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Mass Balance of Glacier №139 in the Eastern Pamir's Lake Karakul Basin

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This article is the translation of the article "Balans massy lednika № 139 bassejna ozera Karakul' Vostochnogo Pamira [Баланс массы ледника № 139 бассейна озера Каракуль Восточного Памира]" published on October 28th, 2022.

ABSTRACT

Mountain glaciers, including the poorly examined ones in the Lake Karakul Basin, are considered the most vulnerable part of the cryosphere directly reacting to the changing climatic conditions. The most recent aerial imaging and single field surveys of the Lake Karakul Basin glaciation were carried out as late as in 1953. The investigation of the basin's glaciers thus is of high scientific relevance, including in terms of glaciology and climatology. The article describes the calculations of the surface mass balance (SMB) of Glacier No.139 in the Lake Karakul Basin allowing, based on the findings, to assess the degree of climate change impact on the glaciation in the target zone, as well as the potential changes in the state of glaciers in the future. During 2018-2019, the mass balance of Glacier No.139, located in the basin's southwestern section, amounted to -0.26 mwe. The data obtained from the Karakul Weather Station allowed establishing that the climate in the target watershed is harshly cold with little snow in winter and mild summer, and the bulk of precipitation occurring in the warm season. Due to the fact that in the past and until recently no glacier mass observations were conducted in the target zone, the research findings can serve as initial data to expand the scientific and applied knowledge, as well as contribute to enhancing the accuracy of glacier dynamics modeling in the area.

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1. Introduction

The investigation of glacier behavior under climate change manifests a key applied glaciological and climatological research task.

Tajikistan's largest lake – Lake Karakul – has the mirror area of 380 km^2, depth of up to 238 m, and volume exceeding 26 km^3. It is located in the flat mountain syncline at the altitude of 3914 m ASL south of the Trans-Alai Ridge in the Northern Pamir Mountains. Several rivers flow into it, the main one being the Karadzhilga, Karart, Akdzhilga, and Muzkol. The study area is enclosed by large mountain ranges up to 5,500–6,000 m high. Lake Karakul is drainless. Its water is bitter salty (Atlas et al., 1975).

Glaciers are most sensitive to climate change. The reconstructions executed based on glacier retreat data and comparative analyses of long-term weather data (Oerlemans, 2005), as well as other methods, do not reflect the past inter-annual fluctuations due to the delayed glacier response and difficulties associated with observed data interpretation. Glacier mass balance represents a direct, i.e. non-delayed, climate signal reflecting the changes in accumulation and ablation values (Dolgova et al., 2013).

The reduction of mountain glacier area in the course of the 20th and early 21st centuries comprises several aspects. Mountain glaciers are considered the most vulnerable part of the cryosphere in terms of response to changing climatic conditions. Their shrinking leads to a relatively fast, although not as significant compared to other sources, increase in the mean global ocean water level (Radić and Hock, 2011). Mountain glaciers regulate river runoff – up to one third of its annual value in mountainous and foothill areas is of glacial nature, with its increasing up to 70% during the warm season (Panov, 2001). Glacial runoff enters rivers during the growing season, when the need for water is especially high, so the reduction of mountain glaciation affects the economy of mountainous and foothill regions. Finally, the downsizing of mountain glaciation likewise affects such an important industry as tourism (El-Sasser, Bürki, 2002).

The glaciers of the Lake Karakul Basin were poorly studied. In 1953, aerial photographing and single field surveys of the basin's glaciation zones were carried out (Atlas et al., 1975). The inaccessibility, remoteness, and drainless nature of Lake Karakul, as well as its location at the altitude of 4,000 m make farming impossible. In addition, regular monitoring of local glaciers is not considered cost-efficient. The execution of scientific research in the basin is nonetheless important, in particular, for forecasting and modeling glacier fluctuations against the background of climate change.

Several glaciers of Central Asia underwent mass balance measurements, including the Batish Sook, Tuyuksu, and Abramov Glaciers, as well as Glacier No. 354

and other representative glaciers (Fig. 1.). In their work, Hagg et al. (2004) described and compared various methods for determining the Tuyuksu Glacier mass balance. Based on the glaciological method, the indicator equaled -16.8 mwe. Kenzhebaev et al. (2017) calculated the Batysh Sook Glacier mean mass balance during 2011-2016 to be -0.34 mwe/year. Kronenberg et al. (2016) reconstructed the mass balance of Glacier No.354 (Akshiyrak Ridge, Kyrgyzstan) during 2003–2012, with its cumulative mass balance amounting to –0.40 mwe a-1 .

The model of the Eastern Pamir Region by Hoelzle et al. (2020) gives the error of ±150 cm (see Fig. 1), which is rather large. The introduction of new data will allow adjusting the deviation.

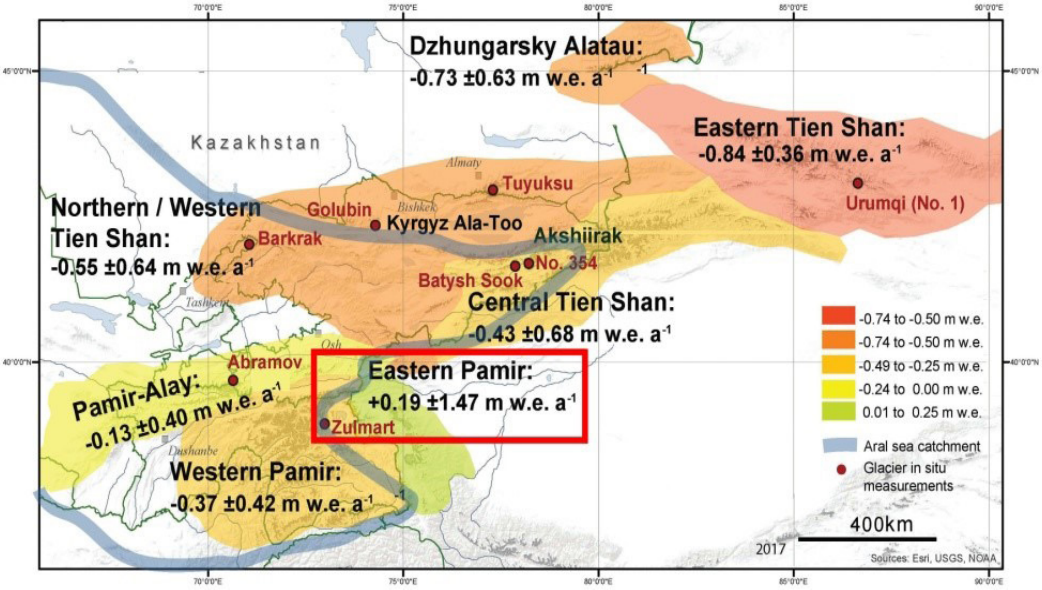

Figure 1. Modeling error (Hoelzle et al., 2020).

The installation of an automatic camera to record glacier movement and an automatic weather station harvesting meteorological data (within the framework of the CICADA Project) will allow not only ensuring continual glacier observation but also obtaining data necessary for further research.

This study aimed to measure the mass balance (specifically, surface mass balance, SMB) of Glacier No.139 in the Lake Karakul Basin. The research findings will make it possible to determine the degree of climate change impact on the glaciation in the target zone as well as assess the trends of glacier changes in the future.

The study's relevance lies in the fact that it was for the first time that the data describing the mass balance of an Eastern Pamir glacier were obtained.

2. Research object

Glaciation area (catchment area 4,210 km^2) in the Lake Karakul Basin is located in the northern part of the Eastern Pamirs. The lake is located in the center of a closed depression limited by the snow- and ice-covered mountain ridges (Trans-

Alai Ridge in the north, Muzkol in the south, Zulumart in the west, and Sarykolsky in the east) up to 5,500-6,000 m high (Atlas et al., 1975). Based on the data of the Karakul Weather Station, the local climate is severely cold with little snow in winter and mild summer, and the main precipitation occurring during the warm period (see Fig. 2. and Fig. 3.) (Mirzokhonova, 2021).

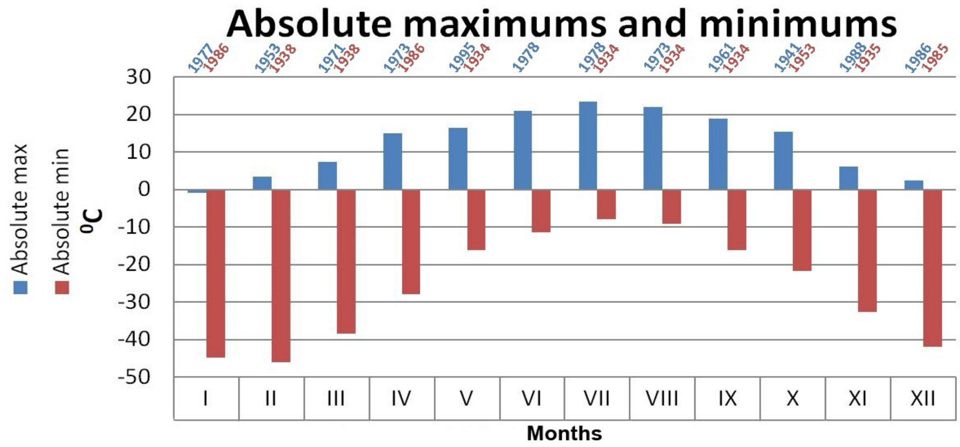

Figure 2. Absolute temperature maximums and minimums as per the data of the Karakul Weather Station (Scientific and Applied Climate Reference Book of the USSR, 1988; website “Weather and Climate”; May 8, 2021).

The diagram (Fig. 2.) shows the data of the Karakul Weather Station in the Eastern Pamirs, specifically the monthly maximum and minimum temperatures over 60 years of observations (1930-1990).

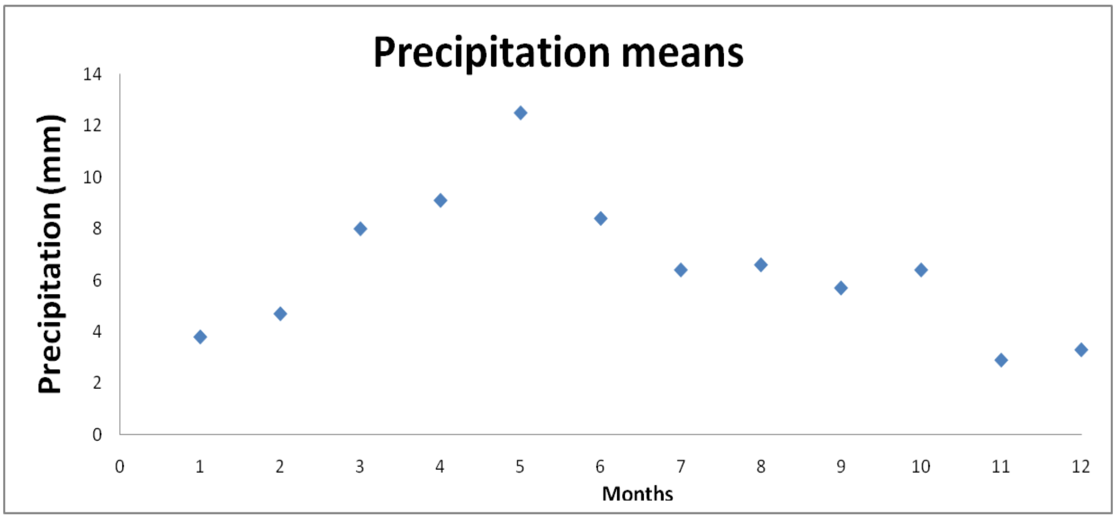

Figure 3. Mean monthly precipitation as per the data of the Karakul Weather Station (Scientific and Applied Climate Reference Book of the USSR, 1988; website “Weather and Climate”; May 8, 2021).

Glacier No.139 of the Lake Karakul Basin (as per the USSR Glacier Catalogue; Atlas, 1975) in its southwestern section was selected as the study object. Morphologically, the glacier belongs to the valley type and has the area of 3.64 km^2. The glacier's lower part is located at the altitude of 4,625 m ASL, and the highest at the altitude of 5,497 m ASL.

The southern side of Glacier No.139 has a steep slope and a rocky ridge in the middle that was excluded from calculations (the triangular fragment in the glacier center, as shown in Fig. 4B.).

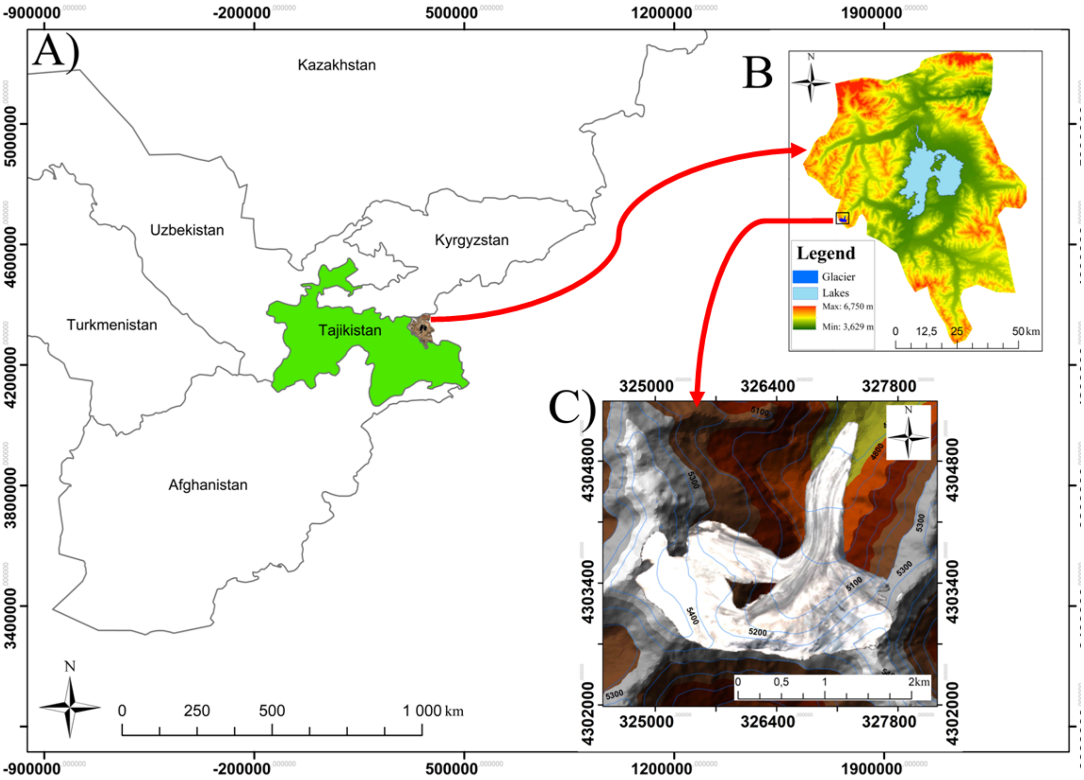

Figure 4. Research object: A) Central Asia (World Shapefiles, 2019; B) Karakul Lake Basin (SRTM radar image); C) Glacier #139 (Sentinel 2 image, ALOSPALSAR radar image).

3. Methodology

The works were carried out according to the existing methodology proven over the years and applied globally. The 2019 Sentinel-2A satellite imagery and ArcGIS were used to build the glacier's schematic and determine its area. The glacier isolines and 3D model were elaborated to better depict the study object and its orography.

The glacier examination was done via direct glaciological measurements allowing only quantitative surface mass balance measurements (Kronenberg, 2016).

Measurement of accumulation and ablation on a glacier surface and referencing them to the previous year's melting horizon represents a conventional method of determining glacier mass balance. In the accumulation zone, snow and firn thickness and density were measured using survey pits. Glacier ablation was determined using depth gauges (stakes) assuming the ice density to be approx. 900 kg/m^3 . Measurements should be carried out in representative points; otherwise difficulties may arise on glaciers with large hard-to-reach segments.

The research included two phases: field survey (see Fig. 5.) and laboratory glacier mass balance calculations. The field efforts are described below.

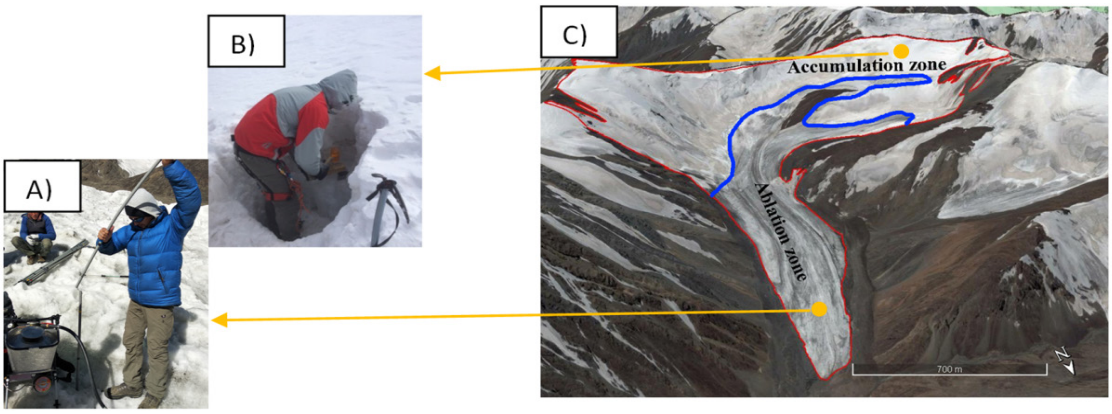

Figure 5. Main field research methods: A) Depth gauge (stake) in the ablation zone; B) Survey pit in the accumulation zone; C) Glacier ablation and accumulation zones (Google Earth image).

3.1. Works in the ablation zone

In 2018, 7 (seven) ablation gauges (stakes) were installed at pre-marked remotely determined points (see Fig. 5A.). The stakes to measure the mass loss in the glacier ablation zone were installed using a steam drill (see Fig. 6A.). In 2019, the data from the previously installed stakes were collected, and the new ones were installed.

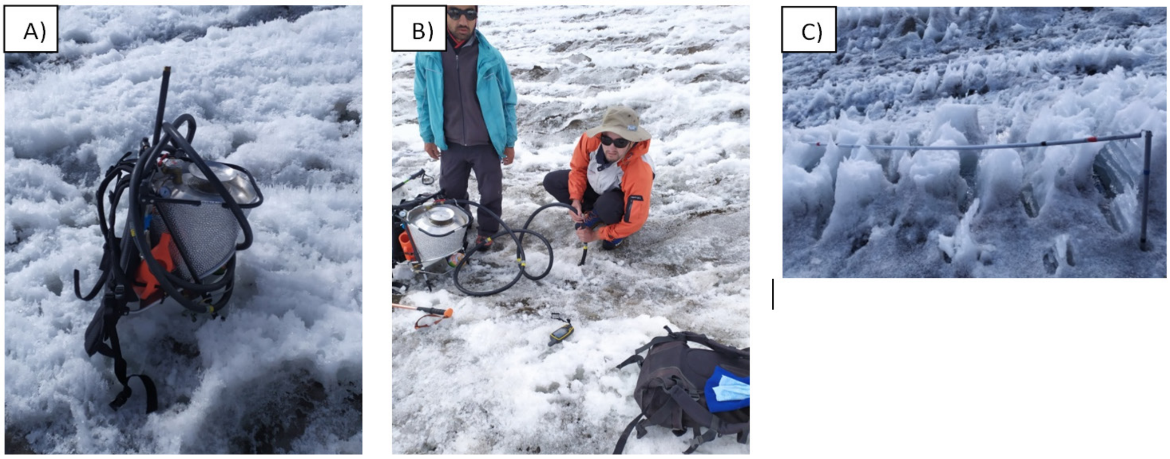

Figure 6. Field works in the ablation zone: A) Steam drill; B) Installation of depth gauges; C) 2018 depth gauge.

3.2. Works in the accumulation zone

The measurements in the accumulation zone allowed obtaining data on the density and depth of the annual snow accumulation (see Fig. 7.).

The potential target area to conduct field research was established based on remote sensing data and field works. After selecting the site, the team dug a pit reaching the last year's snow (last year's snow is denser and gradually turning into firn). After that the snow depth and density were determined (snow density was measured using the VS-43 Snow Gauge (see Fig. 7A.); using a cylinder, snow is harvested along the pit, and then its weight is measured (see Fig. 7B.). The exercise allowed calculating the snow volume and weight to determine its water content (Ostrem and Brugman, 1991; Jackson, 2014).

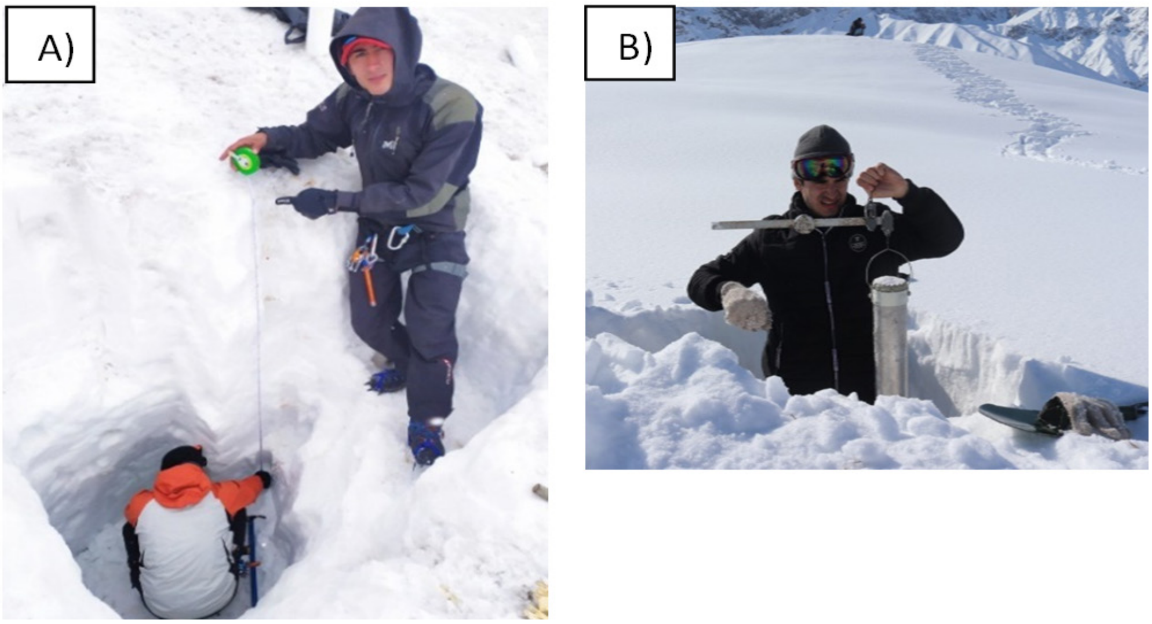

Figure 7. Basic accumulation zone field work concepts:
A) Survey pit in the accumulation zone; B) Snow gauge (stake) operation.

3.3. Application of edge-based (isoline) method for calculating glacier mass balance

To calculate the mass balance of the target glacier, the mean mass balance of each its field and the area of these fields were calculated (see Fig. 8B. and 8C.); then the balance value was multiplied by the field area (see Fig. 8D. and 8E.); then the sum of the obtained values was divided by the total glacier area.

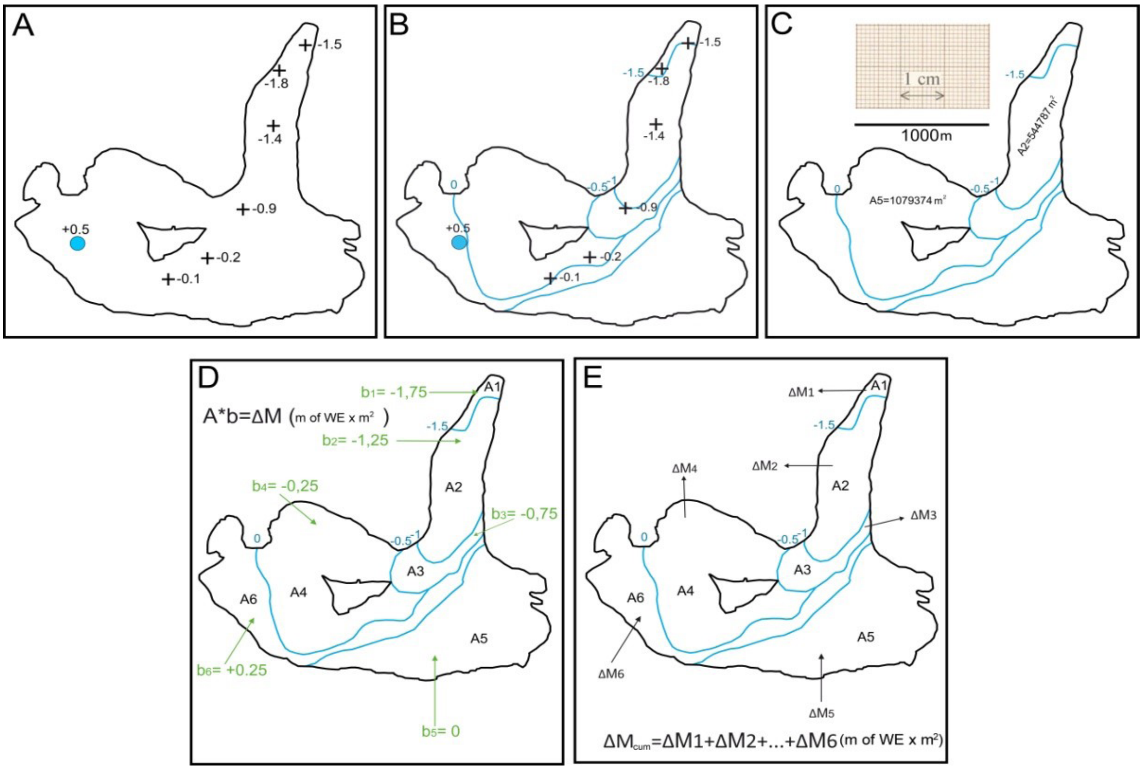

Figure 8. Edge-based method – schematic summation:
A) Point measurement mapping; B) Lines between points; C) Calculation of field area;
D) Determination of mean mass balance for each field; E) Calculation of mass balance for each field.

4. Results

Edge-based (isoline) calculation of glacier mass balance

Based on the data obtained, the detailed glacier map was built with equal mass balance lines. The first line started above the 4,700 m isoline and descended below it due to the uneven glacier nourishment along its right- and left-hand edges. The equal glacier mass balance line went between points equaling 1.5 mwe separating zones A1 and A2 (see Fig. 8.); zone A1 (area of 0.06 km^2) was assigned the value of -1.75 mwe; zone A2 (area of 0.53 km^2) was assigned the value of -1.25 mwe (0.5 mwe difference). Zone A2 is the largest inside this glacier due to its location on a gently sloping terrain and absence of significant vertical difference.

The mean mass balance of zone b1= -1.75 mwe (area equal to this of A1=0.06 km2; based on the formula A*b = ΔM, the zone's mass balance was calculated (ΔM1 = -0.105 mwe). The same calculations were executed for other zones, as indicated below:

A = area with equal mass balance (zones between isolines), km2
b = assigned mass balance value, mwe
A*b = ΔM

ΔMcum = ΔM1+ ΔM2+ … + ΔM6

ΔMcum / Acum = B mwe

Zone area (km^2)	Zone mass balance
A1 = 0.06	ΔM1 = A1*b 1 = 0.06*(-1.75) = -0.105
A2 = 0.53	ΔM2 = 0.53*(-1.25) = -0.6625
A3 = 0.1	ΔM3 = 0.17*(-0.75) = -0.1275
A4 = 1.15	ΔM4 = 1.15*(-0.25) = -0.2875
A5 = 1.21	ΔM5 = 1.21*0 = 0
A6= 0.11	ΔM6 = 0.11*0.25 = 0.0275
A7 = 0.42	ΔM7 = 0.42*0.5 = 0.21
	ΔM1+ΔM2+ΔM3+ΔM4+ΔM5+ΔM6+ΔM7 = -0.945
Mass balance=ΔMcum/Acum=(-0.945)/3.66=-0.26 m WE	

The map (see Fig. 9.) color-indicates the mean annual mass balance in each zone of the glacier. The accumulation zone where the survey pit was located was assigned the value of 0.49 mwe. Based on that, the value of 0.50 mwe was assigned to the upper accumulation zone (see Fig. 9., blue-color area), since the mass balance calculation was done using the 0.5 mwe difference between lines with the same mass balance. To draw the zero line, the probe was used to determine the snow cover depth directly on the glacier and the SENTINEL satellite image that made it possible to determine the snow line. The southeastern section of the glacier had a steep slope (see Fig. 9, white-color area; Fig. 8D. and 8E., zone A5), where snow accumulation is unlikely. For this reason, it was assigned the value of “zero”. At the slope foot, there was a snow avalanche accumulation nourishing the glacier. While interpreting the data, that zone was assigned the value of 0.25 mwe.

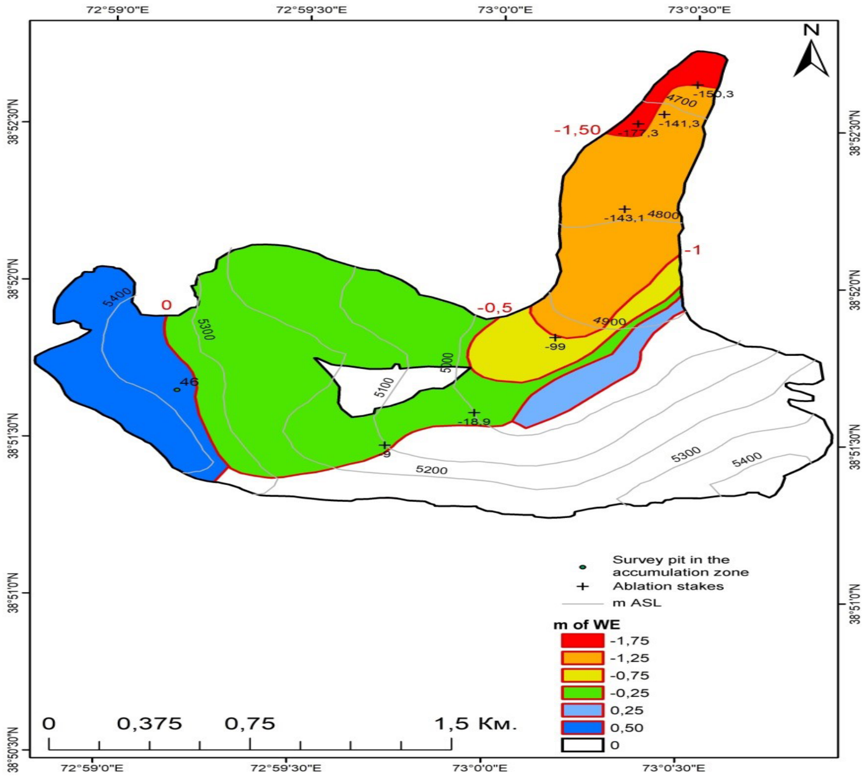

Figure 9. Edge-based calculation of glacier mass balance.

5. Discussion

According to the World Glacier Monitoring Service, during the period from 1960s–1970s to mid-1980s the glacier mass balance has somewhat stabilized in multiple regions across the planet, i.e. in Canada, Alaska, the Alps, the Tien Shan Region, etc. (Global Glacier Change Bulletin, v. 2, 2017). Yet, it deserves noting that in different regions dynamic glacier fluctuations occur differently due to unique climatic features, terrain, glacier locations, as well as other properties of glaciers themselves.

The Eastern Pamir glaciers, including these in the Lake Karakul Basin, are located at the altitude exceeding 4,500 m ASL, and the climatic conditions there belong to the severe cold zone. This may be the reason for the glaciers in the study area being more stable, which was also confirmed by the data obtained from Glacier No.139. However, this factor does not manifest the main indicator of the glacier stability, since other parameters can also influence glacier dynamics. The exposition of Glacier No.139 – located in the circus of the Zulumart Ridge spurs – is northern, reducing direct sunlight, as well as preventing strong winds and removal of snow cover from the glacier (see Fig. 10.). The glacier's southeastern side had a steep slope, and thus during calculations this zone was assigned the "zero" value due to the fact that the zone was overshadowed, i.e. there was no constant sunlight in the zone. The precipitation falling on that slope in the form of avalanches descends to the slope foot and accumulates there, thus according to the empirical pattern, the zone was assigned the value of 0.25 mwe. The snow on the slope was not deep and stayed there permanently.

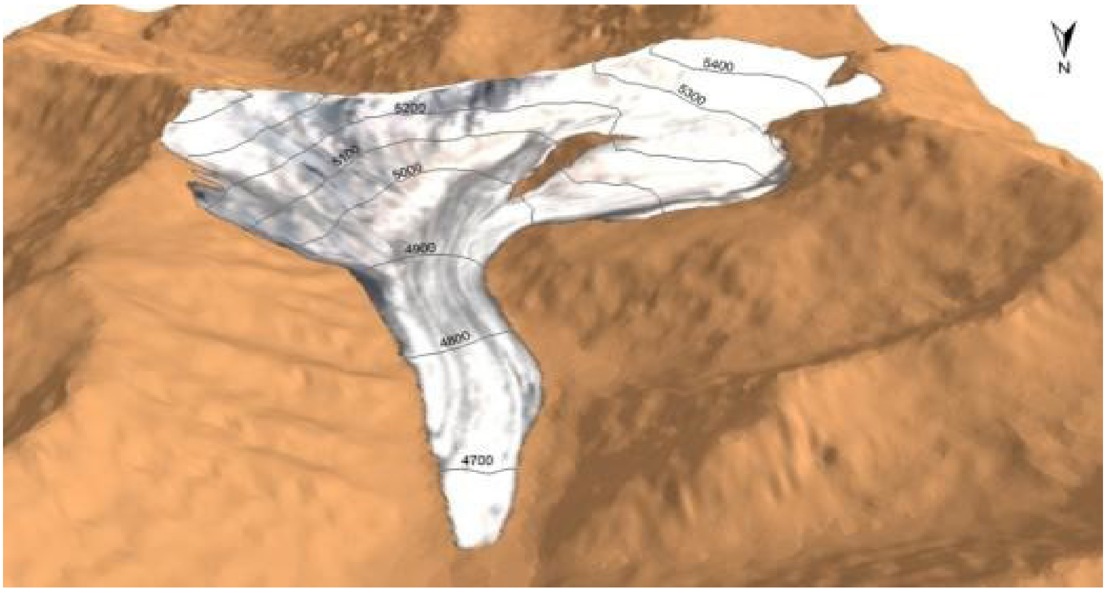

Figure 10. 3D model of Glacier #139 (Sentinel 2, 2018 image, ALOSPALSAR radar image).

6. Conclusion

The study allowed obtaining glacier mass balance data based on direct glaciological measurements, for the first time in the southeastern part of Central Asia.

The article aimed to present the methodology for calculating glacier mass balance using the direct glaciological method for replication at other glaciers, as well as to present the initial mass balance data for a glacier in the Eastern Pamir Mountains, since such works had not been carried out in the area.

The research aimed to obtain the mass balance (surface mass balance, SMB) data and determine the dynamics of Glacier No.139 in the Lake Karakul Basin. The findings will make it possible to detect the degree of climate change impact on the glaciation in the target area, as well as assess its potential changes in the future.

The field works carried out were sufficient to achieve the desired outcomes, including executing the basic measurements that allowed calculating the glacier's mass balance. Laboratory works and establishing isolines for mass balance calculations took account of the unique glacier's features and its surface topography.

The mass balance (surface mass balance, SMB) calculations and the assessment of the dynamics of Glacier No.139 in the Lake Karakul Basin allowed determining the glacier's condition in 2018-2019, i.e. -0.26 mwe. It stands to mention that only continuous observations of the target glacier can ensure the realistic assessment of its dynamics.

The study findings are of significant scientific value, including in terms of glaciology and climatology, and will contribute to enhancing the accuracy of local glacier modeling.

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