

Ablation of Ice and Snow of Kara-Batkak Glacier and Its Impact on River Flow

R. Satylkanov

Tien Shan High Mountain Research Center of the Institute of Water Problems and Hydropower of the National Academy of Sciences of the Kyrgyz Republic, Bishkek, Kyrgyz and Research Center for Ecology and Environment of Central Asia (Bishkek), Kyrgyz
✉ r.satylkanov@gmail.com

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Abstract: This paper considers the results of complex glaciological and hydro meteorological observations in the basin of Chon Kyzyl Suu river for the period of 2013-2017; the analysis of flow formation from the Kara Batkak glacier was carried out. The main and minor factors of ice and snow ablation of Kara Batkak glacier are shown. The analysis of the main climatic parameters (air temperature and precipitation), which are changing in concordance with global warming, has been carried out. In the last 70 years the area of the Kara Batkak glacier has decreased by 21.8%, showing a pronounced trend of diminishing the area of this glacier, which is a consequence of global warming. It is established that the trend of increasing ablation over the entire observation period on the Kara Batkak glacier is associated with an increase in air temperatures over the last few decades.

There is a good synchronization of annual trends of rise in air temperature at the three meteo stations for the period from 1961 to 2015 with a maximum of 7.0 °C at Kara-Batkak. This suggests that the same trend happens in all the regions of Teskey Ala Too, which in recent years, increase the trend of daily melting of ice. The mass balance in these basins over 60 years is negative due to rise in temperature and add to river runoff due to degradation and the reduction in the area of its glaciation confirmed the water-ice balance of mountain-glacial basins of the “continental” type glaciers. The close connection between the changes in climatic parameters, state of glaciations and glacial runoff in these river basin were established in this study.

Keywords: Ablation; Kara Batkak glacier; Air temperature; Atmospheric precipitation; Mass balance; Water discharge; Water flow.

Introduction

In recent decades almost all regions of the globe have seen a significant increase in the rate of glacier shrinkage (Raper and Braithwaite, 2005; Dyurgerov and Meier, 2005). At the same time relatively small mountain glaciers are often more sensitive to climate change and respond to them much faster than glacial cover. It is for this reason that the contribution of “small” glaciers to the increase in the level of the world’s oceans under current conditions is maximally significant. During

the period of 1994-2004 it was 0.77-0.22 mm/year, while the contribution of Greenland and Antarctica was estimated as 0.2-0.1 mm/year and 0.2-0.335 mm/year, respectively (IPCC, 2007). The current stage of glacial development of the Inner Tien Shan Mountains is characterized with the retreat of marginal parts of glaciers, decrease of their volume and its degradation, which has significantly accelerated since 1977 (Aizen et al., 2006). In this connection, the problem of changing glaciation in the arid regions of Central Asia, where glacier feeding has a significant share in the river

runoff, is especially acute. In inner regions of the Tien Shan the amount of precipitation is only 300-400 mm, so the glacial feeding of rivers becomes particularly important there. According to the calculations of Dikikh (Dyurgerov et al., 1995), the share of glacial component in Chon Naryn river is 31.9%. According to modern calculations (Mamatkanov et al., 2006; Kuzmichenok, 2003), after 1972 the amount of river flow within Kyrgyzstan has increased by an average of 6.2%. When calculating and modelling the flow, it is necessary to have an accurate information about the change in the glaciation. Such data make it possible to assess the contribution of various components of water balance equation.

The first glaciers studies in the Inner Tien Shan started in the second half of the 19th century (Kaulbars, 1875), but targeted research has been conducted only from the beginning of the 20th century (Kalesnik, 1935). During the second half of the 20th century, static observations of glaciers began, including mass balance measurements and regular expeditionary surveys were conducted (Dyurgerov et al., 1995).

In the past few years, there has been an increased interest in glacial change in Central Asia. This is primarily due to the problem of lack of fresh water, which requires the most up-to-date estimates of glaciation dynamics. Such estimates for the Northern Tien Shan were studied by several authors (Dyurgerov et al., 1995; Vilesov and Uvarov, 2001). The average decrease in the area of glaciers in Zailiyskiy Ala Too is estimated to be 30-35% for the period from 1950 to the end of the 20th century (Vilesov and Uvarov, 2001). For the Chinese part of the Tien Shan, the retreat of glaciers is somewhat lower—13% over the last 37 years (Bolch, 2007; Li et al., 2006). For glaciers of the Central and Inner Tien Shan there are also a number of estimates of change in the area of glaciation (Jing et al., 2006; Khromova et al., 2003; Aizen et al., 2006). However, for different authors, due to the use of different methods, the results vary significantly. Thus, for the Akshyrak massif, the reduction of glaciers over the period of 1977-2003 is estimated from 8.6% (Khromova et al., 2003) to 23% (Jing et al., 2006). Obviously, our knowledge of glaciers changes in the Tien Shan and is still not enough.

Monitoring of glaciers and hydrometeorological conditions of the nival-glacial zone in Kyrgyzstan was practically stopped in the late 90s of the 20th century. Whereas, scientific community has the following questions on the agenda: How the contribution of melted glacial and snow waters varies in river runoff against the backdrop of climate change? How important is the

melting of snow and ice in comparison with the change in precipitation due to the climate warming? To answer these questions, the Tien Shan High Mountain Scientific and Research Center (TSHMSC) under the Institute of Water Problems and Hydropower of the National Academy of Sciences of the Kyrgyz Republic performs complex glaciological and hydrometeorological observations in the basin of Chon Kyzyl Suu river (the northern slope of the Teskey Ala Too range). Observations of this river basin conducted in the period of 2013-2017 enables analysis of the runoff formation process from the Kara Batkak glacier (Figure 1), establish patterns and factors, as well as the ratio of genetic components of runoff, correlating them to the meteorological conditions of each specific year.

Comprehensive glaciological observations programme was renewed in 2013 as part of the CHARIS Project (*Contribution to High Asian Runoff from Ice and Snow/ Ice and snow contribution to the flow of High Asia*) of the University of Colorado: the Cooperative Institute for Environmental Research (CIRES) and the National Snow and Ice Center (NSIDC) - United States Agency for International Development (USAID). The objective of the project was to develop a model for the melting of snow and ice using satellite remote sensing and ground monitoring of the glaciers in High Asia.

In this project, the role of the Tien Shan High Mountain Scientific and Research Center was to obtain data on monitoring the Kara Batkak glacier through instrumental ground-based observations of the main glaciometeorological parameters. The results of the performed monitoring were used as inputs to assess the accuracy of the above model of snow and ice melting. This work performed in this programme allows us to evaluate the effectiveness of the applied models of thawing (ablation). The results of these studies can be applied to assess the socio-economic consequences due to the impact of global warming on water resources.

Methodological support and scientific advice on glaciology, hydrology and modelling of glacier dynamics was provided by leading Russian and Belgian scientists. In this article we used the results of observations for 2013-2017. Using the results of similar observations over the past years (1956-1968), it became possible to compare them with the observations of recent years, in particular, to determine the change in meteorological parameters (temperature, precipitation), dynamics of glacier melting and change in flow of Kashka Tor river (Chon Kyzyl Suu river basin) against the background of climate change.



Figure 1: Chon Kyzyl Suu river basin, Kara Batkak glacier and periglacial Kara Batkak lake. The lower figure shows the location of hydrological stations and automatic weather stations in the valley of Chon Kyzyl Suu river.

Information about the Basin of Kashka Tor River and Kara Batkak Glacier

The valley glaciers are very homogeneous, and the description of Kara Batkak glacier described below is typical for most of them. Kara Batkak glacier is in the upper reaches of the right tributary of Kashka Tor river (basin of Chon Kyzyl Suu river) and is the object of glaciological monitoring. Continuous station based glaciological observations on the glacier have been carried out since 1948, and they are continued to the present day.

According to the phototheodolite survey carried out in September 1964, the area of Kara Batkak glacier was 4.58 km², 3.38 km² of which fell to the accumulation zone and 1.20 km² to the ablation zone (Dikikh and Mikhailova, 1976). However, according to our laboratory check, the total area of the glacier includes frozen areas. Since the very first measurement (1947) to the present, the total area of the open part of the glacier has changed as follows:

Year	Open glacier area, km ²	ELA, m	AAR, %
1947	3.2	3600	80.9
1964	3.0	3750	71.7
2017	2.5	4030	38.1

The range of fluctuations in the altitude of the firm line of the Kara Batkak glacier has a large amplitude, since the influence of local non-climatic factors is becoming less pronounced on the position of the firm line, and the role of macro-climatic conditions is increasingly evident. Primarily the ratio of the total heat input and annual sum of solid precipitation is typical for the region as a whole. Thus, for 70 years the area of the Kara Batkak glacier has decreased by 21.8%. According to the above data, there is a pronounced trend of diminishing the area of this glacier, which is a consequence of global warming.

The river Kashka Tor originates directly from the Kara Batkak glacier and is the right tributary of Chon Kyzyl Suu river (Issyk Kul basin). Large (62%) area of river basin of Kashka Tor occupies the Kara Batkak glacier (Figure 1). According to our data, in 2017 the snout of the glacier was 3321 m, the maximum height of Kashka Tor river basin is 4800 m, the length of the glacier is 3500 m, the average width is 750 m, the area is 2.5 km², 1.5 km² of which is applied to the glacier ablation zone. The catchment area is separated from the tongue of the glacier by a powerful icefall. The glacier's tongue is bordered by the terminal and lateral moraines, which have buried ice in the core. Between the tongue of the glacier and the wall of terminal moraine is Kara

Batkak glacial lake (Figure 1), the level of which varies considerably during the year.

Overflow stream is carried out by overfilling through the frontal moraine and partly by filtration from under the frontal moraine with the formation of streamlets that merge into a common stream and give rise to Kashka Tor river. Alimentation of this river is glacial-snow, indicator of alimentation type (the ratio of runoff volume for July-September to the runoff volume of April-June) is 4.06 (Bakov, 1983). There is a gauging station “Kashka Tor Istok” on Kashka Tor river. Observations at the gauging station allow us to compare the values of melting with the volume of runoff.

The objective of this paper is to elucidate both the main and secondary ablation factors, as well as drawing of analytic links between them, precise calculation of glacial melt and the proportion of glacial runoff.

Methodology

The surface ablation at Kara Batkak glacier was measured during 1956-1968. The number of rods in individual years in the language at Kara Batkak glacier tongue varied from 58 in 1958 to 15 in 1964. In 1961-63, the ablation was also measured in the firn zone up to an altitude of 3900 m.

In 2013, observations at Kara Batkak glacier have been resumed as the most studied and representative: *glaciological* (snow reserves, ablation and changes in the frontal part of the glacier), *meteorological* (temperature, air humidity and precipitation) and *hydrological* (measurement of flow and water level in June-September on Kashka Tor river).

In 1956, to monitor the temperature and humidity of Kara Batkak glacier at an altitude of 3415 m, a meteorological observation booth was installed with weekly thermographs and hygrographs, with the help of which observations were made during the entire ablation period and are being continued. To measure precipitation on the frontal moraine of the Kara Batkak glacier at an altitude of 3300 m, total and daily precipitation meters were installed, since September 2016 – Automatic Weather Station (AWS). On the glacier at an altitude of 3500 m, a total precipitation gauge is installed, in July 2017, the Campbell Scientific AWS with a video camera and a Sonic Ranger with on-line mode was installed at an altitude of 3415 m.

Ablation stakes on the Kara Batkak glacier were drilled to a depth of 4 to 6 m, depending on the height of their location and the rate of ice melting. As the stakes

were thawed out, they were re-drilled in the same place and thus, by the end of the ablation period, the total value of the melted ice in this section was obtained. The average of the sums of the indications of all the stakes gave the value of the surface ablation characteristic of the glacier. The number of stakes in individual years in Kara Batkak glacier tongue was different, and from 2007 to 2016, it was increased from 12 to 21 in the altitude range of 3300-3500 m. In addition, in the upper part of the glacier, including its accumulation zone, in the altitudes from 3600 to 4100 m, another 13 ablation stakes were drilled. The layout of stakes and the boundary of divisions along the zones of the Kara Batkak glacier are shown in Figure 2a.

The method of genetic hydrograph separation by sources of runoff formation was as follows. Flood hydrograph is multimodal: the first peak is snow, derived from the melting of seasonal snow accumulated in the mountains during the cold period (October-May); glacial runoff—due to the melting of the glacier, on which individual peaks are superimposed due to precipitations of the warm period (June-September). Since Kashka Tor river flows from a small glacial lake located at the glacier, its runoff is somewhat regulated, that is, melt water first enters the lake and then into the river. However, the depth and volume of the lake are small, the water level in the lake and the river is synchronous, and they have a close connection.

The value of each alimentation source is defined in the drainage layer (mm) from the surface (area) of the glacier. Average daily water flow is transferred to the runoff layer by the formula:

$$h = Q \times T/F \times 10^3$$

where Q is the average daily water discharge, m^3/s , T is the number of seconds in appraisal period, and F is catchment area, km^2 .

The calculated layer of runoff by average daily water flow is then summed over the period of snow flood, glacial—during the period from July to September. Rain water feed is defined as the sum of all the precipitation that fell on the surface of the glacier during the period June-September.

The Main Factors of Glacier Melt

The latitudinal position of the Teskey Ala Too ridge (42° N) and large absolute heights have a favourable effect on the total arrival of solar radiation—the main factor affecting the air temperature, ablation and budget of

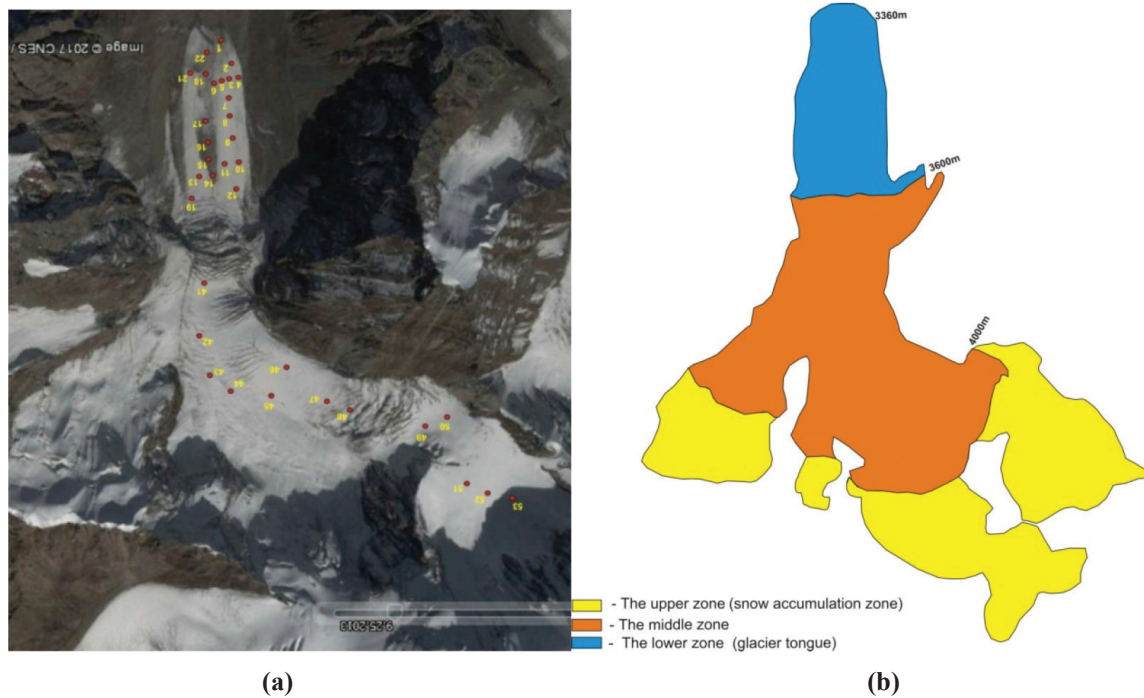


Figure 2: (a) Layout of ablation stakes location at the Kara Batkak glacier; (b) Boundary of the glacier division by zones.

the glacier. The arrival of solar radiation is affected by the height of the terrain, the closed horizon and cloud cover. The possible duration of sunshine in the territory of Kyrgyzstan for the year ranges from 2500 to 2750 hours (Avsyuk, 1953). In peripheral ridges, because of the greater closed horizon and the development of convective processes, the sum of the hours of sunshine is much less (HMS “Chon Kyzyl Suu” - 1800 hours). For comparison, the maximum values of solar radiation, measured in the highland glaciers of Caucasus, Tien Shan and Pamir Alai, reach 1.6-1.7 cal/cm² per min (1.12-1.19 kW/m²).

These values are approximately 15-20% greater than in the plain. The maximum value recorded at the Tien Shan HMS is 1.68 cal/cm² per min, and the solar radiation at the Kara Batkak glacier did not exceed 1.53 cal/cm² per min, and the monthly heat gain was 9.3 kcal/cm² (Bakov, 1983). Because of the low heat capacity, ice cannot accumulate thermal energy, which is characteristic of water. Therefore, the same amount of heat the water retains it for a very long time, while snow loses it in a matter of minutes. And in the warm season, the melting snow and ice by total incoming heat is expended by this process for evaporation, since snow-ice surface cannot be heated above 0°C. On the surface of glacier Kara Batkak, according to Avsyuk (1953), the maximum value of evaporation per day was 0.084 mm, and the maximum condensation value was 0.216 mm.

The Influence of Other Factors on Glaciers Melting

Strengthening the wind contributes to increased heat exchange and moisture exchange on the ice surface. Radiation wind diminishes ablation, convective on the contrary, contributes to its increase (Narama et al., 2006). Extreme maximums are formed as a result of a combination of increased melting of ice and runoff from glaciers with abundant rainfall on them. There were falling showers on glaciers during their active thawing. This has always led to an intensive flow of water from glaciers. The last such case in Chon Kyzyl Suu river basin and in neighbouring valleys was 03.08.2013; that day the water discharge at KashkaTor-source gauging station was 2.02 m³/s, with an average value of 1.3 m³/s in the first week of August.

Dependence of Melting on the Degree and Nature of Contamination of Glacier Surface

The question of the effect of eolian contamination of the glaciers surface on glacier melt was raised and investigated by many authors. In the Central Tien Shan, G.A. Avsyuk and L.D. Dolgushin were engaged in this, in Dzhungar and Zailiysk Ala Too – N.N. Palgov, A.N. Dikikh and others. According to Sumarokova (1965), gravel on the surface of glaciers absorbs 2.1-2.4 times more solar radiation than pure glacial ice. Contaminated ice poorly passes the rays and melts mainly from

the surface. With the continuous coating of ice with morainic material, its melting gradually decreases with an increase in the thickness of the moraine cover, until the glacier melting completely ceases. The determination of the natural contamination of the surface of the Kara Batkak Glacier (Bakov, 1983) showed that the amount of eolian fine earth in the firn area is 191.4 g/m^2 , at an altitude of 3500 m only 27.4 g/m^2 , and at the end of the tongue at an altitude of 3300 m up to 462.7 g/m^2 . Uneven contamination of the glacial surface disrupts the differentiation of melting in height.

The most convenient for calculation and easily predicted meteorological element is the air temperature, which is a function of the influx of solar radiation, advective heat, the influence of precipitation and cloudiness. On the example of the glaciers of Ala Archa basin (the Kyrgyz range), it is established that for every degree of positive air temperature there are from 6.8 to 9.2 mm of melted ice, an average of 7.2 mm (Shultz, 1949). The obtained values agree with the data of Schultz (1949) and other authors dealing with similar calculations (7 mm per 1°C of positive temperature).

Against the background of climate change, the main climatic parameters were analyzed—air temperature and precipitation from observations at the weather station (WS) of Kyzyl Suu located in the basin of Chon Kyzyl Suu river at an altitude of 1740 m and having a long series of observations since 1951. Analysis of the average annual air temperature has unequivocally shown a positive trend. During the 65-year observation period, the average annual air temperature (based on the initial trend) increased in the range from 6.2°C to 7.5°C (Figure 3).

Weather Conditions of the Observation Period

Air temperature firmly holds the first place among the meteorological indicators used to calculate the melting of glaciers. The close connection between the melting of glaciers and the temperature of air is explained

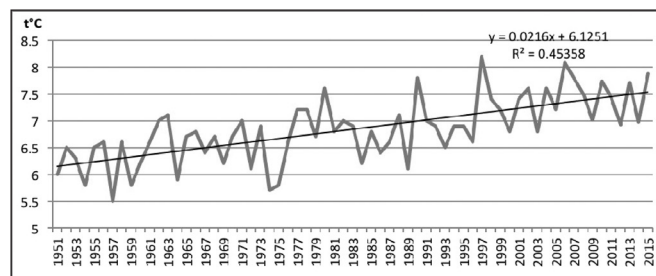


Figure 3: The trend of the average annual air temperature and temperature over the comparative periods by Kyzyl Suu MS.

by the fact that all the main components of the heat balance contain direct or indirect information about this meteorological parameter. In fact, solar radiation plays a decisive role in the intensity of melting snow and ice on mountain glaciers of temperate and subtropical latitudes, accounting for 80-90% of all heat expended for ablation (Tsykin, 1962). Higher values of Bk (balance of Earth-reflected radiation) and air temperature are observed at the same type of weather, namely, in the conditions of anticyclone, with a low-clouds sky and an open solar disk. There is a thermal transformation of the air (i.e., heating of its lower layers from rocks and stony moraine), reaching a glacier with a valley wind or airflow from the nearest slopes. Thus, the connection between the solar radiation absorbed by the glacier Bk and the air temperature is indirect, but it is rather tight.

The relationship between air temperature and the balance of long-wave radiation is direct, functional, but in absolute terms, the contribution of Vd (long-wave radiation balance) is small. A characteristic feature of the temperature distribution over the glacier is its inversion throughout the day. The coldest and densest layers of air, located at the surface, inhibit its mixing and thereby reduce the amount of heat received from the air by the surface of glacier. At the same time, over the land sections, free from snow and ice, in the daytime, air is heated from rocks and moraines and it “floats”, i.e. thermal turbulence (convection) is observed.

The Relationship between Air Temperature and Melting (Ablation) of Glaciers

Voloshina (2006) has explained through the temperature coefficient of melting according to the Hodakova-Krenke formula. The temperature coefficient Kt is the amount of snow or ice that has melted, per 1° of the positive average daily air temperature.

The air temperature serves as a good indicator of the intensity of glacier melting, since it is closely related (directly or indirectly) to all the components of the heat balance. In addition, an important role is played by the fact that the air temperature can be easily measured with a sufficient degree of accuracy on glacier, near it or extrapolated from the nearest weather station.

The easiest indicator used for calculation of ice and snow melting is the temperature factor of melting, i.e. the value of melting at 1°C of the positive average daily air temperature. But it has some uncertainty due to major fluctuations across space and time, especially at low temperatures (below 5°C). This indicator can be used with due accuracy for large averaging (not less than per decade) and for large areas of glaciers

or snowfields. For glaciers in temperate latitudes the average value is 5-7 mm/degree per day.

Figure 4 shows the trends in the change in the average daily air temperatures according to the weekly thermograph at the Kara Batkak glacier during the ablation period of 2014-2017.

Over the ablation period 2014-2017 the highest positive air temperature was in 2015 - 5.5°C, then in 2017 -5.4°C, in 2016 -4.4°C and in 2014 -4.2°C (Figure 4). Analysis of the temperature regime showed that the average temperature of the analyzed period was higher than the multiyear averages, and only in 2014 the temperature was at the level of the multiyear averages (4.2°C). The highest temperature was in July, August 2015 and 2017, and in September 2013, 2016, which led to a high runoff of Kashka Tor river in these months. The average annual air temperature on the Kara Batkak glacier in 1961-1968 amounted to -3.8°C; in 2013-2017 to -2.6°C; this means that over the past five decades the Kara Batkak glacier has become warmer by 1.2°C. Thus, the temperature regime over the analyzed years indicates and confirms the tendency of temperature increase in the nival-glacial zone of the Tien Shan.

To study global warming impacts on the climatic conditions in the different altitude belts for the period from 1961 to the present, there was made comparison of the air temperatures of MS Kyzyl-Suu located in foothill zone of the Teskey Ala-Too range (1740 m), HMS Chon-Kyzyl-Suu (2550 m) located in the middle zone, and the MS Kara-Batkak (3280 m) located at the high altitude zone.

To restore the air temperature data for the missed period of observations at the Chon-Kyzyl-Suu and Kara-Batkak meteo stations, there were used equations with meteorological data of Kyzyl-Suu meteo station.

The obtained air temperature data in TSHSC, the graphs and the calculated vertical thermal gradients at three points with different heights of the Chon-Kyzyl-Suu river basin, confirm the significant air temperature differences in the various altitude belts of Teskey Ala-Too.

From Figure 4a it is obvious that there is a good synchronization of annual trends of air temperature at the Kyzyl-Suu, Chon-Kyzyl-Suu and Kara-Batkak meteo stations for the period from 1961 to 2015. The average annual air temperature for the period from 1961-2015 at the Kyzyl-Suu meteo station was 7.0°C, at HMS Chon-Kyzyl-Suu 0.6°C, at MS Kara-Batkak -3.3°C. This allows suggestion that the same dependence can be in the entire of Teskey Ala Too.

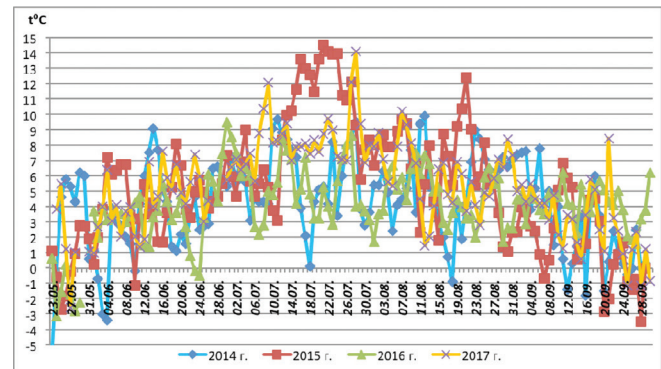


Figure 4: Average daily air temperatures at the Kara Batkak glacier during the ablation period of 2014-2017.

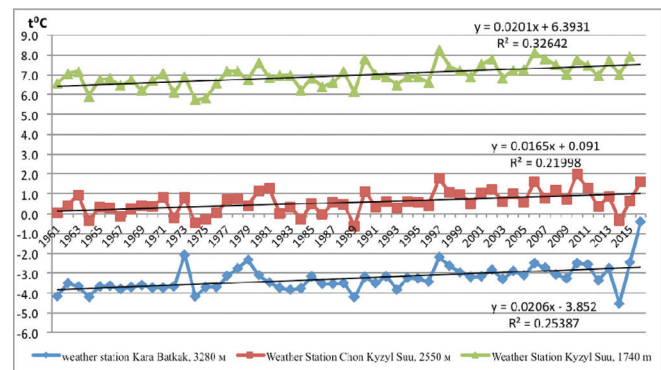


Figure 4a: Annual average of air temperature on vertical zones of Chon-Kyzyl-Suu river basin for the period from 1961-2015.

Precipitation

Figure 5 shows the water reserves in seasonal snow on the Kara Batkak glacier during the period from 2013 to 2017. To measure the daily precipitation, the daily precipitation gauge of Tretyakov was used. The total precipitation gauges installed in the Chon Kyzyl Suu river basin: on the Kara Batkak glacier at a height of 3300 m; under the glacier on the moraine of 3500 m and on the hydrometeorological station Chon Kyzyl Suu at an altitude of 2550 m to measure the amount of seasonal precipitation. The precipitation was collected monthly from the total precipitation chambers in the warm season, the cold season—twice—in October and in May.

The largest reserve of water in seasonal snow was recorded in the 2016/17 balance year. As follows from the graph (Figure 5), there is a trend of increasing the total amount of precipitation as the absolute altitude increases.

The average long-term values of precipitation falling on the surface of the Kara Batkak glacier in the years 1956-1968 and 2013-2017 are shown in Figure 6.

In 2013-2017 years the Kara Batkak glacier received 5.6% more precipitation than in 1956-1968. In 2013-2017 years, winter and spring precipitation was 1.1% more, in summer 1.5% more and in autumn received 0.6% less precipitation than in 1956-1968.

The total amount of precipitation falling on the surface of the Kara Batkak glacier during the flood season of the reporting period and in certain months (June-September) is shown in Figure 7.

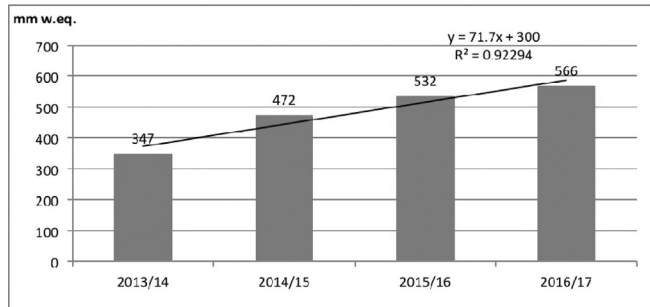


Figure 5: Average reserves of water in seasonal snow of the Kara Batkak glacier.

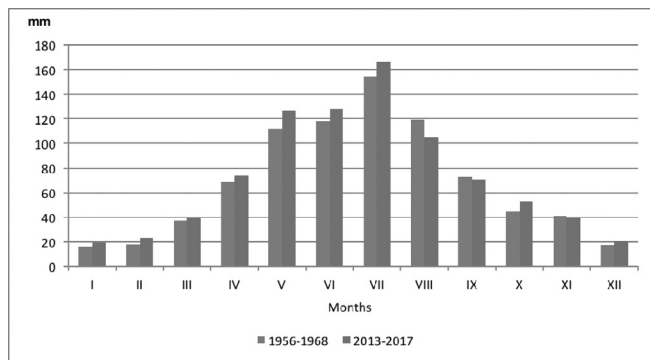


Figure 6: Comparative values of average monthly precipitation at Kara Batkak glacier.

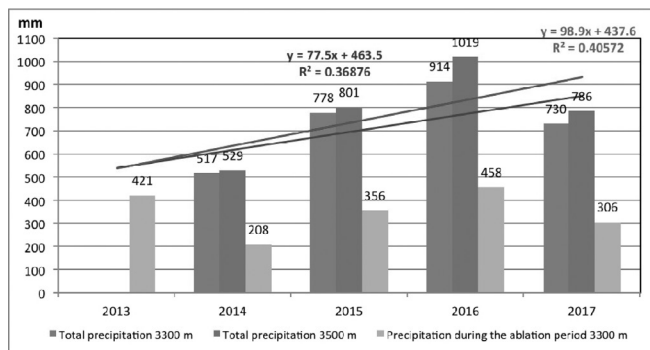


Figure 7: The average values of precipitation amount in 2013/14, 2014/15, 2015/16 and 2016/17 balance years and ablation period (June-September) at the Kara Batkak glacier.

Less wet from all years of observations in the altitude zone of 3300-3500 m was 2014, precipitation of which was 523 mm, or 66% of the norm. The wettest in this zone was 2016, with precipitation of 967 mm, or 122% of the norm. The difference in the amount of precipitation in these years was 444 mm.

Effect of Buried Glacier on the Ablation Magnitude

Figure 8 presents a comparative graph of ablation of the open and buried (debris cover of a glacier) parts of the Kara Batkak glacier.

Over the entire ablation period in 2013-2017 the average total ablation in the open part of the glacier was 308 cm or 2770 mm of water eq. In the same period, the glacier ablation under the moraine cover (in the area of the buried glacier) was 250 cm or 2250 mm of water eq. (Figure 8). From the graph it follows that the ablation of the open parts of the glacier is 23% more than its buried areas. This is because the presence of moraine on ice contributes to a change in the structure of the radiation balance: (a) albedo decrease, which leads to an increase in absorbed solar radiation; and (b) heated moraine particles emit more long wave heat than pure ice. With an increase in the degree of freezing up to a certain limit, the radiation balance of the ice surface increases. When the moraine cover becomes continuous, an essential part of the radiation balance is spent on heating the moraine material and thus does not reach the ice.

Figure 9 clearly shows that the intensity of melting, other things being equal, is a function of the height, expressed in inverse proportion. The correlation coefficient is 0.96 and 0.98, which means a good relationship between the dependence of melting on height. According to Figure 9, during the observation period of 2013-2017 ablation of the glacier at altitudes of 3300-3900 m, in open areas averaged 308 m, in frozen areas 250 cm, which was 23% more.

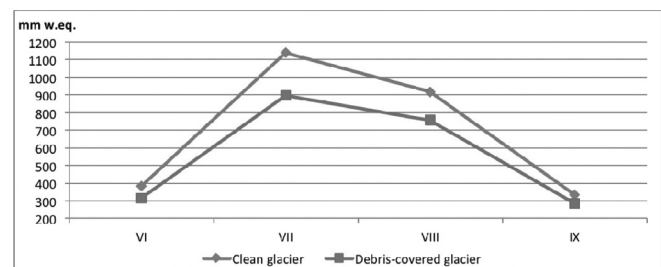


Figure 8: Ablation of the open surface and debris cover of Kara Batkak glacier during the ablation period of 2013-2017.

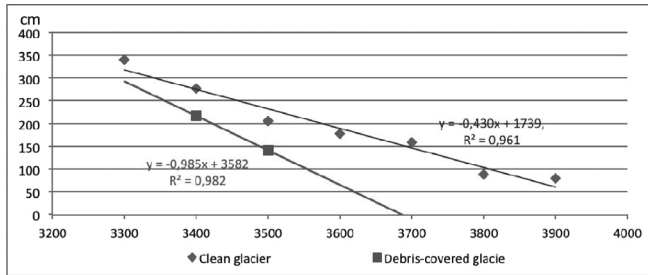


Figure 9: Dependence ablation of Kara Batkak glacier melting from the height and availability of surface moraine.

Thus, it can be concluded that the moraine cover on glaciers significantly slows the ablation of ice.

One of the most important questions of the set task is to determine the duration of the ablation period, i.e. finding start and end dates of thawing period. Dikikh and Mikhailova (1976) proposed the definition of the beginning of the ablation period by the average monthly temperatures, from which, as a rule, snow gathering depends. For clarity, Table 1 is given.

On the Kara Batkak glacier, the average monthly temperature transition through 0°C in the upward direction usually occurs in May, and this depends on when this transition occurs—at the beginning or end of the month, which determines the sign of the mean monthly temperature. Average monthly air temperatures in 2013-2017 in May, at 0.9°C were higher than in 1961-1968, and in June at 1.8°C (Bakov, 1983). The average air temperature during the ablation period (VI-IX) in 1961-1968 was 2.8°C, and in 2013-2017 –4.8°C. The duration of the ablation period in 1961-1968 was 73 days (Bakov, 1983), and in 2013-2017 100 days. A significant increase in air temperature and an increase

in the duration of the ablation period in the last five years have led to the fact that the ablation value of the Kara Batkak glacier in 2013-2017 was 62% more than in 1961-1968.

A comparison of the total ablation of this year with previous years is shown graphically in Figure 10.

On the Kara Batkak glacier in the upper zone (3600-4100 m) in 2015 ablation stakes were installed, according to which the ablation value of the entire open surface of the glacier was determined. Over the entire open surface of the Kara Batkak glacier (3300-4100 m), the ablation in 2015 was 2165 mm water equivalent, 2016 – 1690 mm water equivalent and 2017 – 2148 mm water equivalent. In the 2014-15 balance year, the maximum reserve of water in seasonal snow was 582 mm eq. In 2016-17 the balance year - 639 mm eq., which is 10% more.

The value of the average daily ablation in 2013-2017 was 3.2 cm and in 1956-1968 2.5 cm (Figure 11).

The trend of increasing ablation over the entire observation period on the Kara Batkak glacier is associated with an increase in air temperature. The highest air temperature on the Kara Batkak glacier during the ablation period in 2017 was 5.60°C, in 2015 was 5.40°C and in 2016 was 4.50°C. According to the figure, the trend of ablation changes indicates that the value of the average daily melting of Kara Batkak glacier in the period 2010-2017 was more by 20% than in 1956-1968. This is due to the fact that the average annual air temperature in 1956-1968 was –3.8°C, and in the ablation period, the average daily air temperature was +2.5°C, the ablation period lasted for 72 days, in 2013-2017 respectively: –2.6°C, +3.1°C and 100 days.

Table 1: Dependence of the start date of ablation period from the average monthly air temperature in 1961-1968 and 2013-2017

Year	1961	1962	1963	1964	1965	1966	1967	1968	2013	2014	2015	2016	2017
<i>Ablation start, date</i>	10.06	28.06	02.07	20.07	20.06	18.06	03.07	19.06	21.06	17.06	17.06	17.06	15.06
<i>Ablation end, date</i>	20.09	8.09	20.09	1.09	28.08	15.09	30.08	29.08	19.09	29.09	22.09	29.09	28.09
<i>Average May temperature</i>	2.6	0.7	0.9	-0.7	0.8	-1.0	0.4	0.4	1.2	2.6	1.3	-1.3	3.4
<i>Average June temperature</i>	0.9	3.3	-0.5	3.3	3.3	3.0	3.1	3.1	5.3	3.3	4.4	3.7	4.5
<i>Average July temperature</i>	3.3	3.2	0.9	4.0	4.9	2.5	4.6	5.1	3.6	5.3	8.7	4.8	8.4
<i>Average August temperature</i>	2.5	3.2	1.2	2.8	4.4	4.8	3.8	4.7	6.9	5.1	5.7	4.3	6.0
<i>Average September temperature</i>	2.0	2.8	1.1	0.8	1.3	2.5	2.8	2.0	4.3	2.3	1.6	4.1	3.6

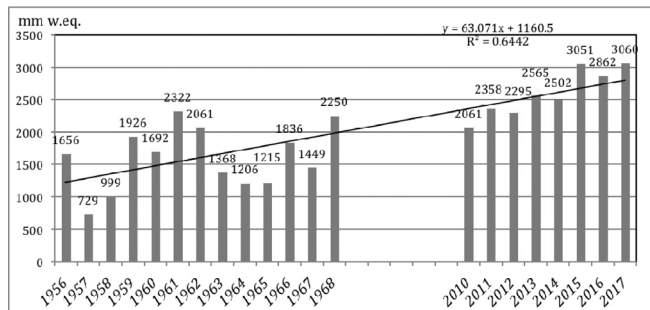


Figure 10: Kara Batkak glacier ablation (3300-3500 m) over the period of 1956-1968 and 2010-2017.

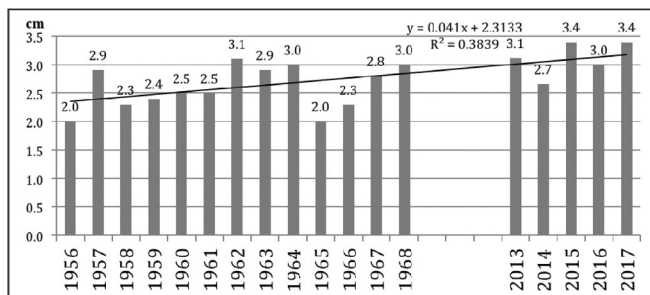


Figure 11: Average daily ice melting of tongue part of the Kara Batkak glacier.

Thus, it becomes evident that in recent years the trend of daily ice melting has increased.

Change in Glacier Melt with the Height

Figure 12 shows the trend of ablation changes in the altitude gradients of the Kara Batkak glacier. The ablation change trend in the period of 2015-2017 has a good connection in terms of altitude gradients, the correlation coefficient is high and equal to $R^2 = 0.97$. The amplitude of the gradient is significant—from 0.12 to 0.63 m per 100 m. The appearance of this gradient is often due to the heterogeneous nature of precipitation. In the summer period, precipitation falls more often in the lower parts of the glacier in the form of rain, while in the upper zone the snow falls out.

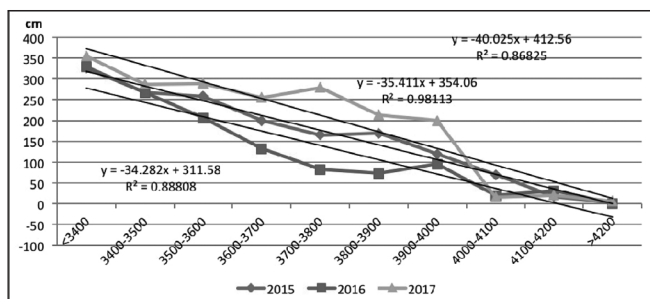


Figure 12: Ice ablation according to heights gradients of the Kara Batkak glaciers in 2015-2017.

Mass Balance of a Glacier

Determination of the glacier mass balance is ultimately the main task of the integrated glaciological observations, since it enables to predict the glaciations development trends in the near future. The balance is made up of the arrival of a solid sediment, which includes solid substances, movement of snow by snowstorm, water condensation, and flow, the bulk of which is the melting of the glacial surface and evaporation. The accumulation of a solid is closely related to the process of ice formation. The justification for distinguishing the types of ice formation and the processes occurring in this case is given by Avsyuk (1953). Later, a more detailed classification of ice formation zones was given by Tsykin (1962), based on the materials of the studies obtained during the IGY (International Geophysical Year).

It is known that the accumulation of solid matter is closely related to the process of ice formation, since only the accumulation of solid matter leads to ice formation, which increases the mass of glacier. Accumulation of solid matter is calculated only for the firn area, whereas ablation is calculated for the entire surface of the glacier. The total precipitation in the firn area was calculated from the precipitation that fell in the glacier tongue. At the same time, corrections were introduced to change the amount of precipitation with altitude. In determining the mass balance of the glacier, the flow is based on the runoff from the entire surface of the glacier.

The Tien Shan physicogeographical station of the Academy of Sciences of the Kyrgyz SSR in the period of 1957-1997 performed reliable field measurements of the mass balance and its components of the Kara Batkak glacier (Figure 13). Beginning in 1976, there was a turning point in the trend of changes in the mass balance of the Kara Batkak glacier with a transition to the negative range (Figure 13).

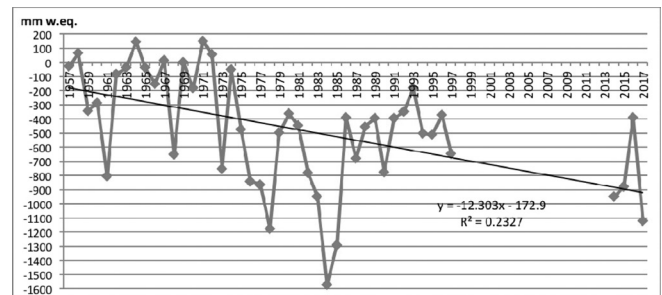


Figure 13: The Kara Batkak glacier mass balance during the period of 1957-1997 and 2014-2017.

The lack of data on the mass balance of the glacier over the period of 1998-2013 is due to the fact that during this period, for objective reasons, observations were not conducted in full. Since 2013 we continued field measurements of the components of glacier mass balance, which allowed calculating the mass balance. The results of these measurements are shown in Figure 14. It follows from the figure that the annual mass balance of the Kara-Batkak glacier in the 2016/17 balance year was the most negative (−1120 mm w.eq.) for the entire observation period (2013-2017). This was associated with the abnormally warm and long summer period of 2017. In 2015/16, the balance year at a relatively close to the average long-term air temperature (4.4°C), an abnormally large amount of precipitation (1348 mm w. eq.) and a long duration of the ablation period (105 days), the mass balance values of the Kara Batkak glacier turned out to be −390 mm w.eq. Figure 14 shows that the mass balance values of the Kara Batkak glacier are closely correlated with air temperature and precipitation. There are extremely negative values of its mass balance in other years (<http://wgms.ch/latest-glacier-mass-balance-data/>).

Thus, the mass balance not only of the Kara Batkak glacier and other glaciers of the Chon Kyzyl Suu river basin, but also of the entire northern slope of Teskey Ala Too, is negative for 60 years. It can be interpreted as an addition to river runoff due to degradation of the glaciation. However, this also reduces the area of glaciation. Therefore, the increase in the specific value of the “glacial additive” after a certain number of years will lead to a decrease in the volume of the glacial runoff. This position is obvious and demonstrated by the example of the glacier Djankuat (Dyurgerov et al., 1995).

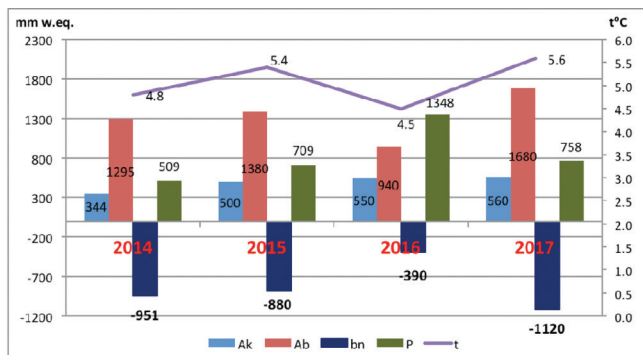


Figure 14: Air temperature (t) during ablation period, precipitation (P , mm), accumulation (Ak), ablation (Ab) and specific mass balance (bn) of the Kara Batkak glacier during 2014-2017.

Hydrological Observations

Since the altitude marks of the Kara Batkak glacier and the Kashka Tor istok hydrological post are more than 3000 m, the zero isotherm rises to this altitude in late May-early June and the process of melting seasonal snow begins. From this period, observations on the water level measurement of the flow of Kashka Tor river was carried out. Based on the data of all the measured water flow, the curve of the dependence of the water discharge on the level is constructed. According to the curve of the water level and flow rate and the regression equation describing this relationship, and according to the data of the average daily levels, the average daily water discharge was calculated and the drain hydrograph was constructed.

Figure 15 shows the average daily water flow of Kashka Tor river in the period from 2013 to 2017 according to the results of daily observations of the level and flow of water. The runoff hydrograph is multi-peak, several snow and glacial flood peaks have been identified, which are clearly consistent with the average daily air temperature. The resulting coupling equation ($y = 0.175x - 0.035$) can be used to calculate the average monthly discharge of water (or the runoff layer) from the Kara Batkak glacier during the high water and individual months (July-September), when observational data are available. The course of the level is closely and synchronously associated with the course of the air temperature (Figure 4). During the period of melting (ablation) of the glacier, the level fluctuations are quite significant, several ups and downs are noted, which are quite synchronous with the course of air temperature and are in ant phase with precipitation. This is due to the fact that in the event of precipitation and cloudiness, the temperature of the air decreases and the

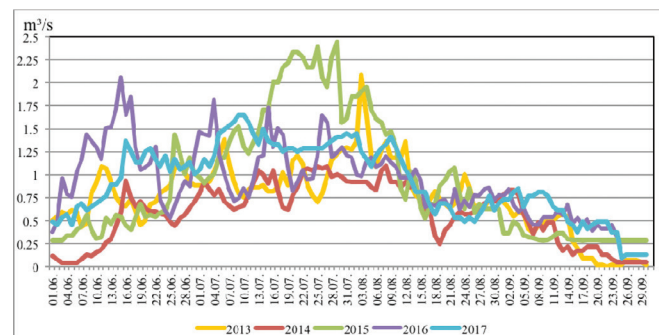


Figure 15: Average daily water discharge of Kashka Tor river during the period of 2013-2017 according to the results of daily monitoring over the water level and discharge.

melting of the glacier decreases, as a result of which the level of water decreases and the flow decreases.

Figure 16 shows a graphical representation of the average monthly flow of Kashka Tor river obtained by us during the period 2013-2017 and our predecessors in the period of 1954-1968. According to the schedule, in the period of 2013-2017 the average monthly flow of Kashka Tor river was much larger than in the previous comparable period. Thus, this clearly demonstrates the consequences of the apparent global warming. This is a clear indicator of climate change.

According to the data of two-day observations of the level (at 08.00 and 17.00), the mean daily water levels were calculated and the average daily water flow was calculated from the dependence $Q = f(H)$. The water table, the average daily air temperature and the daily precipitation sums were plotted in a complex graph (Figure 15), which made it possible to distinguish sources of runoff formation—snow feed (feed from seasonal snow reserves from October to May), glacier feed (due to melting of the Kara Batkak glacier) and rain feed due to the precipitation of warm period (June-September). Table 2 shows the values (in% and mm) of the total runoff of various types of alimentation in Kashka Tor.

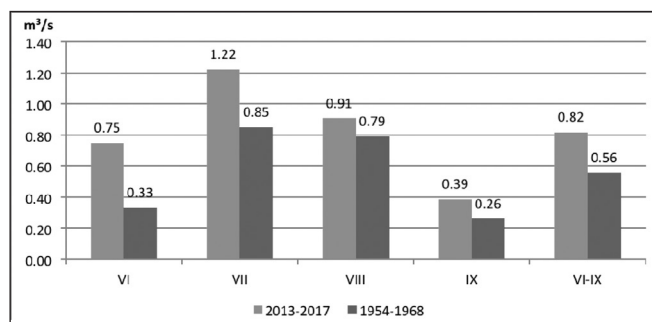


Figure 16. Average monthly runoff of Kashka Tor river at Kashka Tor istok stream gauge during the period of 1954-1968 and 2013-2017 according to the results of daily observations over the water level and discharge.

During the implementation of the CHARIS project, the largest amount of the runoff from the Kara Batkak glacier was in 2017. Compared to previous years, in 2017 the glacial component of the runoff was the largest i.e. 72%. This is explained by the corresponding meteorological conditions of ablation period in 2017:

- With the same number of days with precipitation in 2013 and 2015 there was little amount of precipitation, only 306 mm.
- The highest air temperature is 5.6 °C.
- The longest ablation period is 105 days.

According to Dikikh and Mikhailova (1976), the percentages of the average long-term runoff components are as follows: snow—45%; glacial—50%; rain—5%. Data for the period of 2013-2017 differ from the mean annual data by the ratio of alimentation sources, which was also due to abnormal meteorological conditions.

According to snow measurements, at the glacier Kara Batkak in the period of 2013-2017 maximal water reserve in snow was 1228 mm in the glacier ablation zone and 1797 mm in the accumulation zone, with an average value of 1518 mm. If we take into account the evaporation from snow, which is determined by the calculation method as 19% of total snow reserves (Satylkanov, 2016), then the seasonal water reserves are 1229 mm, multiplied by the area of the glacier ablation; this value was 1840 mm.

From the analysis of hydrometeorological conditions of 2013-2017 we can draw the following conclusions:

- The genetic components of the runoff varied significantly:
 - seasonal snow from 19% to 32% (mean perennial to 45%);
 - glacial from 63% to 79% (with an average of 50%);
 - rainfall from 2% to 5% (with an average of 5%).
- The ratio of alimentation sources depends on the meteorological conditions of each particular year.

Table 2: Components of the total runoff layer of various alimentation types in Kashka Tor river

Year	Runoff component						Total	
	Snow		Ice		Rain			
	mm	%	mm	%	mm	%	mm	%
2013	2694	40	3514	52	510	8.0	6718	100
2014	1350	27	3447	69	234	5.0	5031	100
2015	2082	26	5736	71	312	4.0	8130	100
2016	2615	38	3974	57	383	5.0	6972	100
2017	2484	25	7239	72	271	3.0	9994	100
Average		31		64		5.0		100

- There was a significant increase in the glacial component of the runoff.

Using the meteorological data of Kyzyl Suu MS, trends in the average annual air temperature showed that the most dynamic and significant temperature increase was in the period of 1995-2015 (Figure 3). The change in atmospheric precipitation over 65 years of observations is not so significant, however, the trend is positive and is about 25 mm. There is a more significant variation in the amount of precipitation by years (29). In unison of the indicated regularities, the trend of increasing the water flow of the Chon Kyzyl Suu river, measured at the hydropost “Lesnoi cordon” is shown in Figure 17. The change in climatic parameters affected the state of glaciation and the glacial runoff of Chon Kyzyl Suu river. The trend of average annual water discharge is positive, and the average annual water consumption has increased from 4.25 to 6.45 m³/s, which was most noticeable during the period of 1995-2014 (Figure 17).

Observation results of 2013-2017 on the Kara Batkak glacier and their comparison with the data of the period (1956-1997) allow us to draw the following conclusions:

- Instrumental observations during the periods of 1956-1968 and 2010-2017 showed that the air temperature maintained a tendency to increase.
- During the ablation period there is a close relationship between the melting of the glacier and the average monthly air temperature, which makes it possible to restore the glacial component of the runoff of Kashka Tor river for years of absence of observations.
- The trend of daily melting of ice has increased in recent years.
- For the period from 1947 to 2017 the Kara Batkak glacier area decreased by 21.8%, this result can be used in calculation of the glaciers area change in

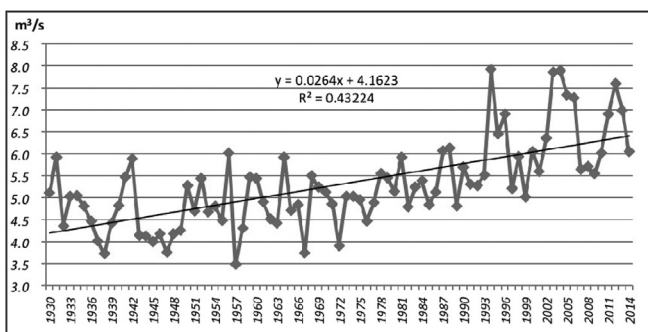


Figure 17: Trend of average annual water discharge in Chon Kyzyl Suu river.

northern exposure of the Teskey Ala Too glaciers during this period.

- Anomalous the maximum water flow rates are formed by the combination of the thawed runoff component and the liquid precipitation falling on the glacier surface.
- It should be expected that with the reduction of glaciation, the interannual variability of the runoff will increase, since the regulating role of glaciers will decrease.
- The mass balance not only of the Kara Batkak glacier and other glaciers of Chon Kyzyl Suu river basin, but also of the whole northern slope of Teskey Ala Too over 60 years is negative. It can be interpreted as an addition to river runoff due to degradation of glaciation. However, this also reduces the area of its glaciations.
- Confirmed modern ideas about water-ice balance of mountain-glacial basins of the “continental” type of alimentation.

Possible general trends that is taking place at the Issyk Kul basin:

1. While maintaining the current trend of glaciation disintegration in the long term, the greatest contribution to the change in river runoff will be attributed to precipitation and glacier flow.
2. During the observation periods since 1956, in the river basins with significant glaciation, the increase in temperature caused an increase in their runoff due to additional water generated from the increased melting of glaciers. However, in the future, while maintaining the current trend of the collapse of the glaciation and, as a consequence, reducing the area of glaciers, a turning point will inevitably lead to a decrease in river flow.
2. With the reduction of glaciation, the inter annual variability of the runoff will increase, since the regulating role of glaciers will decrease.
3. Further increase in temperature should significantly affect the intra-annual distribution of runoff of Central Asian rivers: spring snowmelt will occur more rapidly, the high water will shift to spring.

The existing numerous estimates of the change in runoff under climate change, if they are based on correct assumptions, show exactly this change.

Research and Practical Significance

1. The obtained results of analysis of complex glaciohydrometeorological data of the mountain-

glacial basin of Chon Kyzyl Suu river and extrapolated to other river basins of the Issyk Kul Basin. The outcome will be used by Public work organisations in their design of irrigation projects in their foothills slope. The water management institutions will implement the rational water use. The other scientific institutions and hydro-metreological departments does the hydrological calculations and forecast the flow of mountain rivers.

2. The results of the work performed can be used to improve the effectiveness of scientific research on water balance of mountain rivers and identification of individual balance elements, as well as for water management, which is the main task of our time.

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