IRSTI 37.29.35, 89.57.35 https://doi.org/10.26577/JGEM.2024.v75.i4.2

I.V. Severskiy[1], V.P. Kapitsa[1], N.E. Kassatkin[1], Z.S. Usmanova[1*], T. Saks[2], E. Mattea[2], D.K. Kissebayev[1]

[1]Central Asian Regional Glaciological Centre (Category 2) under the auspices of UNESCO (CARGC), Almaty, Kazakhstan
[2]University of Fribourg, Department of Geosciences, Fribourg, Switzerland
*e-mail: zamira_usmanova@mail.ru

COMPARISON OF THE MODELLED AND MEASURED MASS BALANCE OF THE CENTRAL TUYUKSU GLACIER, NORTHERN SLOPE OF ILI-ALATAU

The study considers the results of numerical modelling of the mass balance of the Central Tuyuksu Glacier, located on the northern slope of the Ile Alatau, Northern Tian Shan, using the DMBSim model. A comparison was conducted between the computed values of both winter and annual mass balances and the measurements obtained during the balance years of 2006-2023. The input data for the modelling included data on glacier accumulation, ablation, and mass balance derived from stakes, as well as snow surveys with pit measurements. Additionally, air temperature and precipitation data from the Tuyuksu weather station and total precipitation gauges were incorporated.

The largest difference between the simulated winter mass balance and the measured values on actual dates was observed during the 2006/07 period, amounting to 0.37 m w.e. (68%), with an average of 0.17 m w.e. (29%). The maximum disparity in annual mass balance, also on actual dates, was 0.34 m w.e. (40%), with an average of 0.05 m w.e. (9%). These findings provide valuable data for use in predictive calculations for the surface mass balance and glacier runoff.

Key words: Central Tuyuksu Glacier, mass balance, mathematical model, ablation, accumulation, snow cover.

И.В. Северский [1], В.П. Капица [1], Н.Е. Касаткин [1], З.С. Усманова [1*], Т. Сакс [2], Э. Маттеа [2], Д.К.Кисебаев[1]

[1]«ЮНЕСКО аясындағы 2-санатты Орта Азия аймақтық гляциологиялық орталығы» ЖШС, Алматы қ., Қазақстан,

[2]Фрибург университеті, Жер туралы ғылымдар факультеті, Фрибург қ., Швейцария
* e-mail: zamira_usmanova@mail.ru

Іле Алатауының солтүстік беткейіндегі Орталық Тұйықсу мұздығының модельденген және гляциологиялық массалық балансын салыстыру

DMBSim моделін қолдана отырып, Солтүстік Тянь-Шань, Іле Алатауының солтүстік беткейіндегі Орталық Тұйықсу мұздығының балансын математикалық модельдеу нәтижелері қаралды. 2006-2023 баланстық жылдарындағы өлшенген өлшемдермен қысқы және жылдық масса балансының есептік мәндерін салыстыру жүргізілді. Мәліметтердің негізгі көзі ретінде рейкалық өлшеулерден алынған мұздықтың аккумуляция деректері, абляция және массалық балансы, сондай-ақ шурфтар қолдану арқылы қар өлшеу түсірілімнің деректері пайдаланылды; Тұйықсу метеостанциясынан және жиынтық жауын-шашын өлшегіштерден ауа температурасы мен жауын-шашынды бақылау деректері де қоса пайдаланылды. Модельденген қысқы масса балансының нақты күндерде өлшенген нәтижелермен максималды сәйкессіздігі 2006/07 жылдары байқалды және 0.37 м w.e. (68%) пен орташа 0.17 (29%) құрады. Жылдық масса балансының максималды айырмашылығы, нақты күндер бойынша, 0.34 М w.e.(40%) орташа есеппен алғанда 0.05 (9%) болды. Зерттеу нәтижесіндегі мәліметтер массаның жерүсті балансы мен мұздық ағынының болжамды есептеулерінде пайдаланылуы мүмкін.

Түйін сөздер: Орталық Тұйықсу мұздығы, масса балансы, математикалық модель, абляция, аккумуляция, қар жамылғысы.

И.В. Северский[1], В.П. Капица[1], Н.Е. Касаткин[1],
З.С. Усманова[1,*], Т. Сакс[2], Э. Маттеа[2], Д.К. Кисебаев[1]
[1]ТОО «Центрально-Азиатский Региональный Гляциологический Центр категории 2
под эгидой ЮНЕСКО», г. Алматы, Казахстан
[2]Университет Фрибурга, г. Фрибург, Швейцария
* e-mail: zamira_usmanova@mail.ru

Сравнение смоделированного и гляциологического баланса массы ледника Центральный Туйыксу, северный склон Иле Алатау

Рассмотрены результаты математического моделирования баланса ледника Центральный Туйыксу, северный склон Иле Алатау, Северный Тянь-Шань, с применением модели DMBSim. Выполнено сравнение расчётных значений зимнего и годового баланса массы с измеренными за 2006-2023 балансовые годы. В качестве входных данных использовались данные аккумуляции, абляции и баланса массы ледника по рейкам, а также снегомерных съемок с закладкой шурфов; данные наблюдений за температурой воздуха и осадками с метеостанции Туйыксу и суммарных осадкомеров. Максимальное несоответствие смоделированного зимнего баланса массы с измеренным, по фактическим датам, отмечено в 2006/07 гг. и составило 0.37 м w.e. (68%); среднее 0.17 (29%). Максимальная разница годового баланса массы, так же по фактическим датам, составила 0.34 м w.e.(40%) при средней 0.05 (9%). Полученные данные могут быть использованы при прогностических расчётах поверхностного баланса массы и ледникового стока.

Ключевые слова: Ледник Центральный Туыйксу, баланс массы, математическая модель, абляция, аккумуляция, снежный покров.

Introduction

Water resources in arid continental regions, such as Central Asia (CA), heavily depend on cryospheric components: snow, glaciers, and permafrost. The two largest mountain systems in the world, the Tian Shan and Pamir, serve as water sources for Central Asia (Hoelzle et al., 2019).The cryospheric components of these mountain systems store substantial volumes of water in solid form and play a crucial role in the current and future availability and management of water resources in the face of a changing climate(Hoelzle et al., 2019).

Glaciers worldwide continue to retreat, with an unprecedented historical loss of mass observed since the beginning of the century, exceeding the rates of ice loss in the 1990s (Zemp et al., 2021; Zemp et al., 2015). According to results from the 2017/18 and 2018/19 hydrological years, and preliminary results for 2019/20 the annual mass balance averaged -1.0 m w.e. per year, which is 25% more negative than the annual mass balance for the first decade of the 21st century (2001-2010: -0.8 m w.e. per year), which was unparalleled on a global scale, at least during the period of available observations. In Central Asia, regional mass balance values for the 2017/18 and 2018/19 hydrological years were -488 mm w.e. and -527 mm w.e., respectively (Zemp et al., 2021). Analysis of the average Accumulation Area Ratios (AAR) indicates that glaciers are in a strong and increasing imbalance with the climate and will continue to lose mass even if the climate remains stable (Zemp et al., 2021; Shahgedanova, 2021; Kraaijenbrink et al., 2017).

Most research has focused on assessing changes in glacier area, for example (Sakai, 2019; Mölg et al., 2018; Severskiy et al., 2016; Cogley, 2016; Petrakov et al., 2016; Farinotti et al., 2015; Osmonov et al., 2013; Kriegel et al., 2013). However, data on changes in glacier area in Central Asia are still incomplete and inconsistent (Barandun et al., 2020; Mölg et al., 2018).

From the perspective of global sea-level changes (Zemp et al., 2019), regional water resources (Shannon et al., 2023; Saks et al., 2022; Huss, Hock 2018; Shahgedanova et al., 2018; Hagg et al., 2018), and the evaluation of modelling results, information on changes in glacier volume and mass is more crucial (Shannon et al., 2023; Kapitsa et al., 2020; Barandun et al. 2020).

Glacier mass balance monitoring was initiated in the mid-1950s during the Soviet era, but many mass balance observation programs were terminated in the early 1990s. To date, there is only one continuous series of observations for the Central Tuyuksu Glacier, Ile Alatau, Kazakhstan, from 1957 to the present. Glacier No.1 in the Eastern Tian Shan, China, has a relatively complete set of observations from the 1980s, with a reconstructed period dating back to the late 1950s (Barandun et al., 2020). Efforts to reinstate glacier observations began in 2010 (Hoelzle et al., 2017). However, such datasets are limited to a few selected, easily accessible glaciers, but they are significant for verifying modelling results and regional assessments. Gaps in long-term mass balance data for several glaciers have been filled using a combination of mass balance modeling and satellite data analysis (Barandun et al., 2020; Kapitsa et al., 2020; Barandun et al., 2018; Hoelzle et al., 2017).

M. Zemp et al., 2019 and Wouters, Gardner, and Moholdt, 2019, estimated glacier mass loss for Central Asia as -0.15 ± 0.12 m w.e. per year from 2006 to 2016 and -0.06 ± 0.09 m w.e. per year from 2002 to 2016, respectively. Studies assessing glacier mass changes in the Pamir region are somewhat contradictory, e.g., (Shean et al. 2020; Barandun et al. 2019; Brun et al. 2017; Farinotti et al. 2015; Kääb et al. 2015; Gardelle et al. 2013), while for the Tian Shan, better consistency has been observed, e.g., (Barandun et al., 2020; Shean et al., 2020; Barandun et al., 2019; Brun et al., 2017; Goerlich et al. 2017; Farinotti et al., 2015; Pieczonka, Bolch, 2015).

Despite differences in published glacier mass loss data, most studies emphasize the complex and heterogeneous response of glaciers in Central Asia to climate change (Barandun et al. 2020).

The aridity of the region means that during dry periods, when water sources like meltwater and precipitation are depleted, glacial meltwater constitutes a significant portion of the region's water resources. From this perspective, forecasting the future extent of glacierization and ice mass volume in the Tian Shan is of great interest (Van Tricht, Huybrechts, 2023).

A reduction in meltwater volume in the future will inevitably lead to water scarcity and a high likelihood of water conflicts (Xenarios et al., 2019; Pritchard, 2019; Huss,Hock, 2018; Sorg et al., 2012).

Another important aspect of forecasting glacier volume and mass is related to assessing the danger of glacier lake outburst floods and the increased frequency and intensity of spring floods and debris flows due to more intense (high, extreme) runoff, as reported, for example, (Van Tricht, Huybrechts, 2023; Compagno et al., 2022; Narama et al., 2018; Sorg et al., 2012; W. Hagg et al. 2006). All of this makes glaciers important for monitoring and prediction (Van Tricht, Huybrechts, 2023; Tennant et al., 2012).

Glacier mass balance models, designed to predict glacier conditions, range from simple models using cumulative air temperature anomalies (positive degree days) to models using the full energy balance (Tennant et al., 2012; Hock, Holmgren, 2005; Hock, 2003; Braithwaite, Zhang, 1999). These models are used to reconstruct gaps in glacier mass balance measurements and the historical and future evolution of glacier mass (Van Tricht, Huybrechts, 2023; Kronenberg et al., 2022; Azisov et al., 2022; Popovnin V.V. et al., 2021; Van Tricht et al., 2021; Rybak et al., 2019; Barandun et al., 2018; Kenzhebaev et al., 2017; Kronenberg et al., 2016; Barandun et al., 2015).

Predicting the state of mountain glaciers requires reliable melt modeling strategies and uniformly distributed data in time and space that can be used to verify these approaches. The use of remote sensing data has allowed an increase in the number of glaciers studied and the expansion of mass balance data in regions where traditional mass balance data are limited. Direct measurements of changes in glacier volume and mass serve as a more reliable indicator of climate change and can be used to verify mass balance model results (Tennant et al., 2012).

The objective of this study is to test the DMB-Sim mass balance model and assess the consistency of results obtained by different methods of glacier mass balance components for the Central Tuyuksu Glacier from 2006 to 2023. The choice of this period is due to the update of the stake field in 2006, increasing the number of stakes to 120 and the frequency of snow density measurements at different elevations. This allowed for minimizing the measurement error of the glacier's mass balance components (Kapitsa et al., 2020).

Study area

The left tributaries of the lower Ile River originate from the glaciers on the northern slope of the Ile (Zailiysky) Alatau, which represents one of the northern most arcs of the Tian Shan Mountain range. It spans 280 kilometers from west to east along 43°N within the range of 75-78°E. The northern slopes of the ridge descend towards foothill plains, transitioning in the north to deserts. To the south, the ridge sharply drops towards the intermountain valleys of Chilika and Chonkemina, separating the Zailiysky Alatau from the Kungey Alatau (Kokarev et al., 2022; Vilesov, 2016).

The region is characterized by significant seasonal fluctuations in temperature and precipitation. In autumn and spring Westerlies dominate the weather pattern, resulting in maximum precipitation in April-May on the plains, shifting to June-July in the mid-mountain and high-mountain areas, where the peak snow accumulation occurs in spring and early summer (Vilesov. 2016). The snow and glacier melting period typically occurs between June, July, and August, though in some years, it can extend into September. In the glacier zone, the average annual air temperature at heights of 3400-3800 meters ranges from -4 to 8°C and decreases to -10-12°C and below at altitudes exceeding 4000 meters. The average annual precipitation ranges from 700 to 1500 mm (Vilesov. 2016; Kapitsa et al., 2020).

The Central Tuyuksu Glacier is located in the basin of the Kishi Almaty River (Figure 1), at 43° 02' 44" N, 77° 04' 46" E. It is one of the most studied glaciers in Kazakhstan and Central Asia, holding a prominent place among the glaciers worldwide undergoing long-term mass balance research.

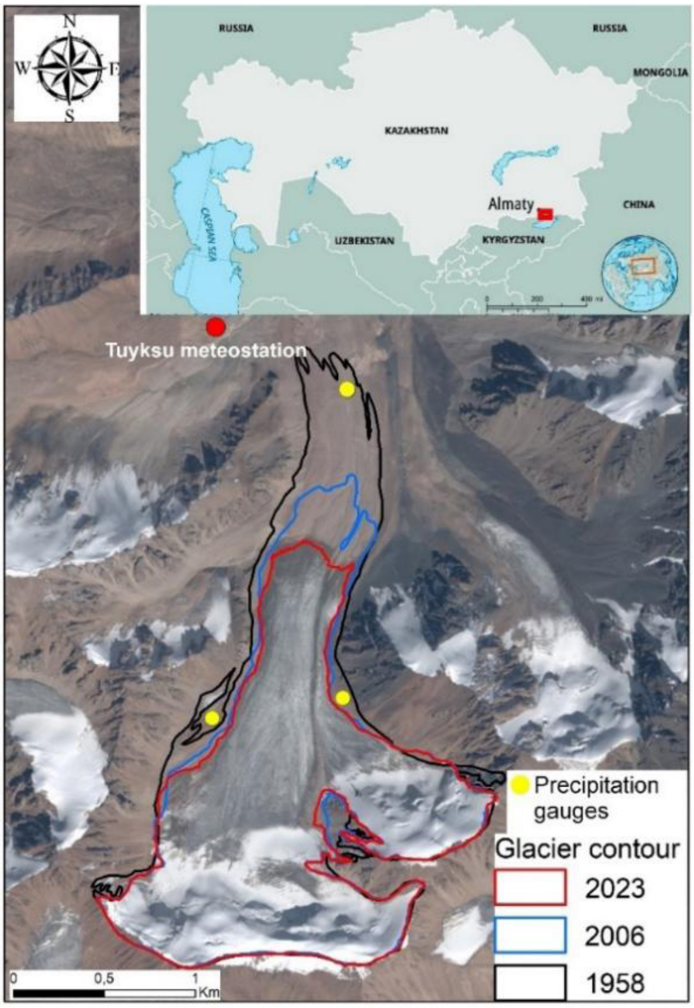

Figure 1 – Study area

Central Tuyuksu Glacier belongs to valley-type glaciers with well-defined accumulation and ablation areas. It has northern exposure, and the maximum elevation is 4219 m a.s.l. The glacier's catchment area occupies a single-cirque, with slope steepness ranging from 35-40°, which presents certain challenges and risks for observations. Nevertheless, detailed measurements were conducted on the slopes and near-cirque areas of the glacier over 18-20 years, allowing the establishment of a relationship between the mass balance components in the altitude zone of 3700-3800 m a.s.l. and the mass balance of the upper glacier sections. The glacier tongue, with rare crevasses and 8-10° slope, is relatively accessible. As of 2023, 87 stakes have been installed for snow measurements, ice and snow ablation observations, ice velocity measurements, and assessing contemporary glacier retreat. The measurement results, including annual accumulation, ablation, and mass balance values, are reported to the World Glacier

Monitoring Service (WGMS) (Kokarev et al., 2022; Makarevich, Kassatkin, 2011).

The glaciation of the northern slope of the Ile Alatau continues to decrease. Between 1955 and 2022, glaciers in the area have shrunk by 140.4 km², representing a 49% reduction, losing about 2.1 km² or 0.73% of their area annually (Mukanova et al., 2023, in press; Severskiy et al., 2016). The area of the Central Tuyuksu Glacier has decreased from 2.99 km² in 1958 to 2.19 km² in 2023. These changes are largely attributed to rising air temperatures and a negative precipitation anomaly observed in the 1970s-1980s, which was caused by changes in atmospheric circulation and affected a significant portion of the Tian Shan region (Kapitsa et al., 2020; Shahgedanova et al., 2018).

Materials and methods

Winter Balance: The maximum snow accumulation, referred to as the winter mass balance, is a key component of the annual mass balance. Typically, the cold period ends between May 25 and June 10, although deviations from these dates can be significant and depend on the meteorological conditions of a particular year. In glaciology, the end of the cold period (also known as the day of maximum snow accumulation during the cold period) is generally defined as the date when the daily average air temperature stabilizes above 0°C. In practice, snow measurements were rarely taken on the exact day when the daily average air temperature exceeded 0°C. They were more often conducted before or after this day. Therefore, from 2006 to 2023, in order to accurately determine the date and magnitude of the maximum snow accumulation, measurements of snow depth were taken approximately every ten days on the glacier, starting from late March. This involved both measuring the snowpack's height from the stake field and excavating five snow pits to measure the snow density along the glacier's centreline from the foot of the back wall to the glacier terminus. The stake field consists of wooden stakes anchored 3 m into the glacier. The number of stakes decreased from 124 to 87 between 2006 and 2023 due to the glacier's reduced size. In areas not directly observed (mainly within the accumulation zone), snow accumulation is estimated using the relationships between the winter balance, annual accumulation, and ablation, obtained from direct continuous measurements within the 3700-3800 m a.s.l. elevation interval (Makarevich, 2007) (Table 1).

Table 1 – Percentage distribution of mass balance components in the slopes with direct measurements within the one hundred-meter height interval 3700-3800 meters above sea level

Elevation interval, m a.s.l.	**Winter balance *Cw*, %**	**Annual accumulation Ct, %**	**Annual ablation At, %**
4 219-4 100	40	64	16
4 100-4 000	74	73	21
4 000-3 900	93	90	22
3 900-3 800	111	104	59

*Example calculation: If the average winter balance (Cw) in the 3,700 m-3,800 m elevation zone is 1000 mm, then in the 3,800 m-3,900 m elevation zone, it is 1110 mm, in the 3,900 m-4,000 m elevation zone it is 930 mm, in the 4,000 m-4,100 m elevation zone, it is 740 mm, and in the 4,100 m-4,219 m elevation zone it is 400 mm.

Based on the obtained data, a map of snow cover distribution is created across the entire glacier area using Surfer or ArcGIS software. The values between measured points are interpolated using the Kriging method.

The annual mass balance of the Central Tuyuksu Glacier has been subject to systematic observations since 1957 and continues to the present day. The calculation is performed using the glaciological method, based on direct measurements of snow and ice accumulation and ablation within specific elevation intervals. The annual mass balance is the algebraic sum of the incoming (annual accumulation) and outgoing (annual ablation) components of the glacier's mass. Observations are conducted according to a stratigraphic system that reflects the duration of the balance year, the start and end of which can vary, depending on meteorological conditions, from early September to mid-October.

The annual accumulation is the sum of the winter mass balance and summer precipitation. Data on the amount of summer precipitation are obtained from three cumulative precipitation gauges located on the lateral moraines and beneath the glacier's tongue. Precipitation is measured twice a year, at the end of the cold and warm periods.

Annual ablation encompasses the volume of melted snow, firn, and ice, derived from observations using an existing network of stakes. Measurements of snow and ice ablation are performed subdecadally, and during the summer period when the glacier's ice surface becomes exposed, the measurement frequency increases to 3-5 days. This is because the melting rate of the ice leads to the collapse of stakes, resulting in data loss. Typically, the stakes are re-drilled when the residual length of the stake within the glacier's body reaches 20-40 cm. For hard-to-reach elevation intervals, a computational method is applied using the relationships outlined in Table 1.

DMBSim model. The mass balance model simulates glacier mass balance on a gridded domain, which is defined by a digital elevation model (DEM). The simulation is driven by a daily meteorological series of air temperature and total precipitation.

The model starts from an initial condition of snow-water equivalent (SWE) distribution, which is computed according to several factors – topography, snow line altitude, avalanches, and (if available) winter measurements of accumulation. Then daily accumulation and ablation are calculated for each grid cell, with an approach derived by Huss and others, (2009).

Snow accumulation is calculated from the measured precipitation. This is first corrected for measurement under-catch using a multiplication factor. Then accumulation is gridded over the model domain, increasing with a constant elevation gradient, and it is additionally redistributed according to topographic curvature (reduced on ridges, increased in depressions).

Melt is computed with an enhanced temperature/radiation index (Equation 1) based on Hock, (1999):

$$m_{1,2,3}(x, y) = [M_f + 24 \cdot r_{1,2,3} \cdot Q(x, y)] \cdot T(x, y) \quad (1)$$

where m is the total melt over one day (mm w.e.), subscripts 1,2,3 refer to snow, firn and ice surfaces, x and y are the grid cell coordinates, Mf is a temperature melt factor (mm w.e. °C-1), r is a radiation melt factor for snow (mm w.e. °C -1 h-1 (W m-2)-1), Q is the daily mean potential incoming solar radiation (W m-2), and T is the daily mean air temperature (°C).

Thus, the model calculates different melt rates for various types of surfaces: snow, firn, bare ice and debris-covered ice. The model can also simulate the occurrence of avalanches using a process-based formula (Gruber, 2007), which redistributes snow also from/to terrain outside the glacier. If mass balance measurements are supplied (such as ablation stakes or snow pits), the model optimizes the parameters over the corresponding observation periods, to find the best match with the measurements. In particular, the melt factor Mf and the radiation factors r1,2,3 are automatically optimized until the simulation is unbiased (at the measured locations) compared to the measurements. When winter snow measurements are also supplied, the model will additionally optimize the precipitation correction factor. The model can be run over multiple years, including periods without mass balance measurements: in this case, it will use the parameters optimized over the measured years to calibrate the simulation for the other years.

Daily mass balance values are recorded over the course of the simulation, to finally compute the total mass balance over specific, standard periods – the hydrological year, and the period between measurements. Additionally, the model calculates the equilibrium line altitude (ELA), the accumulation-area ratio (AAR), and the daily water discharge from the glacier.

When the simulation is finished the model also computes a "corrected" mass balance distribution over each measurement period: the simulated mass balance is corrected within elevation bands, by subtracting the local model bias with respect to the point measurements (similar to the contour-line method: (Østrem, Brugman, 1991). This improves the final estimate for the spatial distribution of mass balance.

In this study, the input data included measured values of winter mass balance and ice ablation across the stake field; daily average air temperature, and daily precipitation sums obtained from the Tuyuksu MS (Meteorological Station) located along the glacier; the glacier contour for each year within the study period (2006-2023), obtained based on annual tacheometric surveys of the glacier. Additionally, a digital elevation model (DEM) from Pleiades for the year 2016 with a 0.5-meter resolution was utilized.

Results and discussions

The obtained results for the winter mass balance of the Central Tuyuksu Glacier from 2006 to 2023 are presented in Table 2 and Figures 2 and 3.

The "DMBSim" model generates two variants of the winter balance values: the first based on fixed dates from October 1 to April 30 of the following year (further in the text "Variant 1"), and the second based on the actual dates of the beginning and end of the cold period (further in the text "Variant 2"). Fluctuations in the winter mass balance values are influenced by the amount of precipitation during the cold period and wind-driven transport of freshly fallen snow from the surrounding glacier slopes and lateral moraines onto the glacier's surface. The total precipitation during the actual and fixed cold periods significantly differs. This is particularly evident in the case of the 2015/16 balance year when an exceptionally large amount of precipitation fell in May 2016, which was not considered by the model in the calculations of the first variant.

The temporal evolution of the winter balance values, modelled using the second variant, shows better agreement and correlation with the measured values, with a correlation coefficient of 0.93 (Table 2, Figures 2 and 3). However, the average balance value over the study period for the fixed dates is closer to the measured one. The difference between the winter balance values from the actual data and the measured data can be explained by the fact that the model assumes an increase in precipitation with altitude every 100 meters, and only on the moraine sections of the glacier does the snow deposition decrease. However, direct observations on the Tuyuksu Glacier have shown that the largest snow accumulations are concentrated in the altitude zone of 3800-3900 m a.s.l. at the base of the cirque. Furthermore, besides solid atmospheric precipitation, large masses of redistributed snow are accumulated here, the reserves of which decrease further up the slope with altitude and are reduced by almost half on the moraine sections (Makarevich et al., 1984: 97). To reduce this difference, additional direct observations in the glacier's accumulation area are required. As a result, adjustments in the model's input parameters during the calibration and validation stages are necessary, including the introduction of an additional input parameter such as the precipitation gradient over altitude intervals. It should be noted that such changes to the model parameters are specifically tailored to the Tuyuksu Glacier.

Table 2 – Difference between the winter mass balance values of the Central Tuyuksu Glacier for the balance years from 2006/07 to 2022/23

Balance year	DMBSim fixed dates, м w.e.	DMBSim actual dates, м w.e.	Measured, м w.e.	Difference м w.e.	
				Measured-fixed	Measured-actual
1	2	3	4	5	6
2006/07	0.784	0.914	0.544	-0.240	-0.370
2007/08	0.417	0.476	0.411	-0.006	-0.065
2008/09	0.591	0.765	0.626	0.035	-0.139
2009/10	0.945	1.247	0.887	-0.058	-0.360
2010/11	0.676	0.861	0.585	-0.091	-0.276
2011/12	0.397	0.537	0.414	0.017	-0.123
2012/13	0.469	0.574	0.466	-0.003	-0.108
2013/14	0.162	0.260	0.195	0.033	-0.065
2014/15	0.755	0.881	0.654	-0.101	-0.227
2015/16	0.688	1.293	1.024	*0.336*	*-0.269*
2016/17	0.695	0.798	0.699	0.004	-0.099
2017/18	0.566	0.651	0.558	-0.008	-0.093
2018/19	0.607	0.809	0.536	-0.071	-0.273
2019/20	0.724	0.693	0.462	-0.262	-0.231
2020/21	0.415	0.461	0.429	0.014	-0.032
2021/22	0.729	0.649	0.526	-0.203	-0.123
2022/23	0.611	0.797	0.733	0.122	-0.064
Mean	0.602	0.745	0.573	-0.028	-0.171

Continuation of the table

Balance year	DMBSim fixed dates, м w.e.	DMBSim actual dates, м w.e.	Measured, м w.e.	Difference м w.e.	
				Measured-fixed	Measured-actual
1	2	3	4	5	6
Max	0.945	1.293	1.024	0.336	-0.032
Min	0.162	0.260	0.195	-0.262	-0.370
Amplitude	0.783	1.033	0.829	0.597	0.337
Correlation coefficient				0.73	0.93

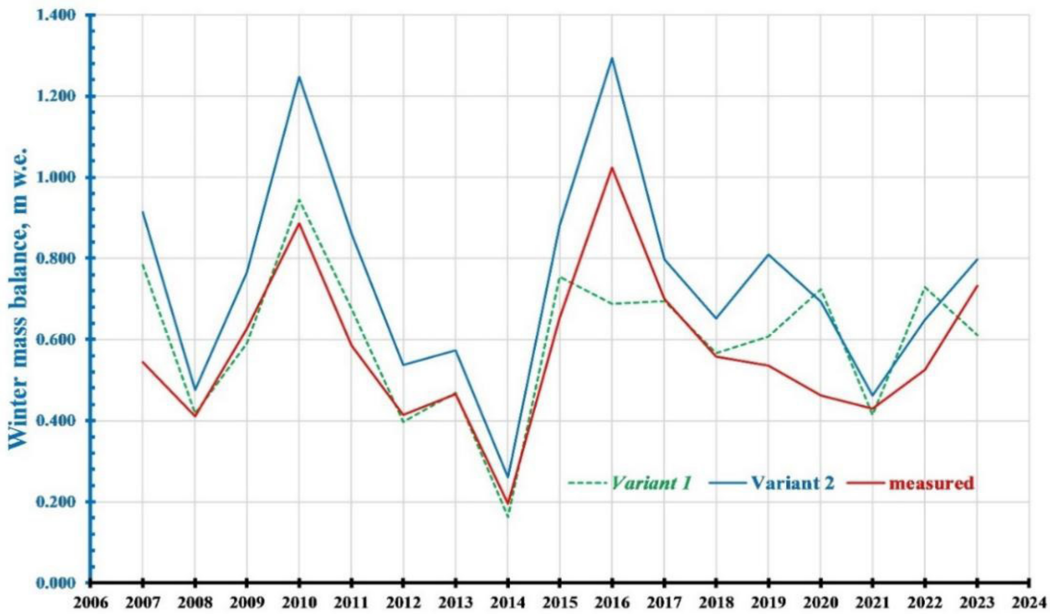

Figure 2 – Winter mass balance of the Central Tuyuksu Glacier from the balance years 2006/07 to 2022/23, as modelled and measured.

Table 3 and Figures 4 to 6 present a comparison of annual mass balance values obtained through modelling.

Over the entire observation period from 1958 to 2023, the mass balance of the Central Tuyuksu Glacier amounted to -28.0 m or -0.43 m w.e a^{-1} (see Figure 7). The average annual mass balance of the glacier for the studied period from 2006 to 2023 was -0.542 m w.e. Positive balances were observed in the balance years of 2008/09, 2009/10, and 2015/16, with the most negative balance year being 2007/08. The modelled annual mass balance values, both based on fixed dates and actual dates of the beginning and end of the balance year, were closer to the measured values compared to the winter balance.

Despite a high correlation coefficient between the modelled and measured mass balance values, significant differences are observed in some years. The absence of direct observations in the accumulation zone is likely one of the sources of this inconsistency when extrapolating data. Maximum differences are observed at around 3770 m a.s.l. (Figure 4), where the ablation stakes end, and the mass balance is calculated based on the relationships (see Table 1).

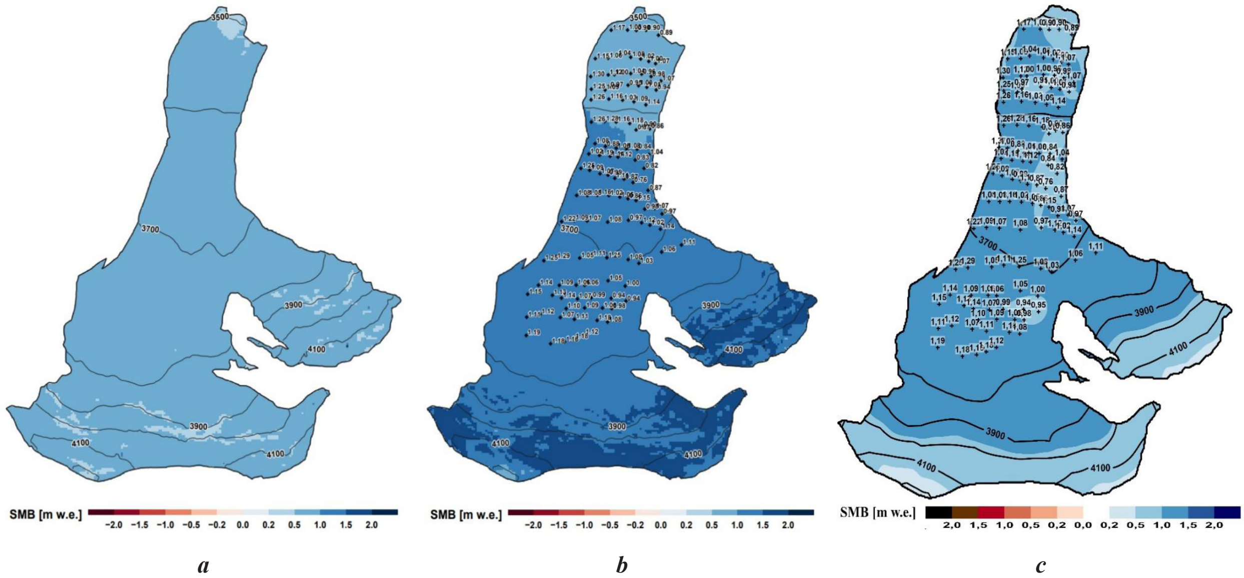

Figure 3 – Winter mass balance for the 2015/16 balance year. Modelled using fixed dates from October 1, 2015, to April 30, 2016 (a), for the period from September 20, 2015, to June 1, 2016 (b), and measured (c).

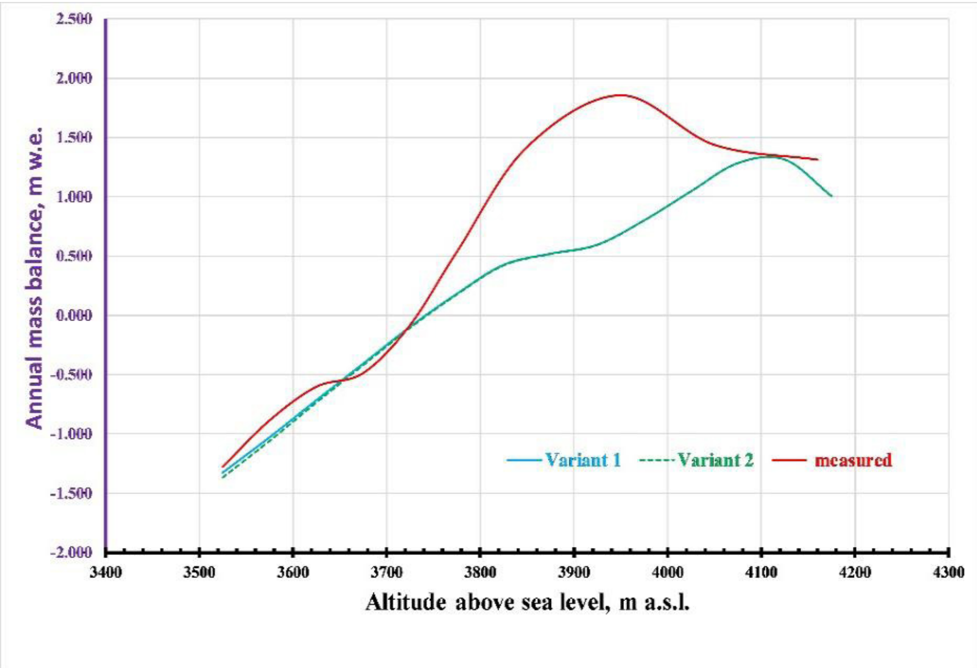

Figure 4 – The relationship between the mass balance of the Tuyuksu Glacier and absolute elevation for the 2015/16 balance year

Table 3 – The difference between the annual mass balance values of the Central Tuyuksu Glacier for the balance years from 2006/07 to 2022/23 simulated using fixed dates (hydrological year from October 1 to September 30), based on the actual dates of stable transition of the daily air temperature to negative values, and those obtained from direct field measurements.

Balance year	DMBSim fixed dates, м w.e.	DMBSim actual dates, м w.e.	Measured, м w.e.	Difference, м w.e.	
				Measured-fixed	Measured-actual
1	2	3	4	5	6
2006/07	-0.579	-0.533	-0.845	-0.266	-0.312
2007/08	-1.425	-1.415	-1.357	0.068	0.058
2008/09	0.199	0.072	0.205	0.006	0.133
2009/10	-0.114	0.052	0.030	0.144	-0.022
2010/11	-0.133	-0.179	-0.314	-0.181	-0.135
2011/12	-1.163	-1.158	-1.023	0.140	0.135
2012/13	-0.411	-0.476	-0.340	0.071	0.136
2013/14	-1.366	-1.289	-1.088	0.278	0.201
2014/15	-0.660	-0.719	-0.756	-0.096	-0.037
2015/16	0.217	0.222	0.561	0.344	0.339
2016/17	-1.247	-1.210	-1.113	0.134	0.097
2017/18	-0.190	-0.194	-0.075	0.115	0.119
2018/19	-0.693	-0.616	-0.580	0.113	0.036
2019/20	-0.039	-0.012	-0.287	-0.248	-0.275
2020/21	-0.747	-0.738	-0.609	0.138	0.129
2021/22	-1.060	-1.062	-1.130	-0.070	-0.068
2022/23	-0.706	-0.793	-0.488	0.218	0.305
Mean	-0.647	-0.591	-0.542	0.053	0.049
Max	0.206	0.222	0.561	0.344	0.339
Min	-1.430	-1.415	-1.357	-0.266	-0.312
Amplitude	1.636	1.637	1.918	0.610	0.651
Correlation coefficient				0.96	0.94

We believe this difference arises due to different approaches (relationship method and model's calculation method) in assessing the influence of local meteorological and geomorphological conditions on snow and ice ablation and accumulation, reaching significant differences in anomalous years (see Figure 5). However, due to the lack of alternatives, model parameter tuning is necessary for a more accurate reproduction of the observed data.

With a given set of parameters, the model shows more negative annual mass balance values for the glacier. It is essential to consider relatively significant interannual variability in precipitation, near-surface temperature, and, consequently, melting rates. This calls for a more precise calibration of the model, which requires a longer series of contemporary observations as the initial data, necessitating additional research.

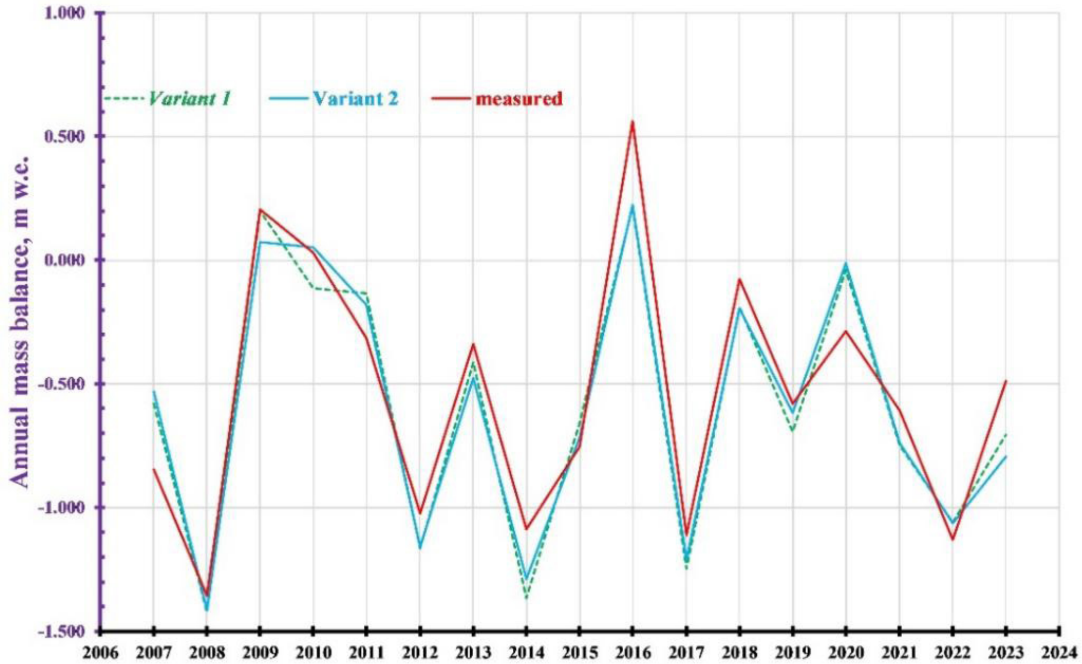

Figure 5 – Annual mass balance of the Central Tuyuksu Glacier from the 2006/07 to 2022/23 balance years, simulated and measured.

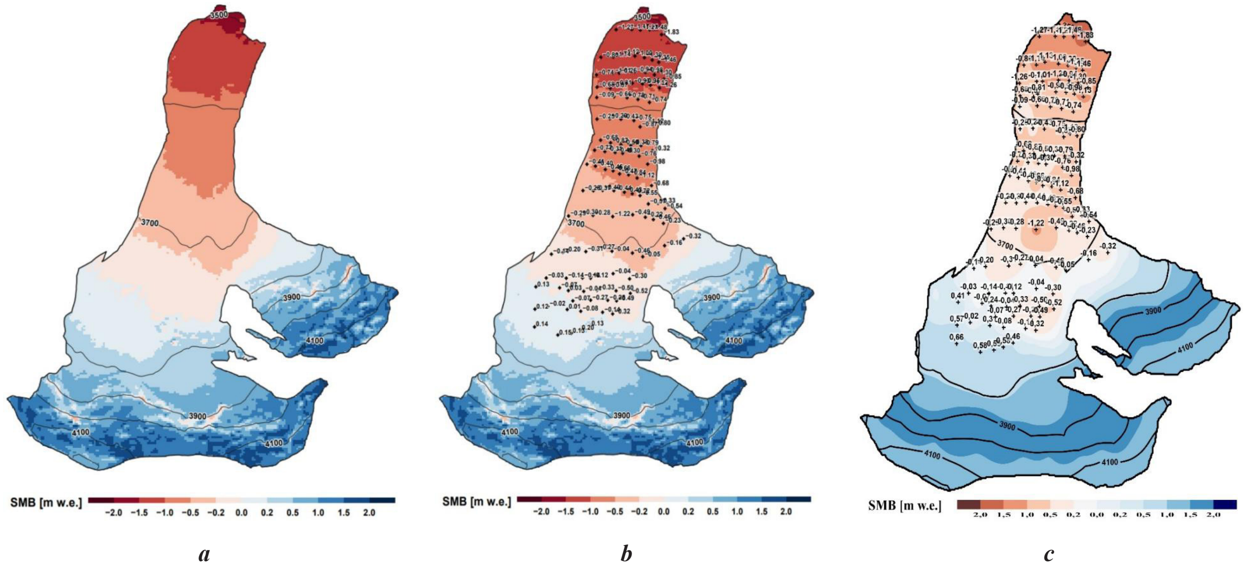

Figure 6 – Annual mass balance for the 2015/16 balance year. Simulated based on fixed dates from October 1, 2015, to September 30, 2016 (a), for the period from September 20, 2015, to September 24, 2016 (b), and measured (c).

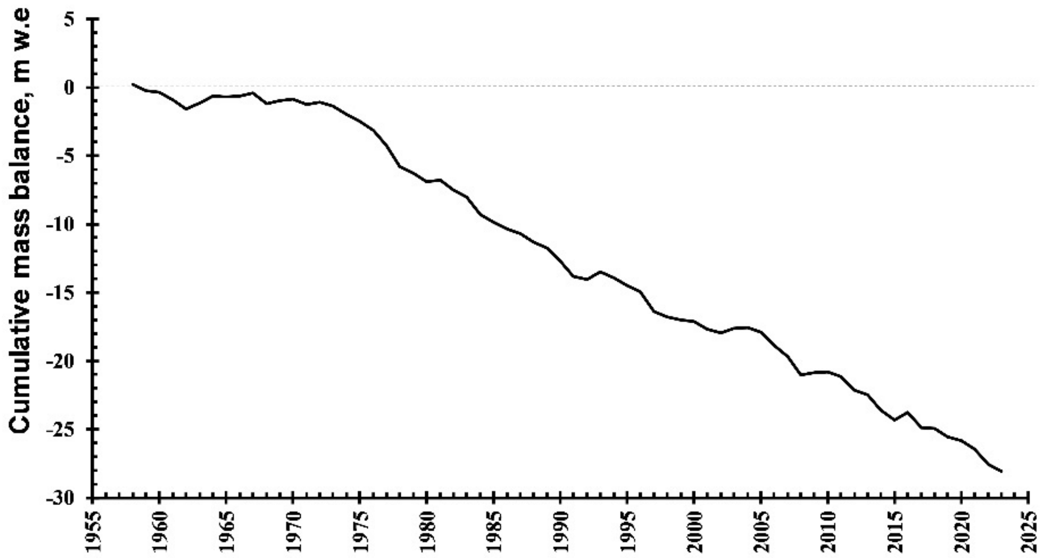

Figure 7 – Cumulative glaciological mass balances of the Central Tuyuksu glacier

The observed changes in the mass balance of the Central Tuyuksu Glacier are consistent with estimates obtained in regional studies conducted for the Tian Shan and Pamir regions, demonstrating a unified negative trend in evolution, differing only in the magnitude of values. For example, in the study by Barandun and others, (2021), the mass balance is reported as -0.30 m w.e. yr^{-1} with a significant negative trend in the period from 1999/2000 to 2017/2018 for the North and West Tian Shan. In (Pieczonka, Bolch. 2015), the mass balance is shown as -0.42 ± 0.66 m w.e. a^{-1} for the period from 1999 to 2012 for the Alatau Glacier Basin, Central Tian Shan. Kenzhebaev and others (2017) reported a mass balance of -0.39 ± 26 m w.e. a^{-1} from 2003/04 to 2015/16 for the Batysh Sook Glacier, Inner Tian Shan. Azisov and others (2022) also showed a negative trend with a mass loss of -0.18 ± 0.17 m w.e. yr^{-1} from 2010/2011 to 2020/2021 for the Golubina Glacier in the North Tian Shan. Popovnin and others (2021) reported an average mass loss of -0.53 m w.e. yr^{-1} for the Sary-Tor Glacier in the Ak-Shiyrak massif, Inner Tian Shan, during the period from 1985 to 2019. Kabutov and others (2022) presented a mass balance of -0.26 m w.e. for the 2018/2019 year for Glacier No. 139 in the Karakul Lake basin, Eastern Pamir. Barandun and others (2019), Hoelzle and others (2019) estimated changes in glacier mass for the Western and Eastern Pamir as 0.37 ± 0.42 m w.e. and +0.19 ± 1.47 m w.e., respectively.

The application of mass balance models for the reconstruction (recovery) of glacier mass balance values and historical and future evolution, despite simplifying the actual conditions of glacier existence and development, shows a satisfactory correspondence between measured and calculated (modeled) glacier mass balance values, as observed in this study and in studies such as (Azisov et al., 2022; Popovnin et al., 2021; Van Tricht et al., 2021; Rybak et al., 2019; Kenzhebaev et al., 2017).

The Central Tuyuksu Glacier is considered as a reference glacier for the Ile Alatau, and the assessment scenarios for its future state can reasonably be extended to other glaciers in the northern slope of the Ile (Zailiysky) Alatau. The research conducted and further studies will allow the development of a methodology for modelling the dynamics of other glaciers in the study area not covered by direct observations. This will improve our understanding of glacier response to observed climate change and provide additional data for assessing changes in runoff in the region.

Conclusions

The mass balance of the Central Tuyuksu Glacier for the observation period from 1958 to 2023 is predominantly negative, with a few individual years being exceptions. This confirms the ongoing loss of glacier mass and volume in the region.

Despite differences between measured and modeled mass balance values, these values are comparable, and the calculated values also demonstrate a negative mass balance trend of the Central Tuyuksu Glacier. Significant differences are mainly observed for anomalous seasons, such as 2009/10 and 2015/16.

Future plans include continuing the calibration and validation of the model for the purpose of its use in predictive calculations to assess changes in glacier mass balance components in the region's changing climate.

Acknowledgments

This research was funded by the Committee for Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan under the topic IRN BR 18574176, "Glacier Systems of Transboundary Basins in Central Asia: Current State, Contemporary and Forecasted Changes, Role in Ensuring Water Security of the Region" and project "Cryospheric Observation and Modelling for Improved Adaptation in Central Asia (CROMO-ADAPT)", contract no. 81072443, between the Swiss Agency for Development and Cooperation and the University of Fribourg.

References

Azisov, Erlan, Martin Hoelzle, Sergiy Vorogushyn, Tomas Saks, Ryskul Usubaliev, Mukhammed Esenaman uulu, and Martina Barandun. 2022. "Reconstructed Centennial Mass Balance Change for Golubin Glacier, Northern Tien Shan." Atmosphere 13 (6): 954. https://doi.org/10.3390/atmos13060954.

Barandun, Martina, Joel Fiddes, Martin Scherler, Tamara Mathys, Tomas Saks, Dmitry Petrakov, and Martin Hoelzle. 2020. "The State and Future of the Cryosphere in Central Asia." Water Security 11 (December): 100072. https://doi.org/10.1016/j.wasec.2020.100072.

Barandun, Martina, Matthias Huss, Leo Sold, Daniel Farinotti, Erlan Azisov, Nadine Salzmann, Ryskul Usubaliev, Alexandr Merkushkin, and Martin Hoelzle. 2015. "Re-Analysis of Seasonal Mass Balance at Abramov Glacier 1968–2014." Journal of Glaciology 61 (230): 1103–17. https://doi.org/10.3189/2015JoG14J239.

Barandun, Martina, Matthias Huss, Ryskul Usubaliev, Erlan Azisov, Etienne Berthier, Andreas Kääb, Tobias Bolch, and Martin Hoelzle. 2018. "Multi-Decadal Mass Balance Series of Three Kyrgyz Glaciers Inferred from Modelling Constrained with Repeated Snow Line Observations." The Cryosphere 12 (6): 1899–1919. https://doi.org/10.5194/tc-12-1899-2018.

Barandun, Martina, Robert McNabb, Kathrin Naegeli, Matthias Huss, Etienne Berthier, and Martin Hoelzle. 2019. "Region-Wide Estimate of Annual Glacier Mass Balance for the Tien Shan and Pamir from 2000 to 2017." In Geophysical Research Abstracts, 1–1. Vienna.

Barandun, Martina, Eric Pohl, Kathrin Naegeli, Robert McNabb, Matthias Huss, Etienne Berthier, Tomas Saks, and Martin Hoelzle. 2021. "Hot Spots of Glacier Mass Balance Variability in Central Asia." Geophysical Research Letters 48 (11). https://doi.org/10.1029/2020GL092084.

Braithwaite, Roger J., and Yu Zhang. 1999. "Modelling Changes in Glacier Mass Balance That May Occur as a Result of Climate Changes." Geografiska Annaler, Series A: Physical Geography 81 (4): 489–96. https://doi.org/10.1111/1468-0459.00078.

Brun, Fanny, Etienne Berthier, Patrick Wagnon, Andreas Kääb, and Désirée Treichler. 2017. "A Spatially Resolved Estimate of High Mountain Asia Glacier Mass Balances from 2000 to 2016." Nature Geoscience 10 (9): 668–73. https://doi.org/10.1038/ngeo2999.

Cogley, J. Graham. 2016. "Glacier Shrinkage across High Mountain Asia." Annals of Glaciology 57 (71): 41–49. https://doi.org/10.3189/2016AoG71A040.

Compagno, Loris, Matthias Huss, Harry Zekollari, Evan S. Miles, and Daniel Farinotti. 2022. "Future Growth and Decline of High Mountain Asia's Ice-Dammed Lakes and Associated Risk." Communications Earth & Environment 3 (1): 191. https://doi.org/10.1038/s43247-022-00520-8.

Farinotti, Daniel, Laurent Longuevergne, Geir Moholdt, Doris Duethmann, Thomas Mölg, Tobias Bolch, Sergiy Vorogushyn, and Andreas Güntner. 2015. "Substantial Glacier Mass Loss in the Tien Shan over the Past 50 Years." Nature Geoscience 8 (9): 716–22. https://doi.org/10.1038/ngeo2513.

Gardelle, J., E. Berthier, Y. Arnaud, and A. Kääb. 2013. "Region-Wide Glacier Mass Balances over the Pamir-Karakoram-Himalaya during 1999–2011." The Cryosphere 7 (4): 1263–86. https://doi.org/10.5194/tc-7-1263-2013.

Goerlich, Franz, Tobias Bolch, Kriti Mukherjee, and Tino Pieczonka. 2017. "Glacier Mass Loss during the 1960s and 1970s in the Ak-Shirak Range (Kyrgyzstan) from Multiple Stereoscopic Corona and Hexagon Imagery." Remote Sensing 9 (3): 275. https://doi.org/10.3390/rs9030275.

Gruber, S. 2007. "A Mass□conserving Fast Algorithm to Parameterize Gravitational Transport and Deposition Using Digital Elevation Models." Water Resources Research 43 (6). https://doi.org/10.1029/2006WR004868.

Gunnar Østrem, and Melinda M. Brugman. 1991. "Glacier Mass-Balance Measurements: A Manual for Field and Office Work." NHRI Science Report 4: 1–224.

Hagg, W., L.N. Braun, M. Weber, and M. Becht. 2006. "Runoff Modelling in Glacierized Central Asian Catchments for Present-Day and Future Climate." Hydrology Research 37 (2): 93–105. https://doi.org/10.2166/nh.2006.0008.

Hagg, Wilfried, Elisabeth Mayr, Birgit Mannig, Mark Reyers, David Schubert, Joaquim Pinto, Juliane Peters, et al. 2018. "Future Climate Change and Its Impact on Runoff Generation from the Debris-Covered Inylchek Glaciers, Central Tian Shan, Kyrgyzstan." Water 10 (11): 1513. https://doi.org/10.3390/w10111513.

Hock, Regine. 1999. "A Distributed Temperature-Index Ice- and Snowmelt Model Including Potential Direct Solar Radiation." Journal of Glaciology 45 (149): 101–11. https://doi.org/10.3189/S0022143000003087.

Hock, Regine. 2003. "Temperature Index Melt Modelling in Mountain Areas." Journal of Hydrology 282 (1–4): 104–15. https://doi.org/10.1016/S0022-1694(03)00257-9.

Hock, Regine, and Björn Holmgren. 2005. "A Distributed Surface Energy-Balance Model for Complex Topography and Its Application to Storglaciären, Sweden." Journal of Glaciology 51 (172): 25–36. https://doi.org/10.3189/172756505781829566.

Hoelzle, Martin, Erlan Azisov, Martina Barandun, Matthias Huss, Daniel Farinotti, Abror Gafurov, Wilfried Hagg, et al. 2017. "Re-Establishing Glacier Monitoring in Kyrgyzstan and Uzbekistan, Central Asia." Geoscientific Instrumentation, Methods and Data Systems 6 (2): 397–418. https://doi.org/10.5194/gi-6-397-2017.

Hoelzle, Martin, Martina Barandun, Tobias Bolch, Joel Fiddes, Abror Gafurov, Veruska Muccione, Tomas Saks, and Maria Shahgedanova. 2019. "The Status and Role of the Alpine Cryosphere in Central Asia." In The Aral Sea Basin, 100–121. Routledge. https://doi.org/10.4324/9780429436475-8.

Huss, Matthias, Andreas Bauder, and Martin Funk. 2009. "Homogenization of Long-Term Mass-Balance Time Series." Annals of Glaciology 50 (50): 198–206. https://doi.org/10.3189/172756409787769627.

Huss, Matthias, and Regine Hock. 2018. "Global-Scale Hydrological Response to Future Glacier Mass Loss." Nature Climate Change 8 (2): 135–40. https://doi.org/10.1038/s41558-017-0049-x.

Kääb, A., D. Treichler, C. Nuth, and E. Berthier. 2015. "Brief Communication: Contending Estimates of 2003–2008 Glacier Mass Balance over the Pamir–Karakoram–Himalaya." The Cryosphere 9 (2): 557–64. https://doi.org/10.5194/tc-9-557-2015.

Kabutov, H., A. Kayumov, T. Saks, H. Navruzshoyev, F. Vosidov, N. Nekkadamovaa, and A. Halimov. 2022. "Mass Balance of Glacier №139 in the Eastern Pamir's Lake Karakul Basin." Central Asian Journal of Water Research 8 (2): 128–40. https://doi.org/10.29258/CAJWR/2022-R1.v8-2/128-140.eng.

Kapitsa, Vassiliy, Maria Shahgedanova, Igor Severskiy, Nikolay Kasatkin, Kevin White, and Zamira Usmanova. 2020. "Assessment of Changes in Mass Balance of the Tuyuksu Group of Glaciers, Northern Tien Shan, Between 1958 and 2016 Using Ground-Based Observations and Pléiades Satellite Imagery." Frontiers in Earth Science 8 (July). https://doi.org/10.3389/feart.2020.00259.

Kenzhebaev, Ruslan, Martina Barandun, Marlene Kronenberg, Yaning Chen, Ryskul Usubaliev, and Martin Hoelzle. 2017. "Mass Balance Observations and Reconstruction for Batysh Sook Glacier, Tien Shan, from 2004 to 2016." Cold Regions Science and Technology 135 (March): 76–89. https://doi.org/10.1016/j.coldregions.2016.12.007.

Kokarev A.L., Kapitsa V.P., Bolch T., Severskiy I.V., Kasatkin N.E., Shahgedanova M., and Usmanova Z.S. 2022. "The Results of Geodetic Measurements of the Mass Balance of Some Glaciers in the Zailiyskiy Alatau (Trans-Ili Alatau)." Journal "Ice and Snow" 62 (4): 527–38. https://doi.org/10.31857/S2076673422040149.

Kraaijenbrink, P. D. A., M. F. P. Bierkens, A. F. Lutz, and W. W. Immerzeel. 2017. "Impact of a Global Temperature Rise of 1.5 Degrees Celsius on Asia's Glaciers." Nature 549 (7671): 257–60. https://doi.org/10.1038/nature23878.

Kriegel, David, Christoph Mayer, Wilfried Hagg, Sergiy Vorogushyn, Doris Duethmann, Abror Gafurov, and Daniel Farinotti. 2013. "Changes in Glacierisation, Climate and Runoff in the Second Half of the 20th Century in the Naryn Basin, Central Asia." Global and Planetary Change 110 (November): 51–61. https://doi.org/10.1016/j.gloplacha.2013.05.014.

Kronenberg, Marlene, Martina Barandun, Martin Hoelzle, Matthias Huss, Daniel Farinotti, Erlan Azisov, Ryskul Usubaliev, Abror Gafurov, Dmitry Petrakov, and Andreas Kääb. 2016. "Mass-Balance Reconstruction for Glacier No. 354, Tien Shan, from 2003 to 2014." Annals of Glaciology 57 (71): 92–102. https://doi.org/10.3189/2016AoG71A032.

Kronenberg, Marlene, Ward van Pelt, Horst Machguth, Joel Fiddes, Martin Hoelzle, and Felix Pertziger. 2022. "Long-Term Firn and Mass Balance Modelling for Abramov Glacier in the Data-Scarce Pamir Alay." The Cryosphere 16 (12): 5001–22. https://doi.org/10.5194/tc-16-5001-2022.

Makarevich K. G. 2007. The Methodological Aspects of Studies of Mass Balance and Fluctuations of Mountain Glaciers. Almaty. 102 p.

Makarevich K.G., and Kassatkin N.E. 2011. "The Half a Century of Researches of Mass Balance and Morphometric Changes of the Central Tuyuksu Glacier in the Zailiyskiy Alatau (Trans-Ili Alatau)." Ice and Snow 1 (113): 36–45.

Makarevich K.G., Vilesov E.N., Golovkova R.G., Denisova T.Ya., and Shabanov P.F. 1984. The Tuyuksu Glaciers (Northern Tien Shan). Edited by Krenke A.N. and Bochin N.A. Leningrad: Gidrometeoizdat.

Mölg, Nico, Tobias Bolch, Philipp Rastner, Tazio Strozzi, and Frank Paul. 2018. "A Consistent Glacier Inventory for Karakoram and Pamir Derived from Landsat Data: Distribution of Debris Cover and Mapping Challenges." Earth System Science Data 10 (4): 1807–27. https://doi.org/10.5194/essd-10-1807-2018.

Mukanova B.A., Severskiy I.V., Kapitsa V.P., Tatkova M.E., Kokarev A.L., and Shesterova I.N. n.d. "Changes in Glaciation of the Northern Slope of Ile Alatau over a Seventy-Year Period." Bulletin of KazNU, Geographical Series .

Narama, Chiyuki, Mirlan Daiyrov, Murataly Duishonakunov, Takeo Tadono, Hayato Sato, Andreas Kääb, Jinro Ukita, and Kanatbek Abdrakhmatov. 2018. "Large Drainages from Short-Lived Glacial Lakes in the Teskey Range, Tien Shan Mountains, Central Asia." Natural Hazards and Earth System Sciences 18 (4): 983–95. https://doi.org/10.5194/nhess-18-983-2018.

Osmonov, Azamat, Tobias Bolch, Chen Xi, Alishir Kurban, and Wanqing Guo. 2013. “Glacier Characteristics and Changes in the Sary-Jaz River Basin (Central Tien Shan, Kyrgyzstan) – 1990–2010.” Remote Sensing Letters 4 (8): 725–34. https://doi.org/10.1080/2150704X.2013.789146.

Petrakov, Dmitry, Alyona Shpuntova, Alexandr Aleinikov, Andreas Kääb, Stanislav Kutuzov, Ivan Lavrentiev, Markus Stoffel, Olga Tutubalina, and Ryskul Usubaliev. 2016. “Accelerated Glacier Shrinkage in the Ak-Shyirak Massif, Inner Tien Shan, during 2003–2013.” Science of The Total Environment 562 (August): 364–78. https://doi.org/10.1016/j.scitotenv.2016.03.162.

Pieczonka, Tino, and Tobias Bolch. 2015. “Region-Wide Glacier Mass Budgets and Area Changes for the Central Tien Shan between ~1975 and 1999 Using Hexagon KH-9 Imagery.” Global and Planetary Change 128 (May): 1–13. https://doi.org/10.1016/j.gloplacha.2014.11.014.

Popovnin V.V., Gubanov A.S., Satylkanov R.A., and Ermenbayev B.O. 2021. “Mass Balance of the Sary-Tor Glacier Reproduced from Meteorological Data. .” Ice and Snow 61 (1): 58–74. https://doi.org/10.31857/S2076673421010071.

Pritchard, Hamish D. 2019. “Asia’s Shrinking Glaciers Protect Large Populations from Drought Stress.” Nature 569 (7758): 649–54. https://doi.org/10.1038/s41586-019-1240-1.

Rybak, O.O., E.A. Rybak, N.A. Yaitskaya, V.V. Popovnin, I.I. Lavrentiev, R. Satylkanov, and B. Zhakeyev. 2019. “Modeling the Evolution of Mountain Glaciers: A Case Study of Sary-Tor Glacier, Inner Tien Shan.” Earth’s Cryosphere XXIII (3): 33–51. https://doi.org/10.21782/KZ1560-7496-2019-3(33-51).

Sakai, Akiko. 2019. “Brief Communication: Updated GAMDAM Glacier Inventory over High-Mountain Asia.” The Cryosphere 13 (7): 2043–49. https://doi.org/10.5194/tc-13-2043-2019.

Saks, Tomas, Eric Pohl, Horst Machguth, Amaury Dehecq, Martina Barandun, Ruslan Kenzhebaev, Olga Kalashnikova, and Martin Hoelzle. 2022. “Glacier Runoff Variation Since 1981 in the Upper Naryn River Catchments, Central Tien Shan.” Frontiers in Environmental Science 9 (January). https://doi.org/10.3389/fenvs.2021.780466.

Severskiy, I., E. Vilesov, R. Armstrong, A. Kokarev, L. Kogutenko, Z. Usmanova, V. Morozova, and B. Raup. 2016. “Changes in Glaciation of the Balkhash–Alakol Basin, Central Asia, over Recent Decades.” Annals of Glaciology 57 (71): 382–94. https://doi.org/10.3189/2016AoG71A575.

Shahgedanova, M., M. Afzal, I. Severskiy, Z. Usmanova, Z. Saidaliyeva, V. Kapitsa, N. Kasatkin, and S. Dolgikh. 2018. “Changes in the Mountain River Discharge in the Northern Tien Shan since the Mid-20th Century: Results from the Analysis of a Homogeneous Daily Streamflow Data Set from Seven Catchments.” Journal of Hydrology 564 (September): 1133–52. https://doi.org/10.1016/j.jhydrol.2018.08.001.

Shahgedanova, Maria. 2021. “Climate Change and Melting Glaciers.” In The Impacts of Climate Change, 53–84. Elsevier. https://doi.org/10.1016/B978-0-12-822373-4.00007-0.

Shannon, Sarah, Anthony Payne, Jim Freer, Gemma Coxon, Martina Kauzlaric, David Kriegel, and Stephan Harrison. 2023. “A Snow and Glacier Hydrological Model for Large Catchments – Case Study for the Naryn River, Central Asia.” Hydrology and Earth System Sciences 27 (2): 453–80. https://doi.org/10.5194/hess-27-453-2023.

Shean, David E., Shashank Bhushan, Paul Montesano, David R. Rounce, Anthony Arendt, and Batuhan Osmanoglu. 2020. “A Systematic, Regional Assessment of High Mountain Asia Glacier Mass Balance.” Frontiers in Earth Science 7 (January). https://doi.org/10.3389/feart.2019.00363.

Sorg, Annina, Tobias Bolch, Markus Stoffel, Olga Solomina, and Martin Beniston. 2012. “Climate Change Impacts on Glaciers and Runoff in Tien Shan (Central Asia).” Nature Climate Change 2 (10): 725–31. https://doi.org/10.1038/nclimate1592.

Tennant, Christina, Brian Menounos, Bruce Ainslie, Joseph Shea, and Peter Jackson. 2012. “Comparison of Modeled and Geodetically-Derived Glacier Mass Balance for Tiedemann and Klinaklini Glaciers, Southern Coast Mountains, British Columbia, Canada.” Global and Planetary Change 82–83 (February): 74–85. https://doi.org/10.1016/j.gloplacha.2011.11.004.

Tricht, Lander Van, and Philippe Huybrechts. 2023. “Modelling the Historical and Future Evolution of Six Ice Masses in the Tien Shan, Central Asia, Using a 3D Ice-Flow Model.” The Cryosphere 17 (10): 4463–85. https://doi.org/10.5194/tc-17-4463-2023.

Tricht, Lander Van, Chloë Marie Paice, Oleg Rybak, Rysbek Satylkanov, Victor Popovnin, Olga Solomina, and Philippe Huybrechts. 2021. “Reconstruction of the Historical (1750–2020) Mass Balance of Bordu, Kara-Batkak and Sary-Tor Glaciers in the Inner Tien Shan, Kyrgyzstan.” Frontiers in Earth Science 9 (November). https://doi.org/10.3389/feart.2021.734802.

Vilesov Ye.N. 2016. Dynamics and Current State of Glaciation in the Mountains of Kazakhstan. Almaty: Kazak universiteti.

Xenarios, Stefanos, Abror Gafurov, Dietrich Schmidt-Vogt, Jenniver Sehring, Sujata Manandhar, Chris Hergarten, Jyldyz Shigaeva, and Marc Foggin. 2019. “Climate Change and Adaptation of Mountain Societies in Central Asia: Uncertainties, Knowledge Gaps, and Data Constraints.” Regional Environmental Change 19 (5): 1339–52. https://doi.org/10.1007/s10113-018-1384-9.

Zemp, M., M. Huss, E. Thibert, N. Eckert, R. McNabb, J. Huber, M. Barandun, et al. 2019. “Global Glacier Mass Changes and Their Contributions to Sea-Level Rise from 1961 to 2016.” Nature 568 (7752): 382–86. https://doi.org/10.1038/s41586-019-1071-0.

Zemp, Michael, Holger Frey, Isabelle Gärtner-Roer, Samuel U. Nussbaumer, Martin Hoelzle, Frank Paul, Wilfried Haeberli, et al. 2015. “Historically Unprecedented Global Glacier Decline in the Early 21st Century.” Journal of Glaciology 61 (228): 745–62. https://doi.org/10.3189/2015JoG15J017.

Zemp, M., S.U. Nussbaumer, I. GärtnerRoer, J. Bannwart, F. Paul, and M. Hoelzle. 2021. “WGMS 2021. Global Glacier Change Bulletin No. 4 (2018–2019). .” Zurich, Switzerland.

Information about authors:
Igor Severskiy – doctor of geographical sciences, professor; scientific director, Central Asian Regional Glaciological Center as a category 2 under the auspices of UNESCO (Almaty, Kazakhstan; iseverskiy@gmail.com);
Vassiliy Kapitsa – senior researcher, Central Asian Regional Glaciological Center as a category 2 under the auspices of UNESCO (Almaty, Kazakhstan, vasil.geo@mail.ru);
Nikolay Kassatkin – researcher, Central Asian Regional Glaciological Center as a category 2 under the auspices of UNESCO (Almaty, Kazakhstan, kasatkinne@mail.ru);
Zamira Usmanova (corresponding author) – researcher, Central Asian Regional Glaciological Center as a category 2 under the auspices of UNESCO (Almaty, Kazakhstan, zamira_usmanova@mail.ru);
Tomas Saks – Dr in Geography, Senior researcher/Project manager, Department of Geosciences, University of Fribourg (Fribourg, Switzerland, tomas.saks@unifr.ch);
Enrico Mattea – Diploma Assistant / PhD student, Department of Geosciences, University of Fribourg (Fribourg, Switzerland, enrico.mattea@unifr.ch);
Daulet Kissebayev – researcher, Central Asian Regional Glaciological Center as a category 2 under the auspices of UNESCO (Almaty, Kazakhstan, daulet-ktl@mail.ru).

Авторлар туралы мәлімет:
Северский Игорь Васильевич – география ғылымдарының докторы, профессор, ғылыми жетекшісі, ЮНЕСКОның аясындағы 2-санаттағы Орталық Азия өңірлік гляциологиялық Орталығы (Алматы, Қазақстан, iseverskiy@gmail.com);
Капица Василий Петрович – аға ғылыми қызметкер, ЮНЕСКОның аясындағы 2-санаттағы Орталық Азия өңірлік гляциологиялық Орталығы (Алматы, Қазақстан, vasil.geo@mail.ru);
Касаткин Николай Евгеньевич – ғылыми қызметкер, ЮНЕСКОның аясындағы 2-санаттағы Орталық Азия өңірлік гляциологиялық Орталығы (Алматы, Қазақстан, kasatkinne@mail.ru);
Усманова Замира Султанкуловна (хат-хабар алмасу үшін автор) – ғылыми қызметкер, ЮНЕСКОның аясындағы 2-санаттағы Орталық Азия өңірлік гляциологиялық Орталығы (Алматы, Қазақстан, zamira_usmanova@mail.ru);
Томас Сакс – география ғылымдарының докторы, аға ғылыми қызметкер/ жоба жетекшісі, Жер туралы ғылымдар факультеті, Фрибург университеті (Фрибург, Швейцария, tomas.saks@unifr.ch);
Энрико Маттеа – аспирант, Жер туралы ғылымдар факультеті (Фрибург университеті, Фрибург, Швейцария, enrico.mattea@unifr.ch);
Кисебаев Даулет Курмангазыевич – ғылыми қызметкер, ЮНЕСКОның аясындағы 2-санаттағы Орталық Азия өңірлік гляциологиялық Орталығы (Алматы, Қазақстан, daulet-ktl@mail.ru).

Received: June 03, 2024
Accepted: November 10, 2024