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EVOLUTION OF GLACIAL COMPLEXES IN THE «AKSU-ZHABAGYLY» RESERVE (ARYS RIVER BASIN, SYRDARIA)

Abstract. The article examines changes in glaciers within the Aksu-Zhabagyly State Nature Reserve area of the Arys River basin (a right tributary of the Syrdarya River). The spatial distribution and scale of changes in glacier boundaries under current climate change conditions were assessed. The average rate of glaciation degradation from 2000 to 2023 was estimated. The main factors and trends under the conditions of contemporary climate change were identified. The average air temperature during the ablation period increased by 0.2-0.4 °C, while precipitation from March to May decreased by 10-20%. Directions for further research into glacial complexes are proposed.

Keywords: glaciers, Aksu-Zhabagyly State Nature Reserve, climate change, change in glaciation area.

Introduction. Global climate changes affect the ecological state of mountain landscapes [1, 2]. Degradation of glaciation, reduction of snow cover, and melting of permafrost cause changes in hydrological processes and contribute to the development of dangerous natural processes and phenomena in the mountains. The current reduction of glaciers contributes to a shift in the boundaries of dangerous zones. As a result, populated areas and infrastructure located in usually safe places and tens of kilometers away from glaciers may be exposed to dangerous glacial processes.

In turn, glaciers are important indicators of climate change, and glaciers retreat indicates a significant change in the conditions of their formation and existence. Glaciers and snow patches are the important component of the mountain ranges landscapes and are also their landmarks. They influence strongly the natural components of surrounding areas, participating in the processes of relief formation, affecting the species composition of the biosphere, and also accumulating water necessary for use outside the glacial zone. According to UNESCO, glaciers in many World Heritage sites could disappear if the global average temperature rise exceeds 1,5°C [3]. Thus, according to experts, by 2050 glaciers will disappear in national parks in the Pyrenees (France, Spain), in the Dolomites, Kilimanjaro and Kenya in Africa, in Yellowstone and Yosemite national parks (USA) [3].

In connection with the plans of the Republic of Kazakhstan for the sustainable development of the recreational potential of the Western Tien Shan and the need to intensively use the region's water resources in economic activities, the data on the dynamics of glacial complexes have become in demand. It is necessary to assess the scale of glacier reduction due to the increased probability of hazardous processes occurring in the study area.

There are some data of studies in the field of assessment of glaciation changes in the Arys River basin. The study of glacial complexes of the State Nature Reserve “Aksu-Zhabagyly”, included in the list of UNESCO World Heritage Sites in Kazakhstan, has not been given significant attention.

The purpose of the work is to study changes in the main glaciers of the Arys River basin within the Aksu-Zhabagyly State Nature Reserve (SNR), using remote sensing data and identifying the main factors for the decrease in glaciers area.

The objectives of the research are:

− to assess the spatial distribution and scale of changes in the boundaries of glaciers in the Arys River basin (within the territory of the Aksu-Zhabagyly SNR);

− to assess the parameters of individual glaciers retreat;

− to analyze available information in order to assess changes in the climatic conditions of glaciers existence.

Study area. The Arys River is one of the major tributaries of the Syrdarya River. It flows from the springs of the Talas Alatau and Karatau ridges. Glaciers are located on the northern slopes of the Talas Alatau and the northwestern slopes of the Ogem ridge [4, 5].

The study area is located within the Arys River flow formation zone, and covers the slopes of the Talas Alatau, Maidantal and Ogem ranges. The first and oldest state nature reserve in Kazakhstan, Aksu-Zhabagyly, which is also included in the UNESCO network of biosphere reserves, is located here. Figures 1 shows the boundaries of the Reserve [6].

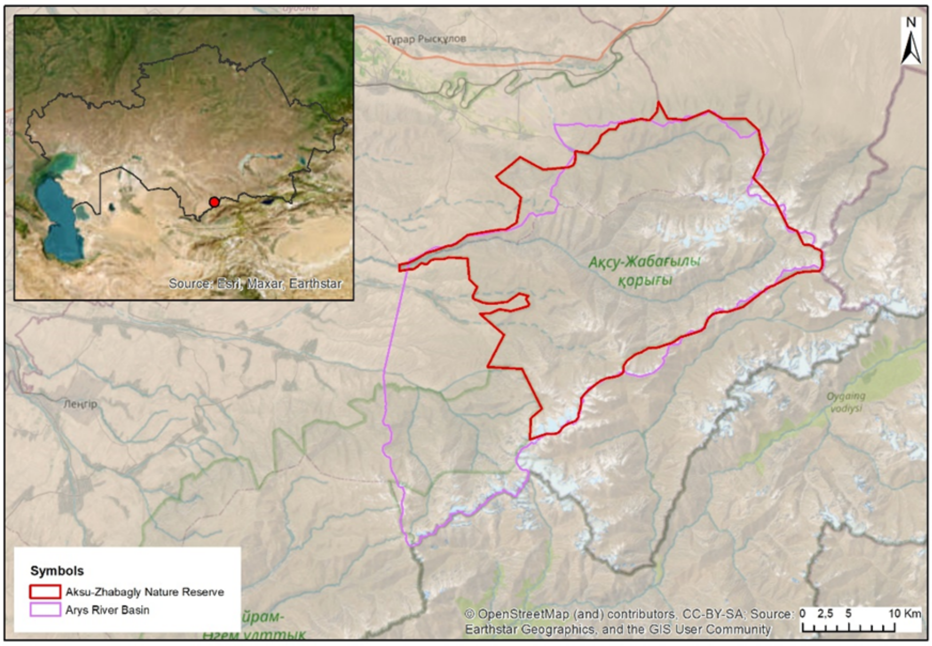

Figure 1 – Arys River basin. Red contour – the boundaries of the Aksu- Zhabagyly State Nature Reserve [6]

The area of the Reserve is currently 1319 km^2. The highest point of the Ogem ridge and the entire Arys River basin is the Sairamsky peak (4238 m). The glaciers of the mountain ranges are one of the most attractive objects of the Reserve. In the immediate vicinity of its borders there are 26 settlements; intensive cultivation of agricultural crops and haymaking takes place on the lands used. Among the geological features of the territory, it should be noted the predominance of limestone rocks, which are poorly resistant to erosion and weathering, which leads to the formation of river canyons with steep slopes, as well as the formation of landslides and screes - potentially dangerous source material for the formation of mudflows.

The climatic conditions for the existence of glaciation are described in sufficient detail [4, 7]. According to observations at the low- and mid-mountain Aul Turar Ryskulov and Shuyldak weather stations, located at the altitudes of 801 m and 1947 m a.s.l., the average annual temperature is +12,0 °C and +6,0 °C, respectively. The average summer temperature, according to our calculations (for the observation period 1961-2021) is 24,4 °C and + 16,4 °C [8].

The air temperature in the glacial zone of the ridges was calculated based on extrapolation of observation data at the plain weather stations. According to the data from the USSR Glaciers Inventory, the average altitude of the firn line for the entire glacial zone of the Arys River basin is 3500-3600 m [4]. Taking the vertical temperature gradient equal to 0,65 °C/100 m [9], we obtain that in the glacial zone the average annual air temperature is negative and is approximately –4,0, –5,0 ° C. The average summer air temperature is equal +6, +7 ° C. Maximum air temperature at the meteorological stations in July-August reaches 34-42 °C, and in the 3500-3600 m altitude interval the maximum is around 20-25 °C.

In the winter-spring period, the study area is under the influence of active cyclonic activity. Mountain ridges which are located in the eastern part of the Arys River basin, combined with the predominant western transfer of air masses, create a barrier effect. The consequence of this is increased moisture in the eastern part of the basin and, accordingly, an increase in the amount of precipitation and the snow cover depth from the plain part to the mountainous part. According to the data from the summary precipitation reservoirs, precipitation amounts vary from 600 mm in the foothills to 800-1000 mm in the highlands [10]. In several years, 1800-1900 mm (Zhabagyly River basin), 1500-1700 mm (Baldyrbek River basin) of atmospheric precipitation were measured.

The snowiest basins are Zhabagyly and Baldyrbek, where the depth of the snow cover, according to field snow surveys, reaches 150 cm or more in the spring [10]. Avalanche activity is quite intense, which creates the preconditions for the existence of glaciers. In the study area in the year 2010 with heavy snow, the volume of avalanches varied from 50-70 (Baldyrbek River basin) up to 170 thousand m^3 (Zhabagyly River basin) [11].

The periglacial zone is an area of distribution of cryophilic vegetation [12-14]. In the glacial-nival belt, the lichens Lecidea, Ochrolechia and others grow, as well as the mosses Grimmia and Tortula [13, 14]. Cryophytic flowering plants appear in rock cracks as thin soil accumulates.

Materials and methods. Since direct glacio-meteorological observations in the glacial zone have not been carried out yet, the basis for assessing climate changes over the area was the data from routine measurements at the meteorological stations Aul Turar Ryskulov and Shuyldak.

To assess the current state of glaciers and identify trends in their change Landsat 7, Landsat 8 satellite images (LE07_L1TP_153031_20000923_20200917_02_T1, C08_L1TP_153031_20230814_20230819_02_T1) with a resolution of 30 m, SRTM digital elevation model [15], current and historical images, Google Earth Pro tools, ESRI World Imagery 2023 with 0.5-1 m resolution were used. The area of glaciers was calculated using a semi-automatic method based on the ArcGIS program for clean-ice glacier part and manually for the debris-covered part. The detailed algorithm of the used method was described in the works [16-18].

The results of automatic interpretation were supplemented by manual correction, high-resolution satellite images were analyzed using archival descriptions of the area, which significantly increased the accuracy of the assessment of the state of glaciers.

Results of the researches. The valleys of the tributaries of the Arys River form narrow canyons with steep slopes, weakly illuminated by the Sun; snow and avalanche accumulation form extensive perennial snow patches on the slopes, which look like small glaciers.

In the individual years, the area of snow patches and glaciers, according to our calculations, reaches 25 km^2 or more, or about 2 % of the total area of the Reserve. Despite the small area occupied by glaciers and snow patches, they play an important role in feeding rivers, the waters of which are intensively used by the population for irrigation.

Issues related to climate change, impacts on the cryosphere and adaptation measures to them have long been the focus of scientists' attention [19]. The climate of Kazakhstan has warmed: according to the calculation of the Service of Hydrometeorology of the Republic of Kazakhstan, the average annual air temperature across the country for 1991-2020 increased by 0,9 °C compared to the previous thirty years 1961-1990 [20]. According to our calculations, throughout the entire territory adjacent to the study area, there is an increase in temperature averaged for the warm period (May-September) [10]. Figures 2 and 3 show the long-term variation of the average air temperature and the amount of precipitation for the spring months (observation period 1961-2022), according to observations at the meteorological stations Aul Turar Ryskulov and Shuyldak.

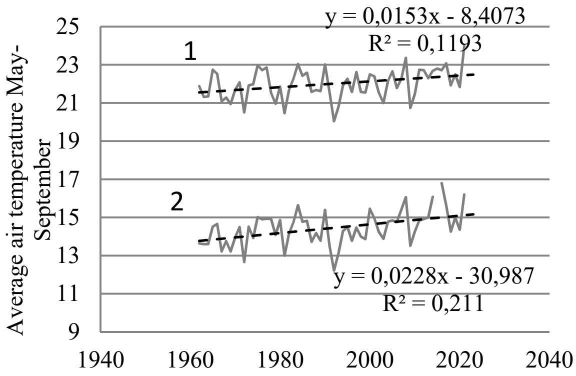

Figure 2 – Multiyear fluctuations of the mean air temperature for May-September according to the data Aul T.Ryskulov (*1*) and Shuyldak (*2*)

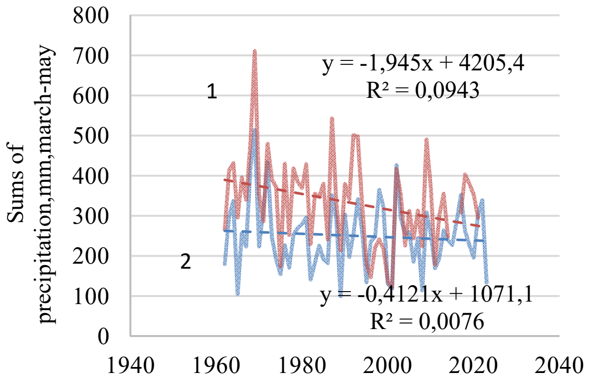

Figure 3 – Multiyear fluctuations of the sums of precipitation for March-May according to the data Aul T. Ryskulov (*1*) and Shuyldak (*2*)

Visually, the graphs show a tendency towards an increase in air temperature and a decrease in precipitation amounts during the spring period in the low-mountain zone, although the trends in changes are statistically insignificant. Table 1 presents the results of a comparison of data on the mean air temperature, precipitation amounts and periods of snow cover for two 30-year periods (1960-1990 and 1991-2021). There is a significant difference in the air temperatures and precipitation amounts averaged over periods. The destruction and melting of snow cover in low mountains begin 5-6 days earlier.

Table 1 – Indicators of the ablation period (May-September) in the Arys River basin for the observation periods 1960-1990 and 1991-2021

Meteorological station	Average air temperature, May-September		Sums of precipitation, mm, for March-May		Dates of the disappearance of the snow cover	
	1960-1990	1991-2021	1960-1990	1991-2021	1960-1990	1991-2021
Aul T. Ryskulov	21,9	22,1	284	247	01.03	25.02
Shuyldak	14,2	14,6	369	301	18.04	12.04

Assessment of the changes in climatic conditions indicate climate warming and a slight decrease in precipitation amounts during the spring period. Analysis of data from the summary precipitation reservoirs located in the Zhabagyly and Baldyrbek River basins showed that trends in precipitation in the mountains often have the opposite sign [10]. This may be due to underestimation of precipitation due to wind activity. In general, in 50 % of the considered data on precipitation measured by the summary precipitation reservoirs, a positive trend was observed, in 50 % - a negative one. Thus, the current climate regime of the glacial zone contributes to an increase in surface ice melting and glacier retreat.

First estimates of glaciers in the Arys River basin were made based on aerial photography from 1957 and published in the USSR Glaciers Inventory [4]. Previously, the first "Central Asia Glaciers Inventory ", compiled by N. L. Korzhenevskiy in 1930, contained information about only one glacier in the Aksu River basin. Only in the 1950s the ideas about the glaciation of the region were slightly expanded by the work of V. V. Akulov, which described the glaciers of the Aksu-Zhabagyly State Nature Reserve. The description was based on visual observations and contained serious uncertainties [4]. The glaciers of the area did not attract much attention due to their insignificant size.

Taking into account some corrections made later, 156 glaciers were identified in 1957 in the Arys River basin. Total clean-ice glacier area was 35.3 km^2 [7]. The glaciers of the Aksu-Zhabagyly State Nature Reserve were not studied separately. According to the available data as of 1957, it was determined that within the territory of the SNR there were 136 glaciers, with an area of 31.9 km^2. The work by E. N. Vilesov and co-authors presents the results of an assessment of changes in the size of glaciation in the Arys River basin from 1957 to 2011. According to manual interpretation of Landsat satellite images as of 2011, there were 99 glaciers with an area of 18,0 km^2 on the territory of the SNR [7].

A. Merekeev and co-authors [20] also conducted studies of changes in the area of glaciers in the Arys River basin using remote sensing data. According to these data, in 2022 there were 58 glaciers in the study basin with a total area of 11,48 km^2. But in this work, not all glaciers located on the territory of the Aksu-Zhabagyly State Nature Reserve were taken into account [21].

As a result of our research, the data on changes in the areas of glaciers in the Arys River basin within the territory of the Aksu-Zhabagyly SNR for 2 time slices: 2000 and 2023 were obtained. As of 2023, there are 83 glaciers on the territory of the SNR, the clean-ice glacier area is 13,2 km^2. Over 23 years, the area of glaciers decreased by 6,3 km^2, or 0,27 km^2/year. The changes in the number (K) and area of glaciers (F, km^2) within the territory of the Aksu-Zhabagyly SNR for 1957-2023 are shown in the table 2. Over 66 years, the area of glaciers has decreased by 18,7 km^2. The relative reduction in the ice area during this period is 58,6 %, and the degradation rate is 0,89 %/year. According to our data, since 2000, more than 30 small glaciers have melted on the territory of the Aksu-Zhabagyly SRN.

Table 2 – Changes in the number (K) and area of glaciers (F, км^2)
within the boundaries of Aksu-Zhabagyly SRN for 1957-2023

1957		2000		2023	
К	F, км^2	К	F, км^2	К	F, км^2
136	31,9	115	19,5	83	13,2

Practically all glaciers are small. According to our calculations, 58 glaciers out of 83 (70 %) have an area of less than 0,1 km^2, only 2 % of glaciers have an area of more than 1 km^2. The largest area is occupied by glaciers of the 0,5-1,0 km^2 category (table 3).

Table 3 – Distribution of the number and area of glaciers by size in 2023

Size of glaciers, km^2	Number of glaciers	%	Area, km^2	%
<0,1	58	69,9	2,05	15,6
0,1-0,5	16	19,3	3,61	27,4
0,5-1,0	7	8,4	4,28	32,5
>1,0	2	2,4	3,24	24,6
Total	83	100	13,18	100

Most of the glaciers are located on the slopes of north-western and north-eastern exposures (figure 4). In terms of morphological types, cirque glaciers predominate (54 %) (figure 5). The largest area is occupied by valley glaciers – 5,29 km^2 (40 %).

Based on monitoring of remote sensing data, the intensity of glaciers retreat in the territory of the Aksu-Zhabagyly SNR was revealed. Figures 6-8 show an example of the reduction in the areas of three large glaciers: No. 2, No. 69, No.70 (Karzhailau) for the period from 2000 to 2023.

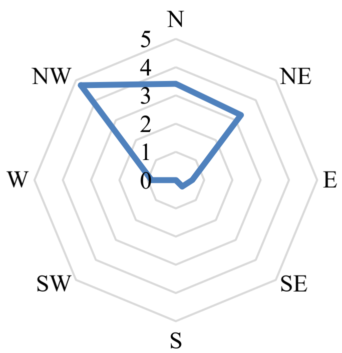

Figure 4 – Distribution of the area
of glaciers according to exposure (km^2)

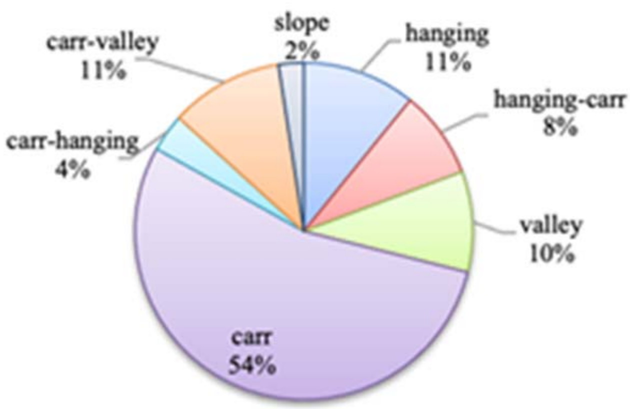

Figure 5 – Distribution of glaciers according
to morphological types

The biggest glacier in the Arys River basin and within the territory of the Aksu-Zhabagyly SNR is the Karzhailau glacier of northwestern exposure (No. 70 according to the USSR Glacier Inventory) (figure 6). It is located on the slope of the Ogem ridge in the Sairam River basin near Sairamskiy peak. According to the USSR Glacier Inventory, in 1957 the clean-ice glacier area was equal to 4,7 km^2, and the total area, including debris-covered part, was 5,3 km^2. According to remote sensing data, in 2000 the glacier was divided into two parts: No. 70 and No. 70a. The clean-ice glacier area reduced to 2,74 km^2. Based on the satellite image of 2011, 2 separate parts of the glacier No. 70 and No. 70a were also identified with entire area 2,51 km^2. Currently, in 2023, the clean-ice glacier area is 2,26 km^2.

Thus, over 23 years, the clean-ice part of the glacier No. 70 Karzhailau decreased by 0,48 km^2 (17,5 %). Over the 66 years since the period of the first inventory, there has been a reduction of 2,44 km^2 (51,9 %). The western part of the glacier as of 2023 has an area of 0,14 km^2 covered with debris (figure 7). The area covered with debris in 1957 was 0,6 km^2.

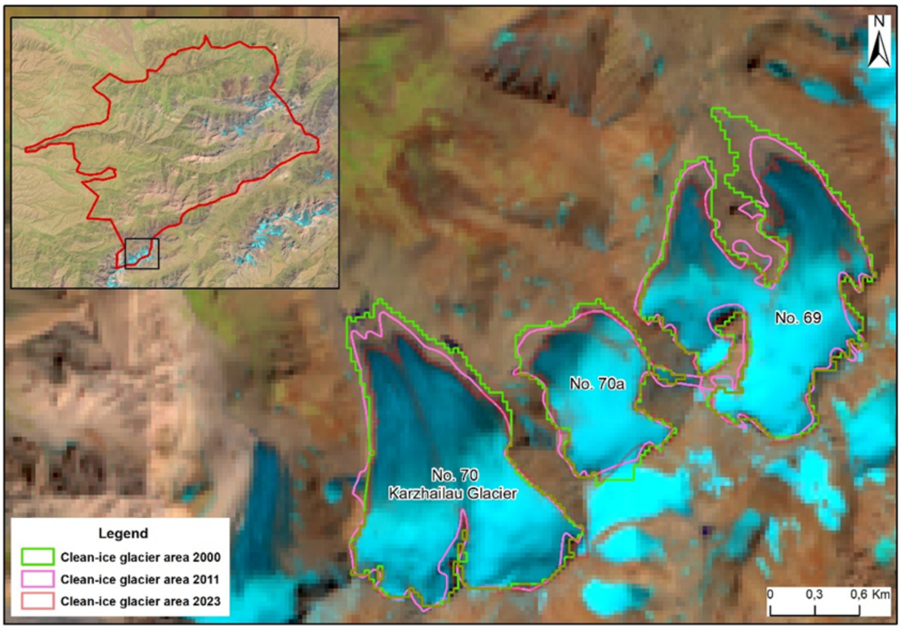

Figure 6 – Reduction in the area of glaciers No. 69, No. 70 Karzhailau clean-ice part for the period 2000-2023

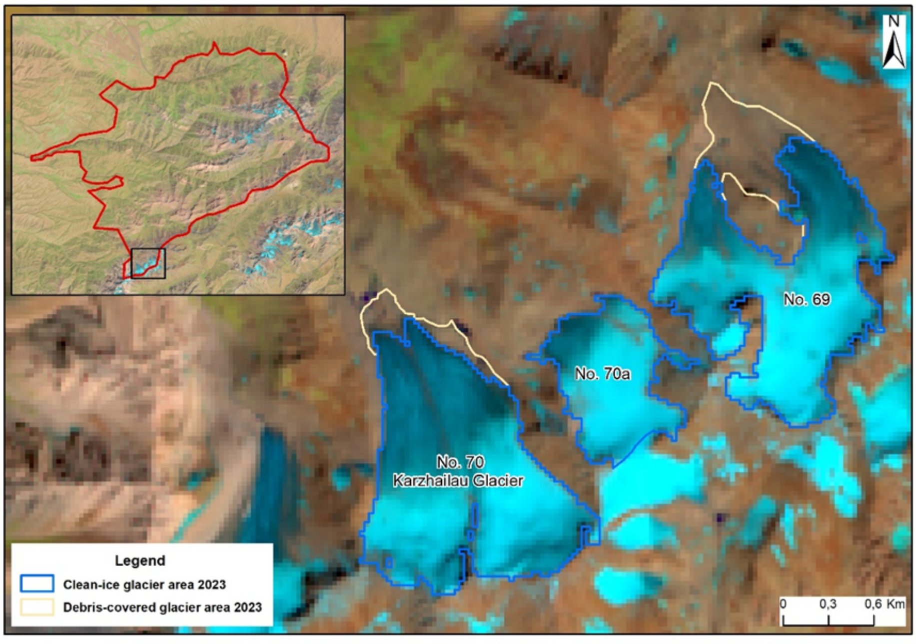

Figure 7 – Glaciers No. 69, No. 70 Karzhailau according to remote sensing monitoring data 2023

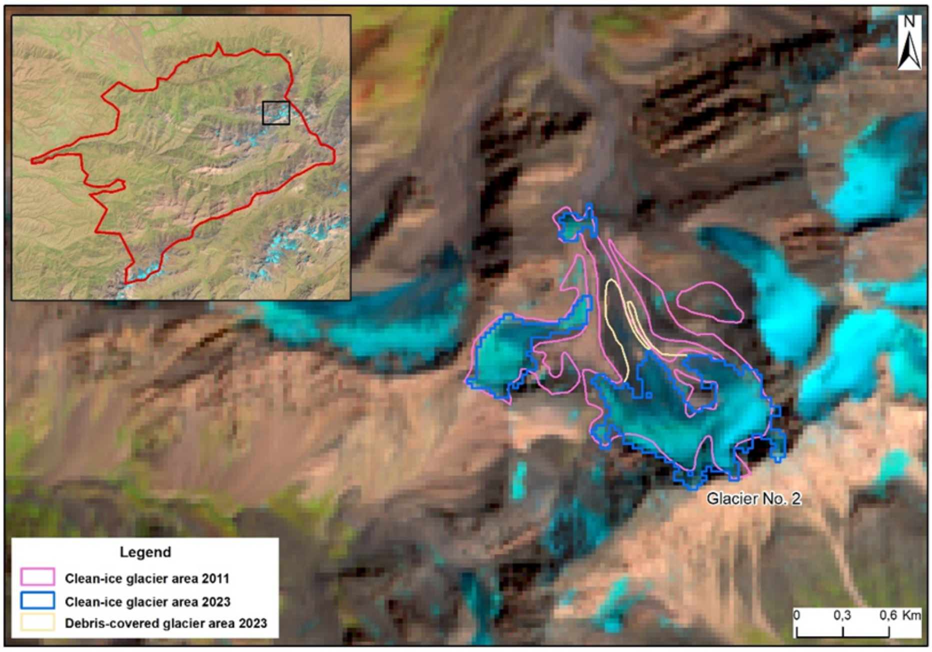

Figure 8 – Reduction in the area of the glacier No. 2 for the period 2011-2023

Valley glacier No. 69 in the Baldyrbek River basin of northern exposure (figure 8), according to the USSR Glacier Inventory, in 1957 had a total area of 2,8 km^2, of which 0,4 km^2 was covered with debris. According to remote images interpretation, in 2000 the clean-ice glacier area was 1,8 km^2, in 2011 – 1,7 km^2, in 2023 – 1,54 km^2.

Thus, for 23 years, the clean-ice part of No. 69 glacier decreased by 0,26 km^2 (14,4 %). Over 66 years, the area of the glacier became lesser by 0,86 km^2, or by 35,8 % of the area in 1957.

The process of "debris expansion" is observed. Figure 7 shows the debris-covered parts of glaciers No. 69 and No. 70 Karzhailau as of 2023. The debris-covered area of glacier No. 69 increased by 40,6 % (from 0,19 km^2 in 2000 to 0,32 km^2 in 2023).

Valley glacier No. 2 (north-western exposure) is located in the Baldyrbek River basin (figure 8). According to the USSR Glacier Inventory, in 1957 its area was 1,7 km^2. Interpretation of space images of 2011 show that the main body of glacier was disintegrated into 2 big parts and several smaller ones. Total area of the separated parts of the glacier No. 2 makes 1,47 км^2. According to the assessment as of 2023, the clean-ice glacier area of No. 2 glacier is 0,92 km^2. Debris-covered part of the glacier is 0,16 km^2 (figure 8). For the last 12 years the area of glacier No. 2 decreased by 0,55 km^2 (or 37,4 %). For 66-years period the glacier lost 0,78 km^2 (or 46 % area).

Superficial moraine on the tongues of active mountain glaciers is a typical feature of regression phase which dominates at present [22]. Debris on glacier surface significantly affects ablation, runoff and their mass balance. As a result of glacier retreat, as it was shown on the example of the glaciers No. 2, No. 69, No. 70 Karzhailau, at their marginal frames the territory not less than 0,2 km^2 area become free of ice. This territory, representing now by moraine material (boulders, sand and loam), is opened for plant expansion.

An increase in the average annual and summer air temperature by 0,2-0,4 °C in the high-altitudinal part of the basin means a shift in natural zones by at least 60 m in altitude. The lower edges of the retreated glaciers are currently represented by moraine material. In place of the disappeared small glaciers, snow patches are identified from satellite images. Certain areas have already been freed from ice, and the process of shrinking glaciers will continue. If the trend towards increasing air temperatures continues, the glaciation of the Arys River basin may disappear by 2100. This is shown by the rate of degradation. The landforms in which the glaciers were located will be occupied by snowfields.

Since the pioneers of overgrowing free spaces are primarily lichens and mosses, we should expect the appearance of these species on frontal and lateral moraines. Vegetation at the margins of snow will be enriched by the growing of cryophytic low-grass meadows. In cracks on rocks and well-warmed screes, flowering plants will develop.

Conclusion. Our assessment of contemporary glaciers in the Arys River basin within the Aksu-Zhabagyly State Nature Reserve has shown that over the past 23 years the number of glaciers and their area have decreased significantly. The rate of retreat was 0,27 km^2 per year. As a result of continued glacial degradation, some larger glaciers have broken up into smaller pieces. Certain glaciers have lost between 14 and 37% of their area. Since 2000, more than 30 small glaciers have melted within the territory of the Aksu-Zhabagyly State Nature Reserve. According to our assessment, the glaciers of the Aksu-Zhabagyly Nature Reserve may disappear by 2100. In our opinion, the reason for the decrease in the area of glaciation is a significant increase in average air temperatures during the ablation period and a decrease in precipitation in spring. Degradation of glaciation can significantly affect the formation of highland relief, changes in the volume of water resources, as well as the species composition of vegetation in the glacial-nival belt. Further monitoring is required to clarify in detail the causes and direction of changes in glacial complexes. The identified features of changes in glacial complexes can be used when organizing recreation in the high-mountain zone, including taking into account the possible occurrence of waterlogged soil, landslides and mudflows.

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«АҚСУ-ЖАБАҒЫЛЫ» ҚОРЫҒЫНЫҢ МҰЗДЫҚ КЕШЕНДЕРІНІҢ ЭВОЛЮЦИЯСЫ (СЫРДАРИЯ, АРЫС ӨЗЕН АЛАБЫ)

Аннотация. Мақалада "Ақсу-Жабағылы" мемлекеттік табиғи қорығының аумағындағы Арыс өзен алабы (Сырдария өзені оң жақ саласы) мұздықтарының өзгерістері қарастырылған.. Қазіргі климаттың өзгеруі жағдайында мұздықтардың шекараларының кеңістіктік таралуы мен өзгеру ауқымын бағалау жүргізілді. 2000-2023 жылдардағы мұздану деградациясының орташа қарқыны бағаланды. Абляция кезеңінде ауаның орташа температурасы 0,2-0,4С-ге өсті , наурыз-мамыр айларында жауын-шашын мөлшері 10-20%-ға азайды. Мұздық кешендерін одан әрі зерттеу бағыттары ұсынылды.

Түйін сөздер: мұздықтар, Ақсу-Жабағылы қорығы, климаттың өзгеруі, мұздану алаңының өзгеруі.

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ЭВОЛЮЦИЯ ЛЕДНИКОВЫХ КОМПЛЕКСОВ В ЗАПОВЕДНИКЕ АКСУ-ЖАБАГЫЛЫ (БАССЕЙН РЕК АРЫС, СЫРДАРИЯ)

Аннотация. Рассмотрены изменения ледников бассейна р. Арыс (правого притока р. Сырдария) на территории государственного природного заповедника “Аксу-Жабагылы”. Выполнена оценка пространственного распространения и масштабов изменения границ ледников в условиях современного изменения климата. Оценены средние темпы деградации оледенения за 2000-2023 гг. Обозначены основные факторы и тренды изменений в условиях современного потепления климата. Средняя температура воздуха за период абляции увеличилась на 0,2-0,4 °С, суммы осадков за март–май уменьшилась на 10-20 %. Предложены направления дальнейших исследований ледниковых комплексов.

Ключевые слова: ледники, заповедник «Аксу-Жабагылы», изменение климата, изменение площади оледенения.