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Current Climate Conditions In The Mountainous Regions In The Republic Of Uzbekistan And Its Impact On The State Of Glaciation, Glacial Run-Off And GLOFS

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Abstract:
The climate situation in Central Asia in the second half of the 20th century and the first decade of the 21st century is characterized by the fact that on the western periphery of the Central Asian Mountain system, horizontal and vertical air temperature gradients change over time and the nature of their changes leads to a reduction in mountain glaciation. Over the past 45 years, glaciers in some Gissar-Alai river basins have lost about 16% of their area, and glaciers in the Pskem river basin have lost 27% of their area. The regime of rivers and the potential for outburst of mountain lakes respond to the reduction of glaciers.
Background*:Climate is one of the main factors shaping the water resources, including river run-off, glaciers and lakes, which, in turn, determine the activity of such negative natural phenomena as landslides and glacial debris flows. Currently, noticeable climate changes are occurring throughout the world. The purpose of this work is to assess the impact these changes have on the mountainous territory of the Republic of Uzbekistan as a whole, and also for a specificimportant region of the Republic of Uzbekistan – the Pskem river basin, the right tributary of the river Chirchik, which belongs to the Western Tien Shan mountain system.*
Materials and Methods*: This survey summarizes previous works written on the matter of glaciation in the subject region, its dynamics due to climate change, glacier run-off and glacier lake outburst floods (GLOFS). Some new results were acquired via field expeditions and GIS-analysis and are presented in this article. Field expeditions included measurements of glacier mass balance, mountain rivers' run-off, mountain lakes bathymetry, and extracting data from autonomous meteorological stations. GIS-analysis mainly included digitizing glaciers and mountain lakes using modern access-free space imagery, and subsequently deriving spatial statistics.*
Results*: In arid years, the portion of glacial run-off is more than 25% of the total river flow, decreasing significantly in humid years. The approximate dates for the disappearance of glaciation on the territory of the Republic of Uzbekistan are derived – 89 years for the Kashkadaryariver basin, 126 years for the Surkhandaryariver basin, and 250 years for the Pskem river basin. The disappearance of glacial run-off will lead to a decrease in the total river flow during the vegetation season by 10-25%, which will extremely complicate agriculture in the region. Another unfavorable consequence of the reduction in glaciation is the formation of lakes in the periglacial zone. The presence of approximately 242 mountain lakes has been established, 15% of which are classified as having a high breakthrough hazard.*
Conclusion:*it is imperative to continue monitoring the nival-glacial zone in the Republic of Uzbekistan to better determine the tempo of deglaciation to correct the policy of irrigation and overall water usage, and to timely anticipate possible glacial lake outburst floods.*
Keywords*:Climate Change, Deglaciation, Glacial Runoff, Mountain Lakes*

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I. Introduction

The purpose of this survey is to assess climate change for the Republic of Uzbekistan in the context of the impact on the state of glaciation, river run-off from glaciers and the potential for glacial lake outburst floods (GLOF). The main study area within the Republic is the upper reaches of the river Pskem, where occasional ground and aerial observations have been carried out since 1961. The results of these works are important for forecasting changes in the environmental situation in the region, since the Pskem River is the main source that supplies the water needs of the capital of Uzbekistan – the city of Tashkent with its three million population, as well as many other settlements, industrial and energy facilities, and vast agricultural lands. The main features of glaciation on the territory of Uzbekistan are: 1) the coincidence of the beginning of the ablation season with the beginning of the vegetation season for the most important agricultural crops in the region; 2) the absence of large forms of glaciation on the territory of the Republic (the largest glacier, Pakhtakor, is not much larger than 3 km^2 in area).

II. Materials And Methods

This study covers a large spatial (mountainous regions of the Republic of Uzbekistan) and temporal (second half of the 20th and early 21st centuries to the present) periods, while the main objects of research: glaciers, rivers fed by them and mountain lakes are characterized by low transport accessibility. The above factors determine the choice of the main research methods:

• analysis of stock materials and literature;

• geoinformation analysis using both modern remote sensing data and archival cartographic and remote sensing data (old satellite images, aerial photography);

• expeditionary research in the basin of the Pskem river (some glacial and dam lakes, the Barkrak glacier and the Barkrak-sai river basin);

• processing of expedition results and statistical calculations in office.

Field works included, along with in-situ observations, "stakes and pits" glaciological mass balance measurements, conductivity measurements in glacial rivers to determine their run-off, bathymetry measurements performed from boats on glacial (and tectonic) lakes. Data was also extracted from the autonomous meteorological station positioned near Barkrak-Middle glacier. The aforementioned glacier was chosen due to its size on the bigger end of the spectrum (~2 km^2, which is amongst the bigger ones in Uzbekistan) and its decent transport accessibility. The latter factor considers not only the means to reach the glacier itself, but also the character of the glacier's surface and how it allows for the accumulation zone accessibility.

III. Results and discussion

Climate characteristics and their dynamics: there are many works related on the matter of climate changes in Central Asia region, and their results are summarized by (Petrov et al., 2022). The main conclusions would be:

1. With time, winter temperatures rise much faster than summer ones, whereas annual precipitation either doesn't change, or changes negligibly;
2. For the longitudinal profile of the annual air temperature, change averaged over decades on the plain as well as on the middle altitudes proceeded non-monotonic with trend increasing during 1998-2010;
3. Comparison of the corresponding average monthly air temperatures between the periods of 1970-1998 and 1998-2010 indicated that main increase (up to 3°C) fell on spring months, March particularly. During winter months, the air temperature was increasing faster on the plain than in the middle altitude zone. Since last decade winters became warmer as a whole, the trend of summer air temperature was significantly lower than one observed in winters.
4. In the Pskem river basin change of winter precipitation with the altitude is not monotonous. This deviation disappears during the summer. Decrease of annual and winter precipitation is observed from Pskem meteorological station (MS) to Oygaying MS. At the same time the main amount of winter and annual precipitation falls in the middle altitude zone.

Change of glaciation: Change of climate characteristics in the region has an impact on glaciation size as well as ice melting in the summer. General processes [2] occurring when glaciation shrinks are following:

1. Disappearance of the glaciers of an area under 1 km^2;
2. Disintegration of large glaciers and tributaries separation;
3. Decreasing of glaciation coefficient at the expenses of accumulation area reduction;
4. Increasing of moraine area and natural pollution of glaciers.

As a whole, climate situation in the second part of XX century was unfavorable for the existence of glaciers in Gissar-Alay and in Pamir-Alay in total. According to [Catalogue, 1968] and [Semakova E.R.., Semakov D.G., 2014] glaciers of the basins of investigated Gissar-Alay rivers lost about 16% of their area since last 45 years, and area of glaciation of Pskem river basin decreased by 27% of the area estimated in 1960 (Table 1).

Table no 1: Change of the total glaciation area (F_{gl}) in the Pskem River basin

Year	F_{gl}, km^2	Source of data
1960	127,8	[Catalogue..., 1968]
2010	93,6	[4]
1970	219,8	[Narama et al., 2010]
2007	168,7	[ibid.]

According to the data by [Narama et al., 2010] aggregated area of glaciation in the Pskem River basin in 1970 and 2007 differs from the other sources listed in the Table 1. The possible reason of this difference between areas is geographical coverage of the area. In the works of E. Semakova, only those glaciers from which the run-off goes into the territory of Uzbekistan were accounted for. Meanwhile, in the works of [Narama et al., 2010] all the glaciers of Tien Shan mountain region are included into calculation, including those from which the run-off doesn't cross the borders of Uzbekistan. Secondly, initial data used by the authors are different: E. Semakova et al. compared data of space images with data from [Catalogue, 1968]; Narama et al. used Corona space images for 1967-1970. Apart from these reasons, methods of decoding and different timing should also be considered.

At the Center for Glacial Geology of the Institute of Geology and Geophysics named after Kh.M. Abdullaev, work continues to monitor the state of glaciation in the Republic of Uzbekistan. Due to the inaccessibility of most glaciers, as well as time and resource limitations, remote sensing methods remain as the main instrument in accomplishing this task. Modern geographic information systems (GIS) provide the opportunity to use current (within 1-2 years) high-resolution images as a cartographic "base layer". Analyzing these images, the authors obtained the following actual values: the total area of glaciers in Uzbekistan is around 155.05 km^2, and the number of glaciers is around 689. Of course, these numbers are by no means absolutely accurate, considering the usual impediments when digitizing large territories: disparity between recent satellite imagesand actual situation, defects of images, subjectivity of interpretation, geodetic distortions in GIS.For comparison, according to A.S. Shchetinnikov for 1960, the area of glaciers in the largest river basin of Uzbekistan was 209.73 km^2, and the number of glaciers was 602 (Table 2).

Table no 2: Comparison of the of data from glacier inventories made in the Soviet Union and in recent years for the territory of Uzbekistan.

River basin	1960 (A.S. Shchetinnikov)		2022 (Center for Glacial Geology)	
	Area, km^2	Number of glaciers	Area, km^2	Number of glaciers
Pskem	121,21	251	97,45	273
Kashkadarya	18,15	62	10,63	98
Surkkhandarya	70,37	289	46,97	318
Overall	209,73	602	155,05	689

From the data presented, we see that the total area of glaciers in all river basins decreased by 26.1%, and the number of glaciers increased by 14.5% due to the fragmentation of large glaciers into smaller ones. If we consider the situation for individual river basins, it is uneven: the reduction in the area of glaciation is 19.6% for Pskem, while for Kashkadarya and Surkhandarya the values are 41.4% and 33.3%, respectively.

The team at the Center for Glacial Geology also conducts observations directly on glaciers to assess their mass balance. To assess the dynamics of glaciation, the Barkrak-Middle glacier (part of a complex of glaciers, which also includes the B. Right and B. Left glaciers) (Fig. 1) was chosen as a reference object due to its size and relative transport accessibility. The Barkrak glacier is located on the northern slope of the Pskem ridge, in the valley of the river Oygaing. From its run-off from the river Barkrak-sai, which is a left tributary of the Oygaing river. Table 3 shows the results of observations of the mass balance of the Barkrak glacier starting in 2016.

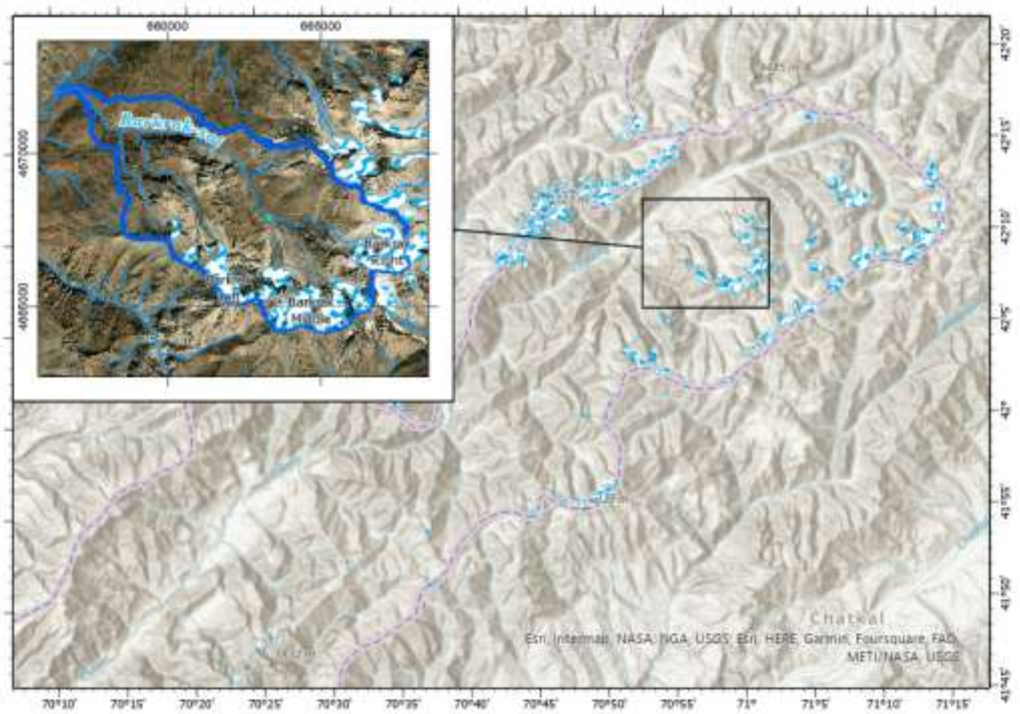

Figure no 1: A map of the upper part of Pskem river basin with Barkrak-sai river basin and Barkrak glacier system on the inset map.

Table no 3: Data on Barkrak Middle glacier mass balance measurements.

Glacier designation	Glacier's designation in WGMS	Hydrological year	Area, km^2	Annual mass balance, cm in water equivalent (w. e.)	Error, cm
Barkrak Middle – the main part	818	2016-2017	2.39	-29.5	±0.5
	818	2017-2018	2.23	-22.5	±0.5
	818	2018-2019	2.20	-32.5	±0.5
	818	2019-2020	2.12	-28.1	±0.5
	818	2020-2021	1.86	-67.1	±0.5
	818	2021-2022	1.90	-57.1	±0.5
	818	2022-2023	1.8	-80.9	±0.5
Barkrak Middle – the right part	819	2017-2018	0.56	-54.5	±0.5
	819	2018-2019	0.55	-52.4	±0.5
	819	2019-2020	0.55	-44.1	±0.5
	819	2020-2021	0.44	-66.2	±0.5
	819	2021-2022	0.80	-49.8	±0.5

As can be seen from table 3, the rate of degradation of the Barkrak Middle glacier has increased sharply in 2021, exceeding 0.5 m water equivalent (w.e.) in its main part. In the right part, separated as a result of glacier retreat and subsequent disintegration, these values constantly exceeded the threshold of 0.5 m w.e. since the start of a continuous series of observations in 2016. At the same time, the area of the middle part of the glacier have actually ceased to reach 2 km^2. These indicators complement the overall picture obtained using remote sensing methods and clearly indicate the negative impact of ongoing climate change on the state of glaciation in this region.

Glacier-derived runoff: The volume of melt-water from glacier is determined by total glaciation area and summer air temperature. It is necessary to emphasize that the definition of glacier-derived run-off used in this article is the one given by A.S. Schetinnikov: this is a run-off "formedby melting of perennial storage of ice and firn (the snow on glaciers which does not melt for more a year after falling)" [Schetinnikov A.S., 1984].

Increasing of summer air temperature leads to change of base ablation values, i.e. snow and ice melt on the glacier's surface. When glaciation is reduced by 30%, the volume of run-off is close to norm with warming of 2°C. When glaciation is reduced by 40% or more, temperature increase will not compensate for loss of run-off [Schetinnikov A.S., 1984]. When calculating ice melting under moraine, it was assumed that moraine's average thickness was 10 cm, and the value of the melting was a half of the free ice melting. Summer snowfalls' impact on ablation is accounted automatically into the change of summer temperatures.

In the work[6] the river basins with different glaciation area in different regions of Central Asia were selected for the assessment of long-term average annual part of glacial run-off. The long-term hydrological and meteorological observation data are available for said basins, as well as information about change of glaciation based on data from three inventories (Catalogues) of glaciers. Overall, impact of glaciation reduction is not significant and falls within the accuracy of annual run-off calculation for the rivers with significant glaciation area at their origins. This run-off data was measured at lower reaches.

However, the role of glacial run-off in the total river run-off for the summer period of defined year depends on dryness of the year. A year when annual (winter) precipitation is not less than 1.15 of their many-years average ($\sum X_{10\text{-}4}I/\sum X_{10\text{-}4}av > 1.15$) can be ascribed to high-water years. A year when this relation does not exceed 0.80 ($\sum X_{10\text{-}4}I/\sum X_{10\text{-}4}av < 0.80$) is a low-water year[7]. Sample of the calculations for the particular Oygaying river basin is in the Table 4.

Table no 4: Portion of glacial feeding (Q_{gl}) in the summer run-off Q of Oigaing river (August-September) in high- and low-water years.

Year	$\sum X_{10\text{-}4}I / \sum X_{10\text{-}4}av$	Q_{gl}/Q
Low-water years		
1961	0,53	25,6
1980	0,73	20,1
High-water years		
1969	2,12	11,4
1987	1,44	13,9

Hence, portion of glacial feeding in summer months of a low-water year can form up to 25% of the total river runoff, decreasing down to 10-12% in a high-water year.

Dangerous phenomena associated with the glaciation reduction: Shrinking of glaciation observed over the world, including Central Asian Mountains, leads to the formation of banks of terminal moraines and so-called "dead ice" on the glacier free area. In the summer when seasonal snow and ice cover melts, melt-water accumulates between these banks and forms lakes, those number and size vary from year to year. Such lakes can burst when ice or moraine dams break down, that leads to occurrence of floods and mud flows, often disastrous. This happened for instance in the upper reaches of Shkhimardan river, downstream from Archabashi glacier in the summer of 1998. Similar flood happened in July 1977 in the Isfairamsay River basin located to the east from Shakhimardan.

The type of lake prone to outburst depends on genesis of impounding dams[8,9]. There are following types in the mountains of Central Asia:

- lakes formed as a result of riverbed blockage with landslides or rockfalls from adjoining slopes. For instance, the famous Sarez lake belongs to this type;
- the glacier-dammed lakes. The well-known Merzbacher lake is the largest in Central Asia. Southern Inylchek glacier serves as a dam for such a lake. Other small lakes of this type can be met in the glacial basins. Most of them are seasonal;
- moraine-dammed lakes are those which are formed in space of retreating glaciers. Their size generally is not large, but they are widespread.

The team of the Center for Glacial Geology, together with scientists from other countries, carried out a new cataloging of the mountain lakes of the Republic of Uzbekistan based on remote sensing data and field research, the results of which were published in [Petrov et al., 2017]. The lakes were interpreted using satellite images of WorldView-2, SPOT5, and IKONOS with a resolution of 2 to 10 m. Only lakes with an area of more than 100 m^2 and at an absolute altitude above 1500 m were taken into account. The results are presented in Table 5.

Table no 5: Results of the cataloguing of mountain lakes prone to outburst in the Republic of Uzbekistan per [Petrov et. al., 2017].

Region (by river basin)	Number	Area, km^2
Tashkent (Chirchik and Akhangaran river basins)	131	2.27
Kashkadarya	38	0.29
Surkhandarya	68	0.50
Shakhimardan	5	0.22
Overall	242	3.28

According to the survey, out of 242 lakes identified, 15% are classified as ones with high outburst potential, 10% – with low potential, and the ret 75% are classified as low outburst potential. The classification was developed according to a number of factors, which includes: type of lake by position relative to the glacier (supra-, pro-, peri- and extra-glacial), genetic type of dam (ice, moraine, collapse, bedrock), height of the shoreline (within 1 m or clearly higher), the presence of connections between lakes (cascade or single), the type of drainage (open/closed), the possibility of impact on the lake as a result of an avalanche/debris flow/rockfall/landslide.

IV. Conclusion

Studies of climate change in Central Asia over the past 50 years have shown that on the western periphery of the Central Asian mountain system, winter air temperatures are growing much faster than summer ones, while annual precipitation amounts remain unchanged or only slightly increased. Climate warming has led to a reduction in glaciation in Central Asia. In particular, glaciers in the Pskem region lost 27% of their area between 1960 and 2010. With the loss of glacial areas, the expected decrease in the glacial component in the annual river run-off does not occur. In most cases, for rivers with a significant area of glaciation at their sources, at posts located in their lower reaches, the effect of a reduction in glaciation on the glacial component of the runoff is insignificant and lies within the accuracy of annual runoff calculations. With regard to the redistribution of glacial runoff in years of different water content, the contribution of the glacial component to the total river flow in summer can reach 20-25% for a low-water year, decreasing to 10-12% in a year with heavy winter precipitation.

The obtained values for the rate of reduction in glaciation, although approximate, allow us to estimate period for the disappearance of glaciation on the territory of the Republic of Uzbekistan. If we take 1960 as the starting point (the creation of the Glacier Catalog), then over the time period from the starting point to the present day, the average rate of reduction in the area of glaciation is: 0.66%/year for the Kashkadarya basin, 0.53%/year for the Surkhandarya basin, and 0.32%/year for the Pskem basin. Thus, taking as a condition the constant rate of reduction of glaciation, the approximate dates for the disappearance of glaciation can be called 89 years for the Kashkadarya basin, 126 years for the Surkhandarya basin, and 250 years for the Pskem basin. However, the actual rate of de-glaciation varies from year to year, which is demonstrated in this article by the example of studying the mass balance of the BarkrakMiddle glacier over several years. It is very likely that the overall trend in the rate of glacier retreat will increase in the foreseeable future, and the actual time frame for the disappearance of glaciers will be shorter. The disappearance of glaciation means the disappearance of glacial meltwater run-off. A phenomenological feature of the glaciation of Central Asia is the coincidence of the beginning of the ablation season with the vegetation season of many agricultural crops. The absence of glacial run-off will lead to a decrease in the total river flow in a given period by 10-25%.

The reduction in glaciation is also accompanied by an increase in the number of moraine lakes, and the degree of their danger in relation to the possible formation of mudflows is unpredictable without additional research. Consequently, monitoring of the periglacial region is necessary, especially in areas where fairly large, but intensively retreating glaciers with developed moraine cover still remain.

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