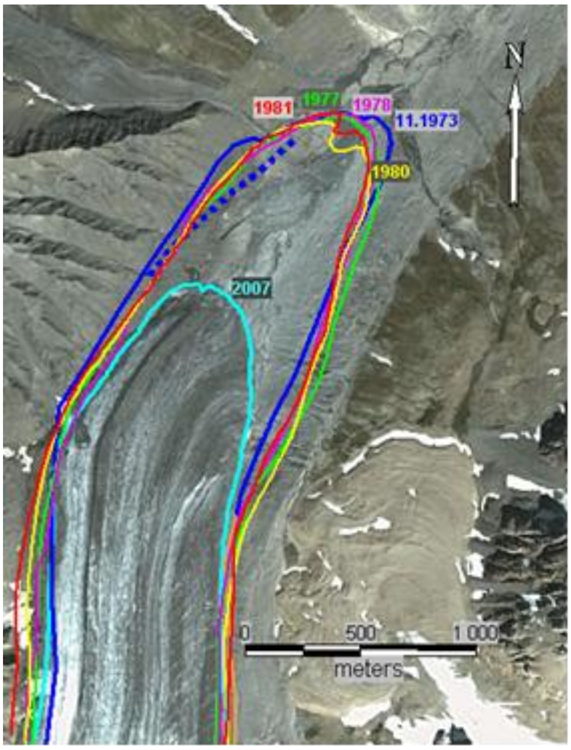


Fig.9

Along with the space images and aerial photographs, for a retrospective analysis of changes in the glacier’s boundary, topographic maps were used. Thus, to determine the glacier’s boundary in 1986, a topographic map of the scale 1: 25000 of the Abramov Glacier area was created, based on the stereo-topographic survey of 1986 and published in 1991 by the Kyrgyz aerogeodetic enterprise of the “Gosgeodesy” of the USSR. This map in the original has a georeference in the local coordinate system, so it was georeferenced in “Pulkovo 42” by a topographic map of scale 1: 100000, and then transformed into WG WGS 84. In this case, the correction of the relative position of the glacier’s boundary in 1986 was carried out in the same way as for space images along the boundaries of stable relief elements. In addition, the correctness of the glacier's boundary on the map is confirmed by the boundary obtained by interpreting the aerial photo from 18/07/1986. The position of this boundary, along with the previously obtained boundaries and is shown in Fig. 10.

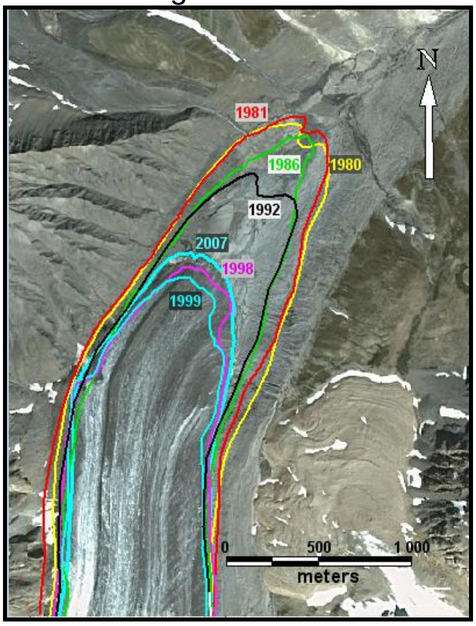


Fig.10

In this case, it should be noted that in 1986 the boundary in the frontal part tends toward the shown above group of boundaries for 1973-1981 (Fig. 9.10), which fix the period of stabilization or deceleration of the glacier's change, this suggests that this period continued, at least, until 1986. During the period from the end of 1973 to 1986, the front part of the glacier's boundary was located and moved along the axis of the glacier in the range of 80-90 meters. The feature of the border shape in 1986 is its wedge-shaped nature. This feature of the tongue form is observed against the background of the arcuate shape of the boundaries in other years, as can be seen in Figures 9, 10. After 1986, the process of glacier degradation continued, but in 1992 the form of the glacier tongue acquired an arcuate shape, which is preserved (according to available data) to the present day. As will be shown below, the wedge shape of the glacier tongue was also observed in other years of glacier functioning. Thus, due to the involvement of the borders in the analysis of the glacier location in addition to the images of the "Landsat" satellite, as well as aerial photographs, topographic maps and "Corona" images, it was possible to obtain a more detailed picture of the glacier boundaries over time.

In order to obtain a more complete picture of the Abramov Glacier development and to integrate previously acquired knowledge into the system of modern digital data, the results of studies of this glacier, given in the publication of Glazyrin G. and others [1], are used, particularly, in the published version of the boundary scheme from 1850 to 1984. This scheme was scaled and georeferenced, with an accuracy of at least 50-100 meters, according to the data given in it on the distances between different-in-time boundaries, along the characteristic stable contours of the relief, the bed of the Kok-Su River and along the boundaries of the glacier obtained as a result of interpreting space images. This scheme is shown in Figure 11, on the background of the previously mentioned "Geo Eye 1" satellite image from 2007. The correctness of the scheme proportions and the geo reference is visible along the boundary of 1850, which fits well into the boundary of the ice erosion impact to the western and eastern sides of the valley that is clearly observed on the cosmic image, by relevance of characteristic turn of the glacier along the western boundary to the northeast, and is also confirmed by alignment of the Kok-Su River's bed on the scheme with the space image and by alignment of general boarder of 1973-74 on the scheme with the boundary of 1973 obtained from "Corona" image (Fig. 7, 11). Thus, Figure 11 shows the boundaries of the Abramov Glacier in 1850, 1900, 1936, 1954, 1967, 1970, 1973-74, 1984 taken from publication of Glazyrin G. et al. The position of the 1954 border on the scheme is determined on the basis of the report in the publication [1] about distance of 650m between the boundaries of 1954 and 1967, obtained during interpretation of aerial photographs. In general, as can be seen in Fig. 11, the glacier boundaries are quite accurately aligned on the scheme and space images, especially in the frontal part of the glacier tongue and somewhat worse along the lateral boundaries, especially along the eastern one. By our assessment, the divergence of the eastern borders by the scheme, as relatively defined by us, does not reflect their real position and requires correction by shifting in the western direction to the position of the western borders of the glacier obtained during interpretation of space images. The need for such a correction is clearly visible in Figure 10 by the position of the boarders' eastern parts of the 1980, 1981, and 1986.

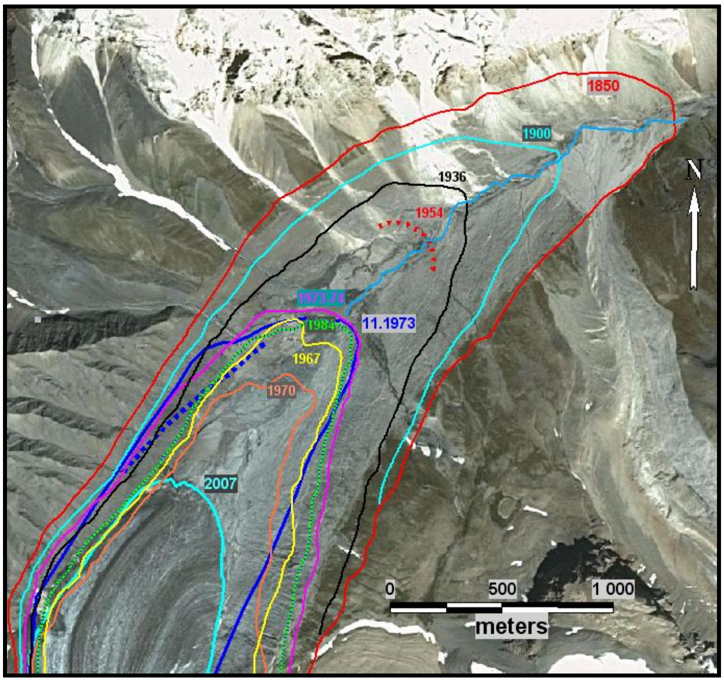


Fig. 11

In order to further detail the change in the position of the glacier tongue between 1969 and 1974, including the significant advanced movement (*surge*) of the glacier in 1972-1973 known from the publication [1], the detailed scheme of Suslov V. F. et al was used [3]. This scheme was also scaled and georeferenced along the boundaries of the glacier, which almost coincide with those obtained from the "Corona" space image dated 22/11/1973 and the aerial photograph from 12/07/1975. Figure 12 shows the position of the glacier boundaries from 1969 to 1975 according to Suslov V.F. et al, against the backdrop of the "Corona" image and the glacier's boundary obtained by our interpretation of this image in 1973. In this case, attention is drawn to the good alignment of the eastern and northern parts of the glacier boundary by the scheme, with the glacier boundary from the space image. Some deviation to the east of the boundary's western part in the scheme from the boundary on satellite image is possibly related to the definition of the glacier boundary when drawing up the scheme on the apparent manifestation of ice, without taking into account the part of the glacier covered by moraine (which is shown in Fig. 9,11,12 with a dashed and darker line). Taking into account the boundaries shown on the scheme of Suslov V. F. et al, as well as the boundaries of the glacier by the scheme of Glazyrin G. et al., as well as the boundary of 1964, obtained by us from the "Corona" image, the location of the borders between 1964 and 1972 (Fig. 13), preceded the pulsating movement of the glacier, was obtained. It should be noted that in the process of geopositioning of the scheme (Suslov V. F. et al), the position of the glacier boundaries in 1969 and 1972, mapped on it, was corrected by a shift in the western direction, in accordance with the boundary of 1970 on the scheme of Glazyrin G. et al. [1].

The result of this correction, shown in Fig. 13, provided the position of the boundaries on the scheme of Suslov V. F. etc., which corresponds to the most probable sequential inherited change in the glacier boundary plan during its change.

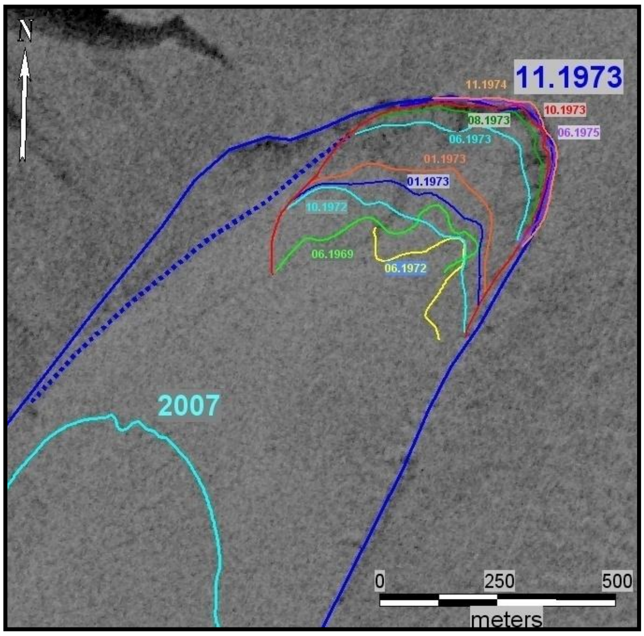


Fig. 12

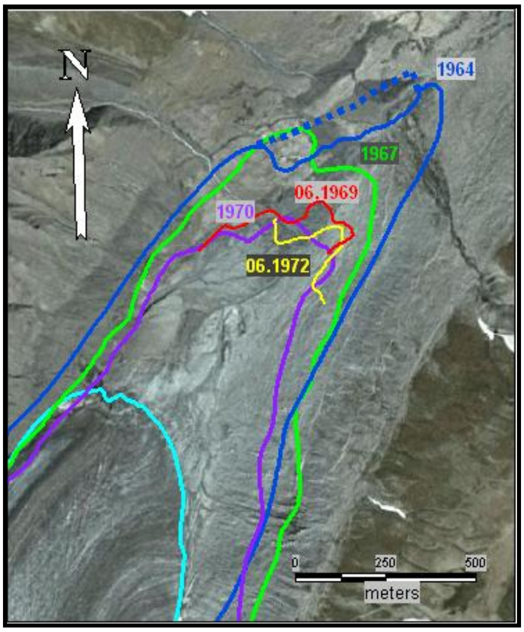


Fig. 13

In the period from 1964 to 1972, as follows from the publication [1], from 1967 to 1970 there was a rapid glacier recession by 290 meters, with an average rate of about 97 m/year. According to our reference to the scheme of Glazyrin G. et al., this distance is 250 m, and the rate is 83 m/year, that is, the difference in distance and speed is about 14%, which corresponds to a possible linear positioning error within 50 meters. And in 1969-1972, according to the scheme of Suslov V. F. and others, the glacier underwent a significant narrowing of the tongue, which acquired a wedge-like shape, compared with the shape of the tongue in 1967. In this case, there are clear signs of increased lateral ablation, manifested in a recession to the west of the eastern border by approximately 100 meters. From the detailed scheme of Suslov V.F. and others (Fig. 12, 13), it also follows that during the period from 1969-1972 the stabilization of the end part of the boundary of the glacier tongue took place, when various changes occurred in the range of about 80 m. Starting from October 1972, as shown in Figure 12, the glacier tongue acquires an arcuate shape, which was probably caused by the beginning of advanced movement. That is, the main movement of the glacier began in late 1972 and then continued until the end of 1973, reaching a value of about 300-350 m, with an average ice speed of about 300-350 m/year. According to the results of direct observations [4], as shown in Figure 14, during this period the maximum speed of movement reached 530 m/year (1.45 m/day).

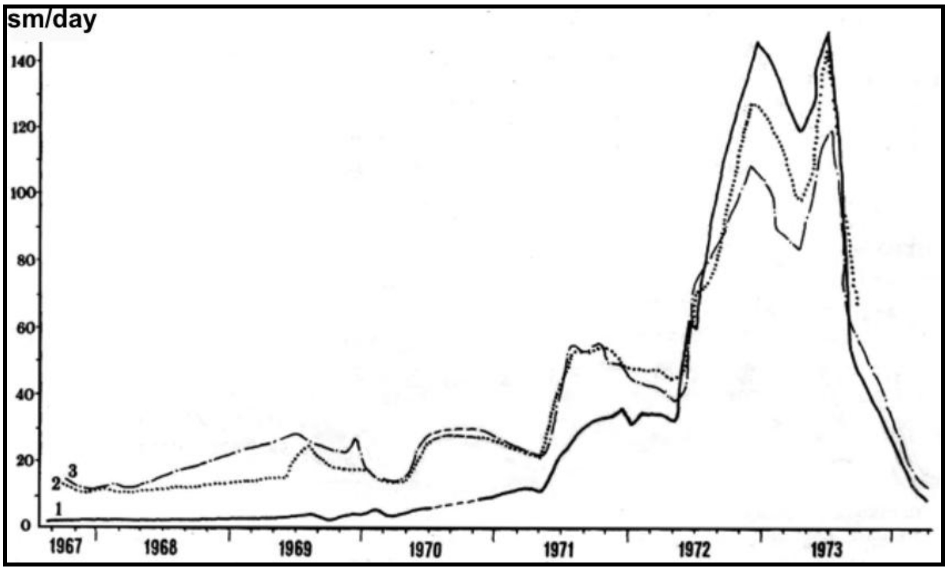


Fig.14 Change in the linear velocity of ice movement of the Abramov Glacier, In its different parts (1-end, 2-middle, 3-beginning of the tongue) in the period from 1967 to 1974.

Then, from 1973 to 1974, the advance rate is significantly reduced to 40 m/year. In this latter position, as follows from their diagrams in Figure 12, the border remained until June-July 1975. Thus, the relatively rapid movement of the glacier continued throughout the year and was replaced by a relatively long stabilization of the tongue boundary. In this case, as shown in Figures 9, 10 and 11, a comparatively long period of stabilization of the glacier boundary from 1974 to 1986, that is, for 12 years, is noteworthy. On the basis of the scheme of Glazyrin G. et al., and our additions to the boundaries of different years, it can be stated that in this interim within the general range of about 50-80m, there were changes in the glacier boundary in different directions: from 1975 to 1978 in the form of recession (-13 m/year), from 1978 to 1980 in a form of possible advancing (+ 47m/year), 1980-1981 - recession (-40 m/year), 1981-1984 - advance (+ 20 m/year) and 1984-1986 recession (-70 m/year). Subsequently, as shown in Figure 10 and 2, until 1999, there is, according to available data, an obvious degradation of the glacier. In general, from 1984 to 2001 there is recession of about 1130 m, with an average rate of 70.6 m/year. The subsequent change in the glacier until 2014 is described above.

Thus, by supplementing the results of the interpretation of “Landsat” images with data from other satellites, maps and published charts, a more detailed picture of the nature and rate of change of the Abramov Glacier was obtained. The general picture of the changes in the boundaries of the tongue of the Abramov Glacier from 1850 to 2013 is shown in Figure 15.

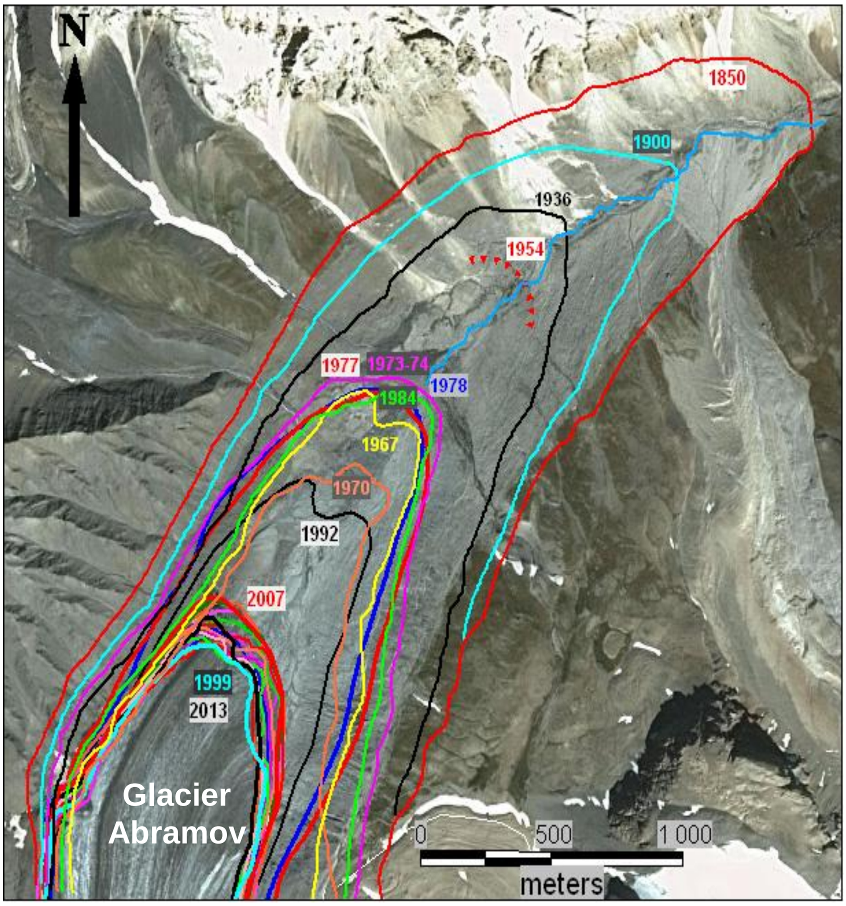


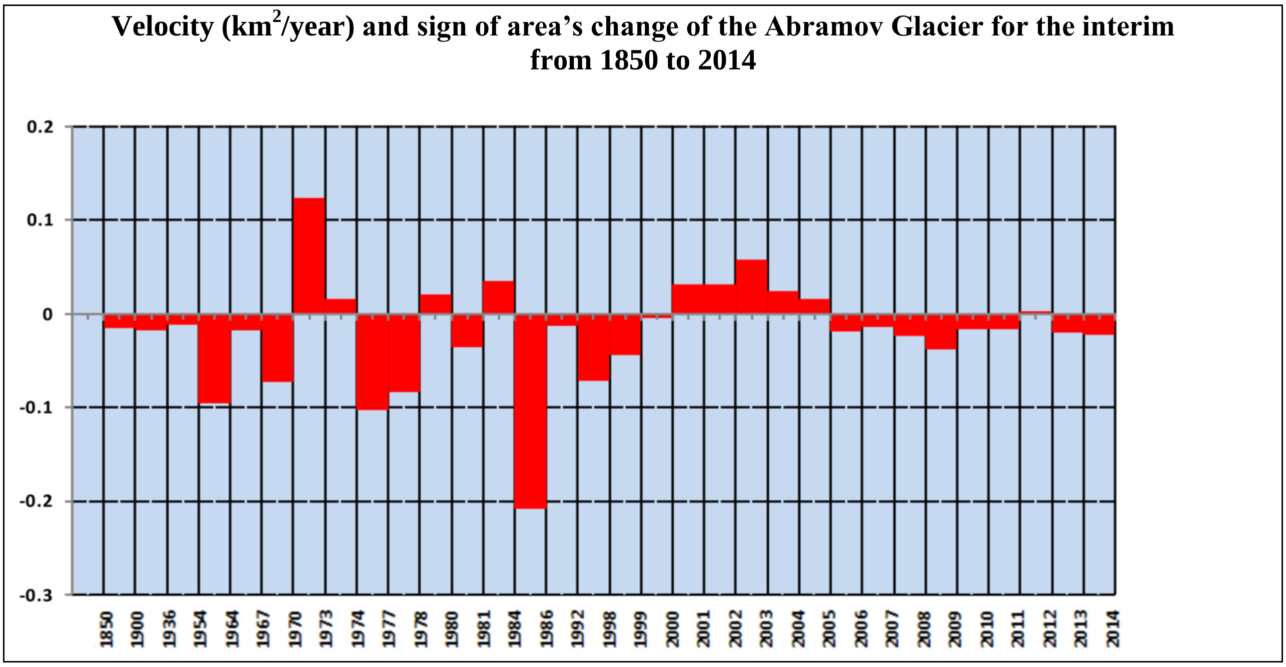
Fig.15

It should be noted that the linear velocities considered above are of an indicative nature, since they are determined from the individual points of the glacier boundaries, which maximally protrude down the relief and do not deviate anomalously from the general character of the configuration of the boundary. In this case, as can be seen from the above figures, the boundary often has a tortuous shape and, in addition, the tongue of the glacier can vary considerably in the lateral parts, narrowing or widening. For this reason, changing the area of the glacier tongue is a more objective and precise parameter that takes into account all the features of the change in the shape of the boundary. Accordingly, for the different boundaries defined above, the changes in area and rate of change in area per year were calculated for the corresponding closed contours obtained with a general comparison line drawn across that part of the tongue where the time-varying side boundaries have a minimum discrepancy. These results, along with an approximate estimate of the linear velocity, are shown in Table 2 and in Figure 16. It should be emphasized that for a short time interval between the definition of the glacier boundaries (in our case, about one year), and correspondingly, small linear changes in their position, there may be a contradiction between the sign of the linear and area change rates, since the first does not take into account the difference in the position of the compared boundaries at their mutual intersection. In this case, a more accurate result provides a longer time interval of comparing boundaries. The fact of the contradiction in the speed sign is reflected in Table 2 for linear velocities in the form of their values, enclosed in parentheses, the same reason has a difference in the linear and area estimates of the beginning of the advance of the glacier in 2000-2001. In the same table, the relatively rapid advancing of the glacier is shown in red color (1972-1973) without a significant change in the volume of ice, which can be determined as a pulsation, probably is directly related to the increase in the input part of the glacier balance; and in blue color (2000-2005) a relatively slow advancing, possibly more dependent on an increase in the incoming part of the balance. It is necessary to emphasize that in both cases there was a prerequisite for advancing in the form of an increase in the incoming part of the mass balance of the glacier. Thus, from the publication [2], it follows that in 1972 the glacier had a positive mass balance against the background of previous and subsequent years with a negative balance (Fig. 23). And from the publication [5] it follows that in the period from 2000 to 2005, the two years of 2001 and 2002 had a minimum negative balance, relatively to the preceding and subsequent years.

Table 2

Years	**Change in area Δ S (км^2)**	**Rate of change in area Vs1 (km^2/year) (Mandychev A.)**	**Rate of change in area Vs2 (km^2/year) (Glazyrin G. et al., 1993)**	**Δ % (Δ = Vs1 - Vs2)**	**Linear speed VL (m/year)**
1850-1900	-0.762	-0.015	-0,014	6.7	-11.2
1900-1936	-0.607	-0.017	-0,013	23.5	-12.8
1936-1954	-0.202	-0.011			-13.9
1954-1964	-0.953	-0.095			-34
1964-1967	-0.051	-0.017	-0,027	-37	-103.3
1967-1970	-0.215	-0.072	-0,077	-6.5	-73.3
*)1970-1973	0.372	0.124	0,18	-31.1	116.7
**)1972-1973	0,109	0,109			300 - 350
1973-1974	0.016	0.016	0,007	56	40
1974-1977	-0.307	-0.102			-12.7
1977-1978	-0.083	-0.083			(25)
1978-1980	0.042	0.021			46.5
1980-1981	-0.035	-0.035			-40
1981-1984	0.108	0.036	0,024	33.3	20
1984-1986	-0.416	-0.208			-70
1986-1992	-0.077	-0.0128			-51.7
1992-1998	-0.427	-0.071			-101.7
1998-1999	-0.044	-0.044			-80
1999-2000	-0.0037	-0.0037			-20
2000-2001	0.0317	0.0317			10
2001-2002	0.032	0.032			49
2002-2003	0.058	0.058			56
2003-2004	0.025	0.025			39
2004-2005	0.016	0.016			27
2005-2006	-0.0185	-0.0185			-20
2006-2007	-0.0139	-0.0139			-20
2007-2008	-0.0234	-0.0234			-60
2008-2009	-0.0369	-0.0369			-30
2009-2010	-0.0164	-0.0164			-25
2010-2011	-0.0161	-0.0161			-30
2011-2012	0.0038	0.0038			(-15)
2012-2013	-0.0199	-0.0199			-15
2013-2014	-0.0217	-0.0217			-30

*) according to the scheme of Glazyrin G. et al.. **) according to the scheme of Suslov V.F. et al..
(-) recession, (+) advance of the glacier.



Years of boundaries' determination

Fig.16

Table 2 compares the rates of glacier changes obtained earlier (Glazyrin G. et al., 1993), [1] and obtained by us in this paper. As can be seen, the maximum discrepancy in the speed estimate is 56%, with our estimate exceeding by almost 2 times, observed for the period 1973-1974. This is explained by the calculation of the area in our case by more detailed scheme of Suslov V. F.. The average difference in the estimate of the rate of change in the glacier's area, without the above extreme value, is 21% for the positive and 20.5% for the negative value. It should be noted that the boundaries of 1969 and 1972 from the scheme of Suslov V.F. were not used to estimate the rate of change in the glacier's area because of uncertainty of the position of the tongue lateral boundaries.

In general, at relatively large time intervals, the sign and value of the change in the glacier area, given in Table 2, correspond to the changes above in its boundaries on linear measurements. But the measurement of the area allows to take more fully into account all the features of the glacier's shape change in plan, in contrast to the measurement of length. In particular, an example of such case is the analysis of the glacier change in the period 1984-1986. The high rate of glacier's area reduction is 0.21 km^2/year between 1984 and 1986, is apparently due to the fact that by 1986 there was a significant lateral melting of the glacier, so that, with a slight reduction in length, its width in the tongue part decreased significantly. This feature was reflected, as already mentioned, in the formation of the narrowed wedge-shaped form of the glacier tongue (Fig. 10). In the case of an exception of the 1986 boundary, the rate of change in the glacier's area from 1984 to 1992 is 0.06 km^2/year, that is, which is not abnormally high. It should be noted that the phenomenon of the narrowing of the glacier body in its tongue part is not exceptional and was manifested only in 1986. A similar phenomenon, when the form of the tongue had a narrowed appearance, was observed in 1964 (Fig. 7), and also according to the scheme of Suslov V. F et al (Fig. 12, 13) in 1969 and 1972, and according to the scheme of Glazyrin G. et al. (Fig. 11, 13), in 1970. In the latter case, as shown in Table 3, a significant change in the area (0.37 km^2) between 1970 and 1973 is due to the narrow form of the glacier tongue in 1970, so the main change in the area of about 0.26 km^2 falls on the period 1970-1972. Thus, unlike the arc-shaped form that fills the entire width of the valley, a narrowed or wedge-shaped form of the glacier's tongue is rarely observed, filling only part of the valley in width. Such a situation is possible if lateral ablation is predominant over the longitudinal, that is, probably, under the condition of temporary deceleration, growth cessation or decrease in the average annual vertical air temperature gradient in the glacier area. As shown in Figure 23 and according to the data of the *Abramov Glacier* weather station, such conditions periodically occurred in the area of the Abramov Glacier in the periods: 1971-1972, 1973-1974, and 1977-1986.

Based on the data on the glacial area change from Table 2, a cumulative graph of the glacier area change over the entire observation period is shown in Figure 17. Since the change in the glacier area is related to the change in ice volume, this graph approximately reflects a mainly negative mass balance of the glacier for the entire period of observation, taking into account the fact that the pulsating movements of the glacier, which lead only to an increase in its area, are not directly related to the increase in the input balance of the glacier mass balance. The graph in Figure 17 indicates that from 1850 to 1954 the average recession rate of the glacier was about 0.014 km^2/year. From 1954 to 1970, the recession rate significantly increased to 0.061 km^2/year. And in the period 1970-1974 there was an increase in the area with an average speed of 0.07 km^2/year. And anomalously, of 0.11 km^2/year in the period from 1972 to 1973 (according to the scheme of Suslov V.F, et al.), after which, until 1978, the area reduced with an average speed of 0.09 km^2/year. In 1978-1980 the area increased (0.021 km^2/year), in 1980-1981 it decreased (0.035 km^2/year), and in 1981-1984 it increased again (0.036 km^2/year). From 1984 to 2000, the area reduced with an average speed of about 0.068 km^2/year. From 2000 (since 2001 according to the linear estimates above) until 2005, the glacier area increased at a rate of 0.033 km^2/year and then, until 2014, it decreased at a rate of about 0.021 km^2/year, close to the speed at the beginning of observations and below those values that were observed in some previous periods of time. In this case, attention is drawn to the proximity of the area change rate in the initial period and in the final period of observation, that is, there is no unambiguous tendency to increase the degradation rate, which could be due to the constant increase in anthropogenic impact. Considering the fact that the process of degradation of the Abramov Glacier began earlier than 1850 and that the technogenic impact on the atmosphere at that time in the Central Asian region was minimal for at least for 100 years before 1950, one can assume the significant role of natural factors in the glacier change. This means that at least a 164-year half-period of the glacier degradation phase is possible in its irregular periods of cyclic changes in the form of a successive change of the regression phase by a phase of progress.

In general, the area of the Abramov Glacier in the interim of 1850 - 2014 decreased by 3.65 km^2 with an average speed of about 0.02 km^2/year. Over the same period of time, the length of the glacier decreased by approximately 2950 m with an average speed of about 18 m/year. Based on the mentioned above topographic map of 1991, the scale 1: 25000 (the glacier area in 1986 was determined as 23.28 km^2) and the scheme from the publication [1], the total area of the glacier in 1850 was about 26.4 km^2, and in 2014 It decreased by 3.65 km^2 and amounted to 22.75 km^2, that is, decreased by 13.8%.

Thus, during the period under study from 1850 to 2014, the length, area and, correspondingly, the volume of the Abramov Glacier, the unevenness is observed both in magnitude and in sign with the prevailing general degradation.

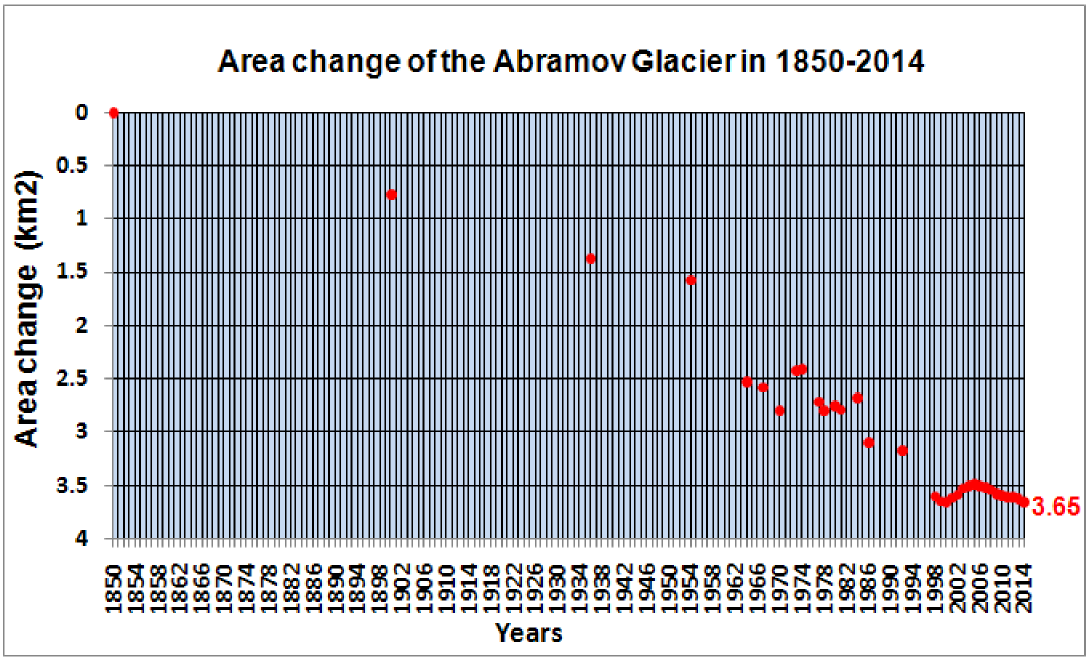


Fig. 17

The main climatic factors affecting the sign and magnitude of the glacier mass balance are known to be the air temperature and the amount of atmospheric precipitation in the glacier's vicinity. Measurements of these parameters were made in the immediate vicinity of the Abramov Glacier between 1967 and 1994 at the *Glacier Abramov* weather station, installed by the Central Asian Regional Research Institute (CARRI, Uzbekistan) and at remoted weather stations of Kyrgyzstan and Tajikistan. So, according to the data of the *Abramov Glacier* weather station (3837 m), the *Sarytash*_weather station (3155m, ≈ 142 km, is located east of the *Abramov Glacier* weather station) and the *Dehavz* weather station (2,564 m, ≈124 km, located west of the *Abramov Glacier* weather station), the surface air temperature directly near the Abramov Glacier and at a considerable distance have a long-term tendency to increase, as shown in Figure 18. Analysis of long-term series of temperature measurements shows that the gradient of the temperature increase on linear trend on the *Abramov Glacier* weather station is 0.008 ° C/year and is the lowest of the three stations; and the maximum amplitude of the change in the average annual temperatures are close on the three stations and have a value of about 2°C. In this case, a high degree of synchronism in the variation of the mean annual temperatures at the above-mentioned weather stations is noteworthy. This manifests itself in the practical coincidence in time of the maxima and minima of short-period uneven periodic oscillations of the mean annual temperatures. This fact may indicate the same conditions for the formation of a multi-year temperature regime of the surface air layer in the area of the three stations and the possibility of using them to complement the measurement data.

Atmospheric precipitation at the three stations under consideration, in the multi-year section, for the period from 1934 to 2011, also tend to increase, as shown in Figure 19. The maximum gradient of annual precipitation increase on the linear trend was recorded by the *Abramov Glacier* weather station (6,6 mm/year), much less by the *Sarytash* weather station (0.9 mm/year) and even less by the *Dehavz* weather station (0.2 mm/year). Moreover, the maximum amplitude of a long-term change in annual precipitation for the *Abramov Glacier* weather station is about 300-400 mm, while for the other two stations it is about 200-300 mm.

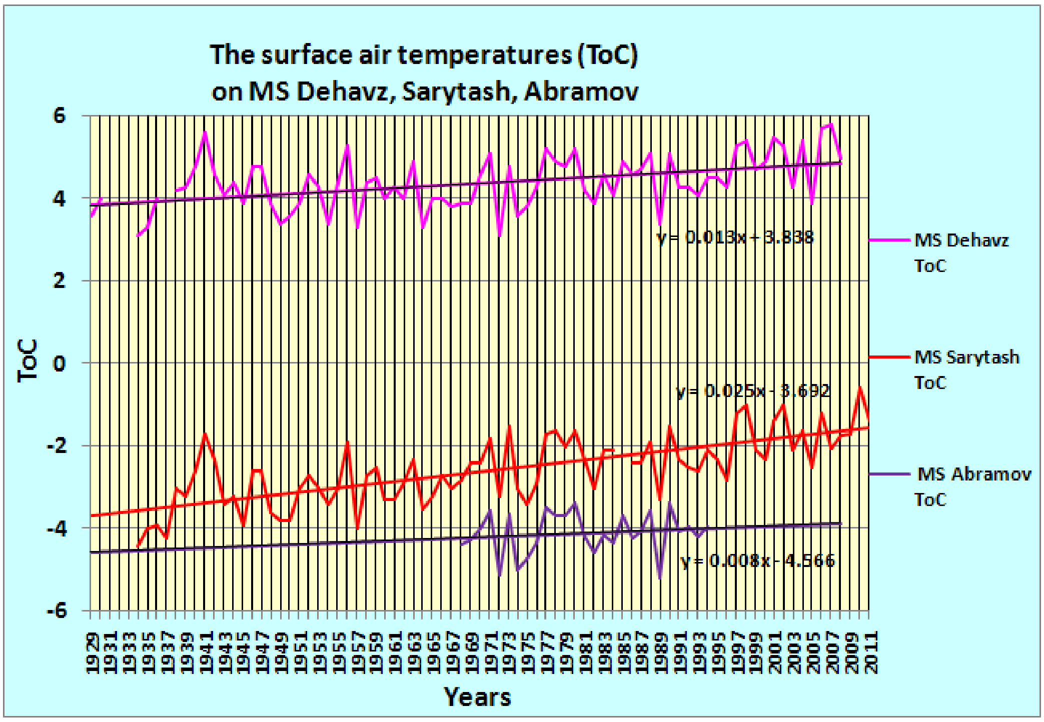


Fig.18 The surface air temperature(t^oC) by MS Dehavz, Sarytash, Abramov

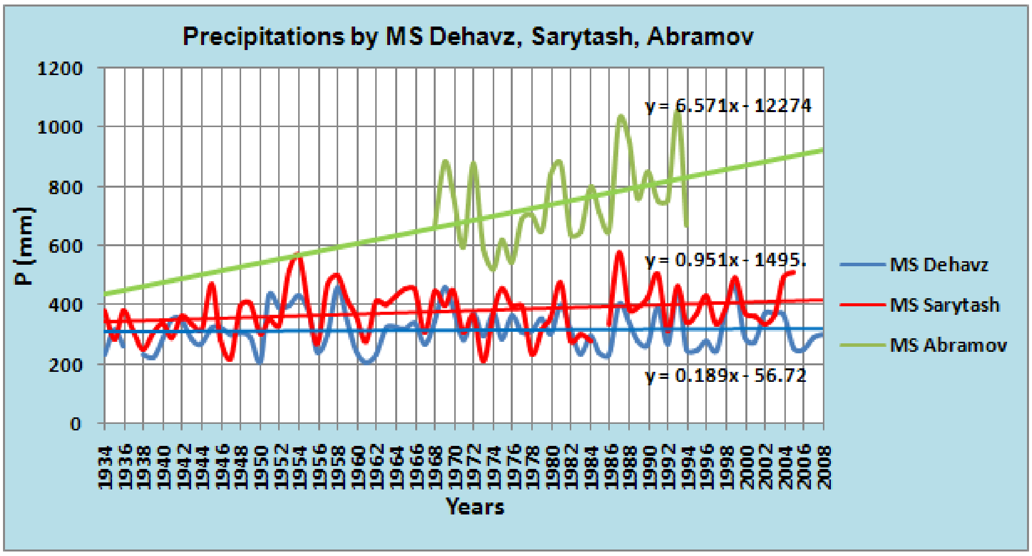


Fig.19 Precipitations (mm) by MS Dehavz, Sarytash, Abramov

Since 2011, an automatic weather station, located 1.1 km east (N39.6486 °; E71.5858 °) from the former *Abramov Glacier* weather station at an altitude of 4102 m, has started operating in the Abramov Glacier area. This station was made by the Central Asian Institute for Applied Geosciences (CAIAG) in cooperation with German and Swiss colleagues in the framework of the Water in Central Asia (CAWa) project http://www.caiag.kg/en/departments/department-3/monitoring-system/monitoring-network/ abramov. The data for this station are shown in Figure 20. In this case, due to technical interruptions in the measurement of air temperatures in 2011 and 2012, it is not possible to correctly calculate the average annual temperature, but the average monthly temperatures are determined fairly well. The average monthly temperatures for the automatic station, in comparison with the previous years of observations at the *Abramov Glacier* meteorological station, are shown in Figure 21. It follows that the air temperatures obtained by means of the automatic weather station are within the range of temperature variations obtained earlier by traditional methods.

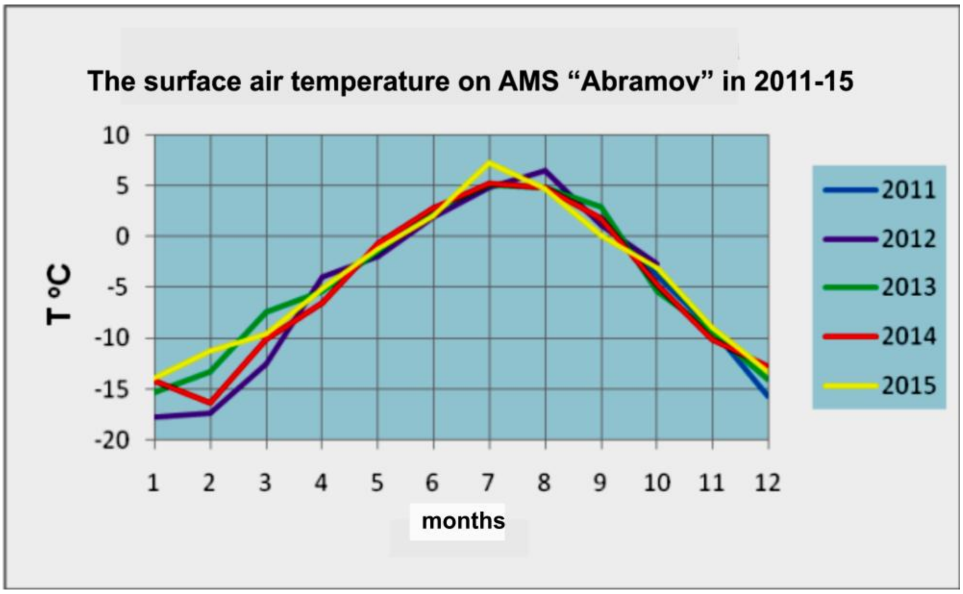


Fig.20

The average annual temperatures for three years from 2013 to 2015 have the following values: -4.653, -5.059, -4.343^{o}C, at temperatures from 1992 to 1994: -3.942, -4.192, -3.925^{o}C. That is, from 1992 to 2015, for 23 years, there is a tendency to increase the surface air temperature on average by 4.685-4.020 = 0.65°C, with a gradient of 0.029°C/year. This value is 3.6 times greater than the gradient on the *Abramov Glacier* station over the period of 26 years, from 1968 to 1994 and is close to the temperature gradient on the *Sarytash* station (Fig. 18). Thus, the temperature degradation factor of the Abramov Glacier has intensified in recent decades.

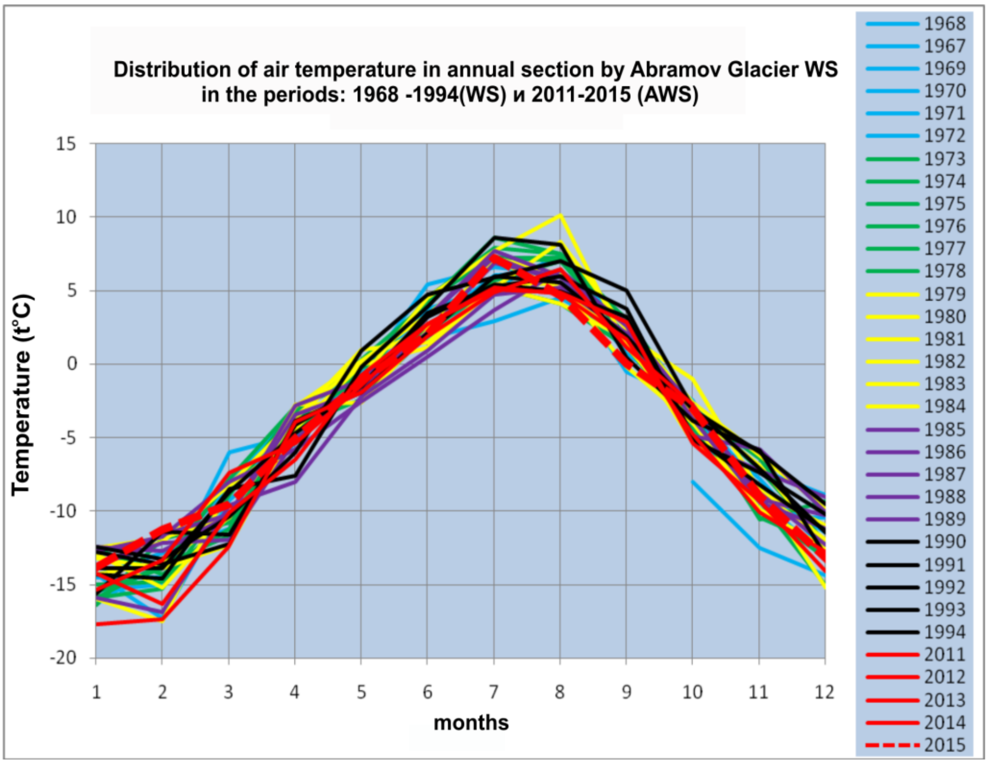


Fig.21

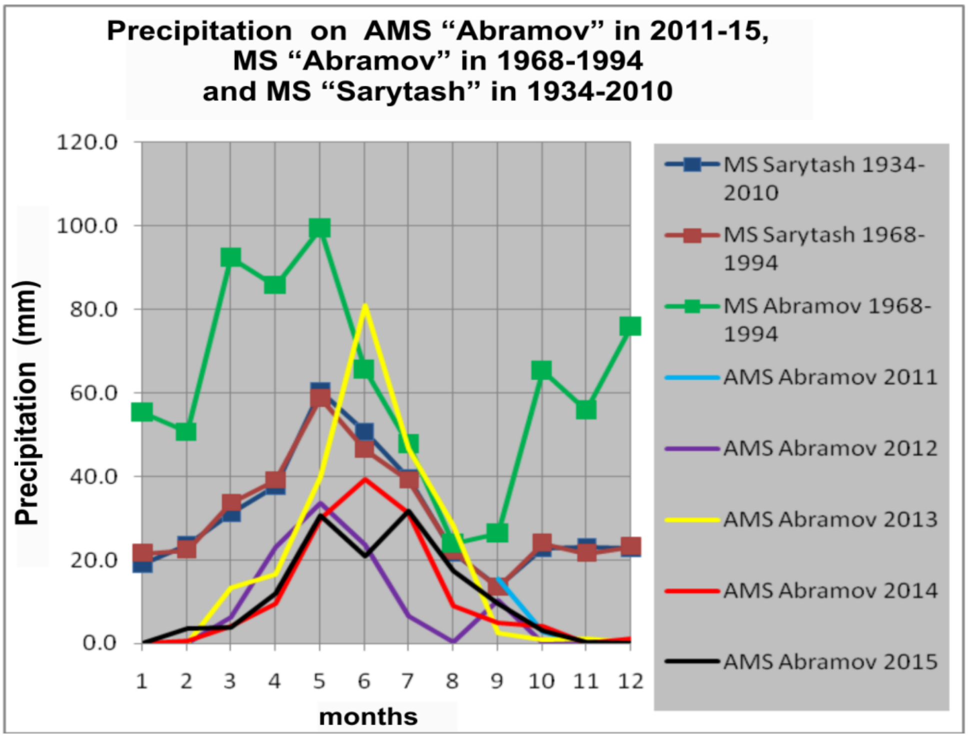


Fig.22

Figure 22 shows the monthly atmospheric precipitation obtained by traditional methods at the *Abramov Glacier* and *Sarytash* weather stations for the periods from 1968-1994 and 1934-2010, respectively, and by the *Abramov* automatic weather station for the period 2011-2014. As follows from this figure, the precipitation values for the automatic station for the period 2011-2015 differ significantly from those of the previous measurements. First of all, very low values attract attention during the period of negative temperatures, which are clearly not true, and in the period of positive temperatures, the precipitation is much smaller than it is typical for the Abramov Glacier region, which is characteristic of the past observations. This situation seems to be related to the features of the automatic rain gauge operation, absence of heating and wind protection, and it requires further study to refine the measurements and obtain objective data on precipitation.

In general, it can be stated that, despite the growth of annual precipitation in the area of the Abramov Glacier, a similar increase in temperatures ensures the formation of a negative mass balance of the glacier, which leads to a continued reduction in its area and volume.

Analysis of the data of Perziger F.I. et.al. [2], Figure 23, shows that there is a direct dependence of the water flow of the Abramov Glacier (measured in the past on the gauging station of the *Abramov Glacier* station, on the Koksu River) on the mean annual surface air temperature in the area.

The mass-balance of this glacier is directly dependent on atmospheric precipitation, which is most noticeable during the periods: 1968-1974; 1981-1988 and in inverse relationship to the average annual air temperature and runoff from the glacier, which was particularly evident during the period 1971-1974. In this case, the water runoff is mainly glacial due to the location of the previously operating gauging station in the immediate vicinity of the glacier (1968 ≈320 m, 1998 ≈1200 m). The linear nature of the graph in Figure 23 is used for clarity and is not interpreted as a physical connection of annual parameters.

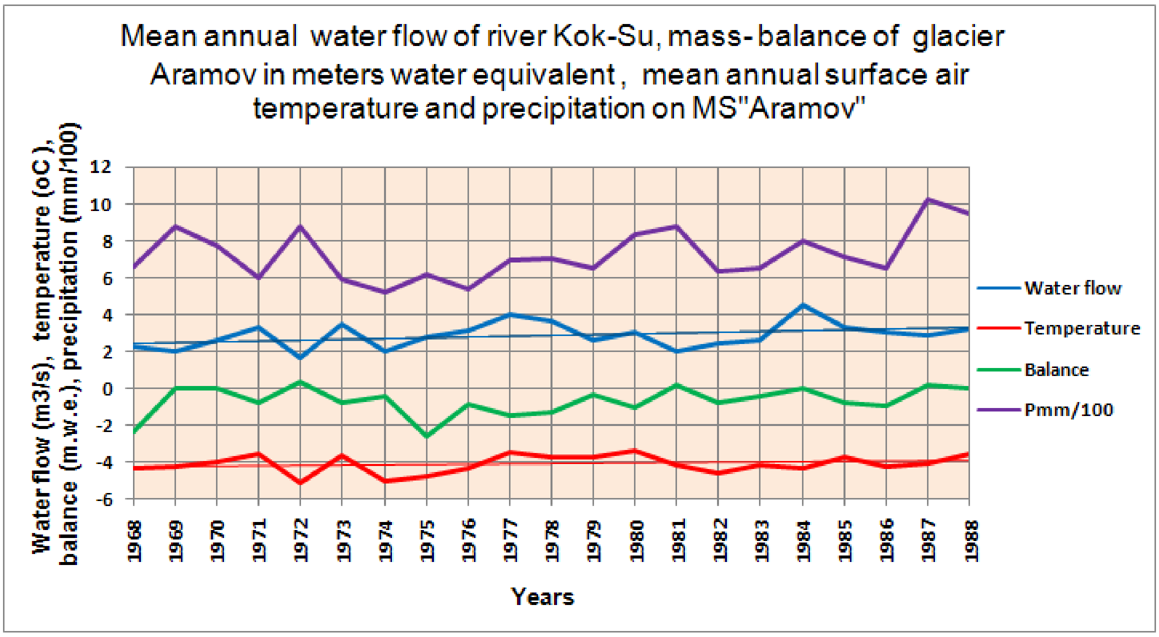


Fig.23

Conclusions

The interpretation of various space images, aerial photographs, and analysis of topographic maps, field measurements and published results allowed to determine the boundaries of the Abramov Glacier in different years and to assess the speed and nature of the glacier changes.

Based on the analysis of available data, as of 2014, the continuation of the trend of a long-termed recession of the Abramov Glacier is confirmed. However, against this background, there are periods of relative stabilization of the position of the frontal part of the tongue with minor movements of one or different signs, as well as periods of advance movements of different duration and intensity. In general, the change in the volume of the Abramov Glacier is uneven in time, which is reflected in the difference in the average rates of change in its area.

Slow changes in the glacier, both recessions and advancing, are mainly due to a change in the balance in the ice arrival and consumption. Relatively rapid changes in the shape of the glacier, which can be defined as pulsations, occur without a significant change in the ice mass. It happens due to the redistribution of ice, in the process of movement of individual parts of the glacier due to changes in the physic-mechanical properties of ice, the unevenness of the ice "accumulation - consumption" within the local negative forms of the glacier bed relief in the feeding area.

The rates of change in the glacier area vary within the limits of: +0.12 ÷ - 0.1 km^2/year, with an average value of: + 0.036 and -0.044 km^2/year, and the rates of glacier length change in the range: +117 (extreme 350) ÷ -103 m / year, with an average value of + 42 (extreme 78) and - 39 m/year. In the case of significant advanced movements (pulsations), the speed can reach abnormal values of about 300-530 m/year (0.8-1.45 m/day) for a short time. In this case, attention is drawn to the proximity of the values of the average velocities of the positive and negative signs, with the exception of anomalous values.

The total glacier's area in 1850 was about 26.4 km^2, and in 2014 it decreased by 3.65 km^2, that is, decreased by 13.8%. In addition to the observations of previous researchers, during field observations in 1972-1973, a significant advanced movement (pulsation) of the Abramov Glacier, with a displacement of about 350 m, this study identified an advanced movement in 2001-2005 with the average displacement of 155 m.

The similarity of the change rate in the glacier's area in the initial period and in the final period of observations is revealed, that is, there is no monotonous tendency in the speed increase, which should have been due to the constant enhancement of anthropogenic impact. This fact of a very minor effect of industrial atmospheric pollution in the Central Asian region, for at least 100 years from the beginning (1850) of the observation period, may indicate a significant role of natural factors in the nature of glacier change.

And also about the presence, at least, of a 164-year half-cycle of the glacier degradation phase in its uneven in magnitude natural periods of cyclic changes in the form of a successive change of the regression phase by a phase of progress.

It is established that along with the arcuate convex form of the tongue, which completely fills the glacial valley in the width, it is likely that under the conditions of relative stabilization of the position of the tongue by stopping the growth of air vertical temperature gradient, there is a predominance of lateral ablation over the longitudinal with formation of a wedge-shaped form of the tongue. In addition, the fact of the change in the shape and size of the glacier tongue under the influence of temporary water or mudflows was discovered.

In the vicinity of the Abramov Glacier, the main climatic factors forming the mass balance, represented by air temperature and atmospheric precipitation, according to the weather stations of Uzbekistan, Kyrgyzhydromet,Tajikhydromet and CAIAG automatic weather station, have a long-term tendency to increase, with the average annual temperature gradient in direct proximity to the glacier in last decades increased 3,6 times. There is a direct correlation between the glacial runoff of the Abramov Glacier measured in the past at the Abramov hydro gauge station on the Kok-Su River, and the average annual surface air temperature in the area. At the same time, the mass balance of this glacier is directly dependent on atmospheric precipitation and is in reverse relationship to the average annual air temperature and runoff from the glacier.

In general, despite the long-term increase in annual precipitation in the area of the Abramov Glacier, a similar increase in temperature ensures the formation of a negative mass balance of the glacier, which leads to a continued reduction in its area and volume.

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