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# Recent Mass Balance Anomalies on the Djankuat Glacier, Northern Caucasus

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**Abstract:** A 54-year-long series of continuous instrumental measurements of mass balance and its main components has already been accumulated at the Djankuat Glacier, which is representative of the Caucasus and the most studied glacier in Russia. The anomalies of these indicators in 2017/2018–2020/2021 were evaluated against an analysis of meteorological reasons that predetermined them. Each of the four balance years under consideration represents a particular anomaly of varying severity. As for conditions of mass income, three years saw accumulation higher than average, and in one year (2018/2019) it approached the norm. As for summer ablation conditions, similarly, in one season (2019) the melting differed from the average only slightly, but in the other three it was much higher. Consequently, in one year (2020/2021) the state of the glacier was close to normal, in another (2017/2018) the budget situation was much more favorable for Djankuat, and in the other two the final losses significantly exceeded the average annual mass loss rate. At the same time, in 2019/2020, an absolute record of ablation since the beginning of monitoring in 1967/1968 was recorded (4360 mm w.e.). Nevertheless, although negative mass balance values continue to be recorded annually, signs of an inevitable slowdown in the rate of glacier degradation in the Caucasus have appeared in the last 4-year-long period: the continued growth of winter snow accumulation overlaps the ongoing intensification of summer melting. The growth of debris cover in terms of area and thickness also affects this mass loss slowdown to some extent. This inhibits ablation, exerting a heat-insulating effect. Because of this, the congruence of mass balance parameters vs. altitude curves is distorted. Also, a tendency toward increasing annual glacier mass turnover was revealed for the last half-century. This fact gradually increases the energy of glaciation and indirectly indicates a weakening of continentality in the climate of the Caucasian highlands.

**Keywords:** glacier; mass balance; time series; air temperature; precipitation



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## 1. Introduction

One of the most reliable indicators of the exceptional dynamism of modern climatic processes is the state of mountain glaciation of the planet. In turn, the best indicator characterizing this state is mass balance, $b_n$, i.e., the difference between the mass of solid precipitation deposited on the glacier and the loss of matter. Most often, an elementary time span for which this indicator is calculated is a balance year, consisting of annually alternating periods of accumulation and ablation. The mass balance of an alpine glacier is an integral feature that comprehensively reflects its changes under changing environmental conditions. In terms of its informative value, it significantly exceeds any morphometric parameters, also varying in time, such as terminus fluctuations, glacier area, average altitude of its surface, etc. In contrast, mass balance is a much more significant parameter, since it reflects the glacier response to the specific climatic conditions of a given year directly and immediately, while all others react to this specificity with a certain delay. Such response time is predetermined by plenty of dependencies too complicated for parametrization describing relationships between the glacier geometry and indicators of its internal mass turnover due to ice flow caused by gravitational forces.

Glacier mass balance is of particular practical importance primarily because it provides the key to solving one of the most pressing problems of mankind — availability of fresh water as the most valuable natural resource. It is well known that about 95% of this planetary treasure is contained on Earth as glacier ice, so the evolution of glaciation can directly affect the most vital aspects of society. An indicator such as the amount of meltwater that annually flows from glaciated areas to the foothills during the warm season, where it is used for agricultural and other human needs, is crucial from a practical standpoint. The share of glacial feeding of all rivers of the Earth does not exceed 1% [1], but for rivers whose sources are located in the alpine belt, accounting for glacial feeding is necessary for the correct reproduction of the hydrological regime. Thus, 60% of the runoff of large rivers in Kyrgyzstan consists of snow- and glacier-bound meltwater [2]; the glacial component of the total river runoff in Tajikistan is 10–15%, and in abnormally dry and warm years, it can become as high as 70% [3]; in the Caucasus, this value averages about 10%.

The long-term series of glacial runoff volumes at the degradation stage of glaciation is affected by two opposite trends. On the one hand, the warming of the summer seasons leads to an increase in the meltwater layer; this trend is primarily characteristic of the initial phase of deglaciation. On the other hand, the resulting reduction in the runoff-forming area of the glacier generates an inverse tendency toward a fall in the meltwater volume. Over time, when the glaciated areas will steadily tend to zero before the onset of the next interglacial, the second trend will undoubtedly prevail, and the discharge of glacial rivers will inevitably decrease. In the intermediate stages, the dominance of both trends is possible. Because of this, the forecast of further fluctuations in glacial runoff becomes a task that is in great demand, since plans for the agricultural development in the region and any other prospects for rational water use depend on its solution.

The reduction rate of the total area of mountain glaciers on the planet is currently estimated at 1%/year [4]. Thereby, at the beginning of the XXII century, the population in many regions, including those on the territory of Russia, may face an acute shortage of fresh water and, consequently, economic problems. In addition, intensive glacier recession in the XXI century is expected to lead to a noticeable level rise of the world ocean; by 2100, for example [5], the sea level may rise by 0.08 m due to the melting of alpine glaciers and ice sheets, according to the RCP2.6 scenario, and in the critical case (RCP8.5 scenario) by up to 0.16 m. Finally, the rapid areal change in mountain glaciation in the XX–XXI centuries provokes an increase in natural risks in alpine zones and reduces the recreational attractiveness of tourist areas—primarily, ski resorts. Therefore, the need for physically justified mass balance estimates for alpine glaciers, as well as for assessing their sensitivity to meteorological and climatic anomalies, is very relevant.

Nevertheless, today, only 5% of the planet's glaciers are under direct monitoring and research. Nowadays, the mass balance is calculated annually for no more than 150 glaciers scattered around the world [6]; however, only a few of them have continuous and statistically representative series of direct instrumental observations necessary to reasonably identify modern evolutionary trends on their basis. The Djankuat Glacier in the Caucasus is among them.

In many ways, this glacier is considered representative of the Caucasus. Its long time series of mass balance previously made it possible to reveal dominant trends in its long-term evolution. This has led to the conclusion that general glacier degradation has accelerated in the last 20 years. Additionally, this database can be helpful in identifying peculiarities of present glaciation response to climatic changes on different time scales. In particular, one can often find published opinions that global warming inevitably increases the frequency of natural disasters and other rare and abnormal phenomena. If so, mountain glaciers should certainly respond by increasing the variation of their budget parameters. Observations on the Djankuat Glacier seem to corroborate this hypothesis. Changes in regional climatic parameters of the last decade have primarily caused anomalies in its balance features. The continuous growth of the glacier mass turnover, revealed clearly during the monitoring period, has accelerated significantly in recent years. It was just the time slot that spanned 4 balance years from 2018/2019 to 2021/22, which was particularly characterized by various budget anomalies of considerable magnitude, up to extreme ones. An important role was played by heat balance anomalies associated with the peculiarities of regional circulation pattern and fluctuations in westerlies during the mentioned years. Thus, the main objective of the presented study was to assess the degree of anomaly in mass-balance parameters of the benchmark glacier, registered over the past four-year period, and to investigate the causes that determined these anomalies.

## 2. Data and Methods

### *2.1. Study Area and Research Object*

An extensive mountain system of the Greater Caucasus (Figure 1) stretches for more than 1300 km between the Caspian Sea and the Black Sea, its crest forming the southern border of Russia in its SW section. The modern orographic appearance of the Caucasus was formed in the Cenozoic, though formation of its main tectonic structures had been initiated yet since the Jurassic time when the territory began to undergo intensive uplift, accompanied by magmatic intrusions. An alpine relief was created in the late Neogene, and the origination of the main strato-volcanoes of the Caucasus, Mt. Elbrus and Mt. Kazbek, dates back to 2 million years ago.

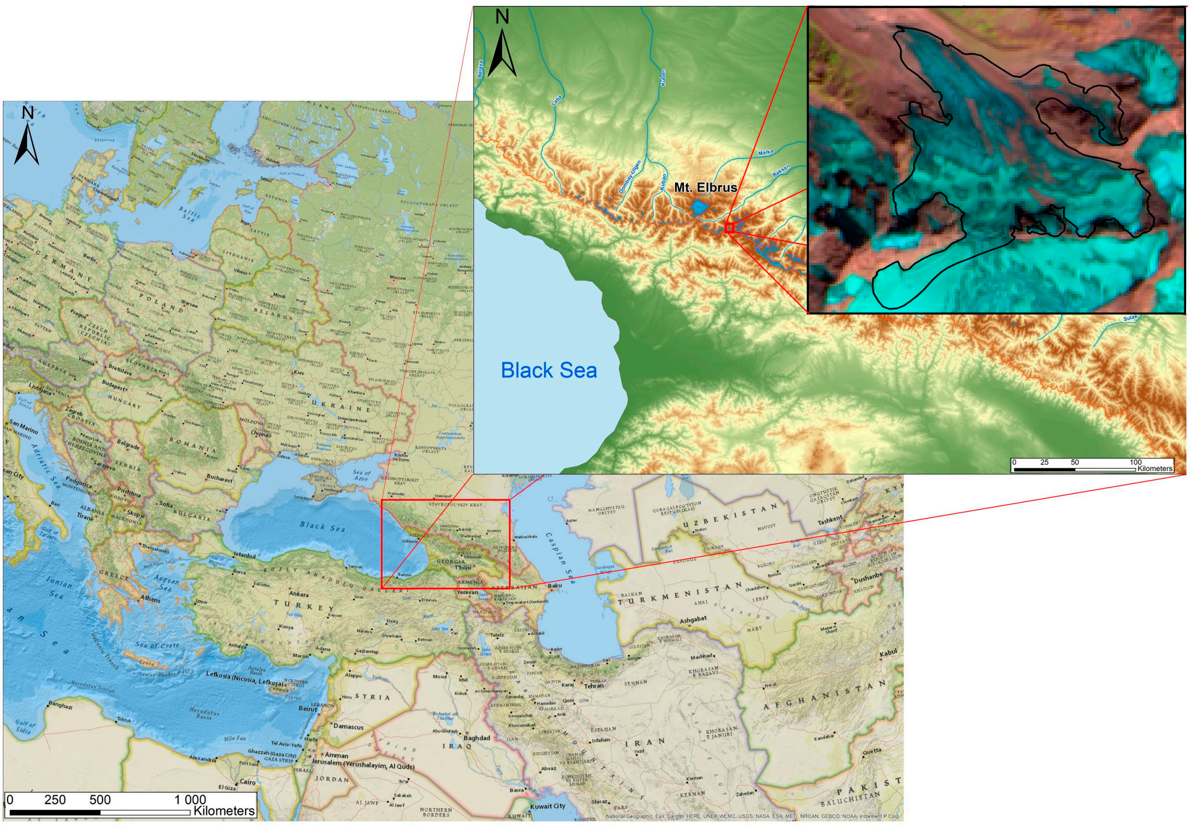
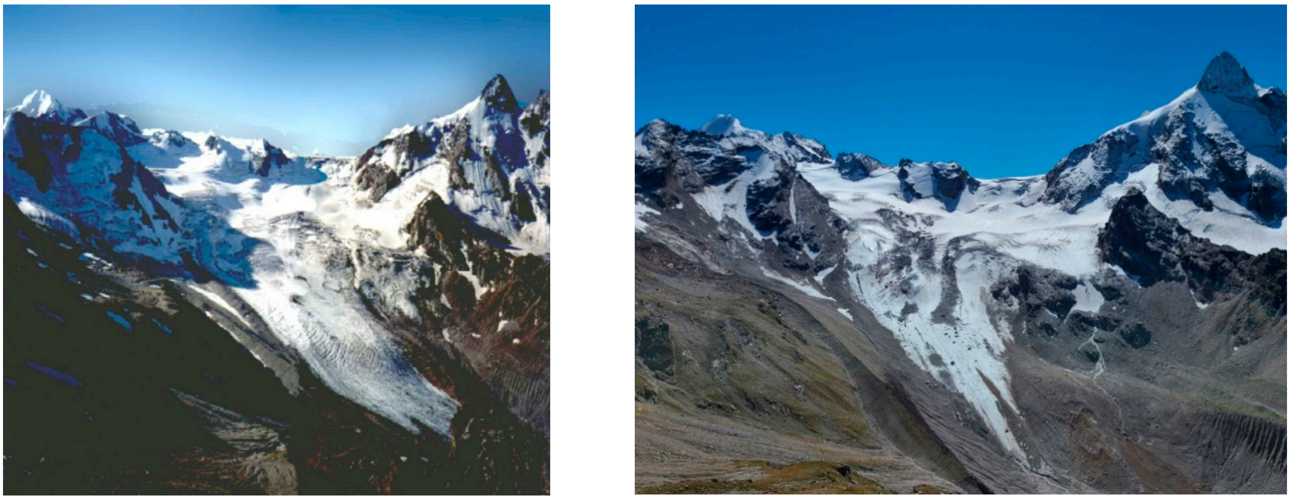



**Figure 1.** A study area.

Today the dormant Elbrus Volcano is the highest peak of the Caucasus, reaching an altitude of 5642 m a.s.l. The prevailing westerly flow delivers moisture from the Atlantic Ocean with baric depressions, intensifying over the Mediterranean and the Black Seas. Mean annual precipitation sum decreases eastwards from >2000 mm in the western section to <200 mm in the eastern [7]. Relief and climate promote extensive alpine glaciation. The Greater Caucasus is represented mainly through valley-type glaciers, though extinct volcanic cones are covered with star-shaped glacial systems. At the beginning of the 21st century, the Randolph Glacier Inventory v6.0 [8] included 1638 glaciers for the Caucasus, their total area amounting to 1276.9 km$^2$, whereas the latest estimates [9] come to 2046 glaciers and 1067 km$^2$; the total area decreased thereby by 28% since the 1980s. The degradation pattern is dominant here after the climax of the Little Ice Age in the mid-19th century. In the USSR, i.e., prior to 1990, several glaciers were thoroughly monitored here. However, currently, only two glaciers, Djankuat and Garabashi [10], both situated in the central section of the northern macro-slope, remain investigated.

The Djankuat Glacier (Figure 2) is located approximately 25 km east of its highest point, Mt. Elbrus. Djankuat is a valley glacier, geomorphologically typical for the Central Caucasus, which justifiably plays the role of representative for the Caucasian glaciation, according to its evolutionary features. Its regular glaciohydrometeorological monitoring was started by Moscow State University in the 1967/1968 balance year under the program of the International Hydrological Decade (IHD) [11], such that it has continued uninterruptedly for more than half a century until the present. Today, Djankuat is the most studied glacier in Russia. In addition, by choice of the main coordination center for mountain glaciology—the World Glacier Monitoring Service (WGMS)—it has been recognized as one of the 10–15 reference glaciers of the planet for judging the current evolutionary trends of the Earth's water and ice resources [12].



(**a**) (**b**)

**Figure 2.** The Djankuat Glacier: (**a**) in 1995; (**b**) in 2022.

The Djankuat Glacier lies within the altitudinal span between 2750 and 3670 m a.s.l. (status 2020). It is a classic temperate sub-isothermal glacier: by the end of the summer season, the temperature is leveled along its entire thickness and becomes as close as possible to 0 °C. According to the results of the latest radar survey, its thickness varies greatly, reflecting the rather complicated geometry of the bedrock (a cwm staircase). On average, it is 31 m, but its values can increase several times in large areas. The thickest ice (105 m) was found in the upper part of the snout.

Over the past 55 years, the physical area of Djankuat has decreased from 3234 to 2507 km$^2$. At the same time, its front retreated by 545 m, which means an average annual retreat rate of 9.9 m/year. The cumulative glacier mass loss since 1968 amounts to ca. 16.5 m in the water equivalent. Nevertheless, this reduction over the past half century has been far from uniform. After a moderate mass loss in the first 20 years of observations, a ten-year episode of relatively favorable conditions for the glacier budget began. It lasted from 1987 to 1997, when the cumulative mass balance even acquired a positive value. Subsequently, however, the tendencies to degradation of mountain glaciation resumed like they have been prevailing almost all over the Earth since the middle of the 19th century.

They significantly accelerated after 2005. In the last 18-year period, the mass balance of Djankuat did not reveal a positive value in any year. Such a long period with only negative values is unprecedented at least since the 1870s [13].

### 2.2. Methodology of Mass-Balance Studies

More than half a century of mass-balance monitoring of the Djankuat Glacier has always proceeded from three basic methodological principles.

Firstly, absolute priority has always been given to direct instrumental measurements when conducting regime observations. Indirect and remote methods, of course, were also used (primarily when direct measurements were associated with objective difficulties and dangers); still, every time they were only auxiliary and clarifying, nothing more.

Secondly, during the entire observation period, we tried to treat the continuity of methodological schemes as delicately as possible to preserve the isotropy of a sequence of measured values in order to be statistically correct when analyzing time series. It is obvious that since 1968 the calculation scheme of mass-balance parameters has been incessantly improving (more precise techniques appeared, new devices and installations were invented and applied, etc.), but these innovations were introduced gradually and only after careful verification of consistency with previous methods.

Finally, thirdly, all mass balance indicators should be mapped. Since the mid-1970s, the direct glaciological method has been used at Djankuat as the most accurate from the point of view of quantifying mass balance and its components. Its essential mandatory methodological condition comes down to drawing continuum fields of balance parameters that cover 100% of the glacier area, followed by their digitization by nodes of a regular grid. Annually compiled fields of accumulation, ablation and mass balance, covering the entire glacier area, represent layers of the local GIS. Geo-information superimposition of the fields of the above-mentioned parameters of external mass turnover on the fields of parameters of internal mass transfer (ice flow velocity) provides an independent verification of glaciological observation data by geodetic methods. In this case, the cumulative field of total (external and internal) mass transfer over several years should coincide with the alteration in glacier geometry over the corresponding time lapse. Traditionally, calculating components of mass balance ($b_n$) was based on the methodological techniques widespread in the practice of glaciological monitoring worldwide [14]. A stratigraphic reporting system has been adopted at Djankuat.

The income component of the balance (accumulation, or winter balance $b_w$) is calculated after processing the results of snow depth surveys undertaken annually on the date of the maximum seasonal snow accumulation. This moment varies between mid-May and late June in different altitudinal belts of the glacier. Accumulated snow cover thickness is measured by metallic rods in $N$ = 250–450 measuring points scattered more or less evenly over the entire accessible area of the glacier, which varies from 70 to 90% of the total in different years; an example of a measurement network is shown in Figure 3. These values are converted into their water equivalent by multiplying them by the snow density averaged over the entire seasonal cover along the vertical in the snow pit. To do this, 2–4 reference pits were dug in Djankuat, each characterizing its own altitudinal span. The natural variability of accumulation predetermines the density of the measurement network to satisfy the ratio:

$$\Delta = \frac{\sigma_E}{\sqrt{N}},$$

where $\Delta$ is the absolute measurement error, and $\sigma_E$ is the standard deviation for the array of snow accumulation values in points. Imitating the pattern of measuring points by nodes of a regular grid thrown over the true physical (curved) surface of the glacier predetermines the difference in the grid cell size from one altitudinal zone to another. In the lower reaches of the glacier, where the surface is complicated by frequent and morphologically contrasting forms of moraine meso-relief, the dispersion of snow accumulation is large, and the grid cell size drops to its minimum values of 30–50 m. On the contrary, it increases to 120–150 m in the firn basin. When compiling the final $b_w$ field over 100% of the glacier area, drawing isolines on the inaccessible 10–20% is facilitated by applying principles of physical (factorial) extrapolation and the concept of temporal congruence (similarity) of accumulation fields formulated earlier [15].

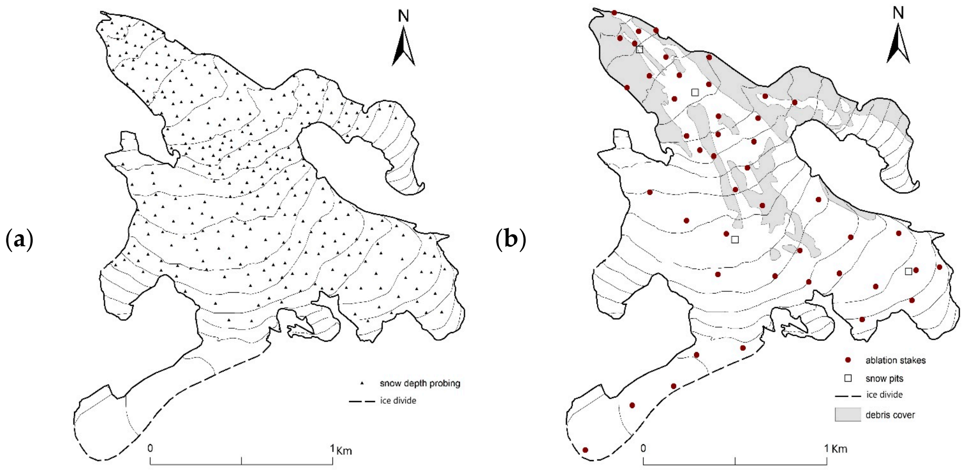



**Figure 3.** Observational network on the Djankuat Glacier: (**a**) snow accumulation measurement points (a case study of 2021); (**b**) traditional network of ablation stakes and snow pits. Isolines mean 50-m isohypses (2800–3650 m a.s.l.).

The wastage component of the mass balance (ablation, or summer balance $b_s$) is calculated using the standard method of stakes and pits. It consists of 2 parts: (a) ablation of snow (on the whole glacier area), and (b) ablation of firn and ice (below the firn line), including debris-covered ice. The observational network on Djankuat consists annually of 45–60 ablation stakes (20–25 on the snout and 25–35 in the middle course and in the accumulation area). This is entirely consistent with the highest class of glaciological observations, which, according to the authoritative opinion of V. Schytt [16] and H. Hoinkes [17], is satisfied with a density of 10–20 km$^{-2}$; even more liberal is the point of view [18] that even 10 stakes are enough for an adequate ablation assessment on any glacier, regardless of its size. Since spring, clusters of flexibly connected stakes are drilled with a steam-generating Heucke Ice Drill to a depth of about 6–8 m, which in the Caucasus is usually enough to characterize the total melting for the entire warm season in any altitudinal zone. The principle of physical extrapolation of discrete stake data to the whole glacier area for drawing the $b_s$ field is similar to that described for accumulation, but before that a number of amendments are introduced into the calculated values.

For example, on particularly crevassed plots of the glacier, a local change in ablation is taken into account due to thawing of the crevasse walls. This effect was quantified in Djankuat through the results of a unique experiment. It showed that the amendment in each case may have a different sign, depending on the width and orientation of the crevasse. Therefore, the entire glacier was divided into so-called crevasse areas, differing in the contribution of disjunctive glacial dislocations to the wastage component of the mass balance. The area-weighted average result turned out to be weakly positive: in general, thawing of crevasse walls increases all-glacier ablation by about 2%.

Another correction, which has been playing a progressively increasing role, accounts for the influence on ablation, exerted by debris cover. It has expanded and grown rapidly in area and thickness in recent years [19]: thus, in 1983–2010 its volume increased by 141% (from 70.3 to 169.5 thousand m$^3$). A mathematical model of this process with thermo-physical and lithological constants, intrinsic for Djankuat [20], showed that sub-debris ice melting under a layer of stones up to 5–7 cm thick exceeds the melting of pure ice, whereas a thicker lithogenic envelope plays, on the contrary, a screening and thermal insulation role, inhibiting ablation. Four repeated surveys of debris-cover thickness, undertaken at

Djankuat over the past 39 years, allowed for differentiating the value of the corresponding amendment for various sections of the glacier surface.

Finally, part of the meltwater, retained inside the glacier as a result of infiltration deeper than the layer of the current balance year, does not leave the glacier due to regelation and, therefore, cannot be classified as a loss of matter. This mass, not very aptly called internal feeding in glaciology, represents an ablation decrement [21] and is assumed to be relatively unchanged in time for each specific glacier [11]. At the present stage, this value, by which the surface ablation should be reduced annually, is assumed to be 140 mm w.e. at the Djankuat Glacier.

In addition to the fact that mass balance and its components are annually calculated for the whole glacier, the distribution of these parameters within its limits is also studied. Most often, systematization by altitudinal 100 m zones is accepted in glaciology, but presentation of these data by so-called alti-morphological zones (AMZs) is also practiced at the Djankuat. Their boundaries do not always run along isohypses—the main criterion for delineating AMZ is the unity of morphometric features, such as steepness and glaciotectonic peculiarities, primarily. Djankuat Glacier is divided into 13 AMZs (Figure 4), their numbering increasing with height. The lower 4 zones belong to the snout, zones V and VI form a belt of inter-annual migration of the equilibrium line, zones VII–XI represent a firn basin on the northern macro-slope of the Caucasus, zone XII frames it along a steep firn-ice revetment, and zone XIII is located on the southern macro-slope, on the territory of Georgia, occupying a sector of the vast crestal Dzhantugan firn plateau, divergently flowing to the north and to the south, from where ice enters the Djankuat system. It is just zone XIII that in recent years, unfortunately, contributes to the share of the glacier area not covered by direct measurements (which is clearly depicted in Figure 3), due to problems with crossing the Russian-Georgian border under the current political tension between the two adjacent countries; everyone sincerely hopes that shortly the situation will normalize again and the problem will come to naught.

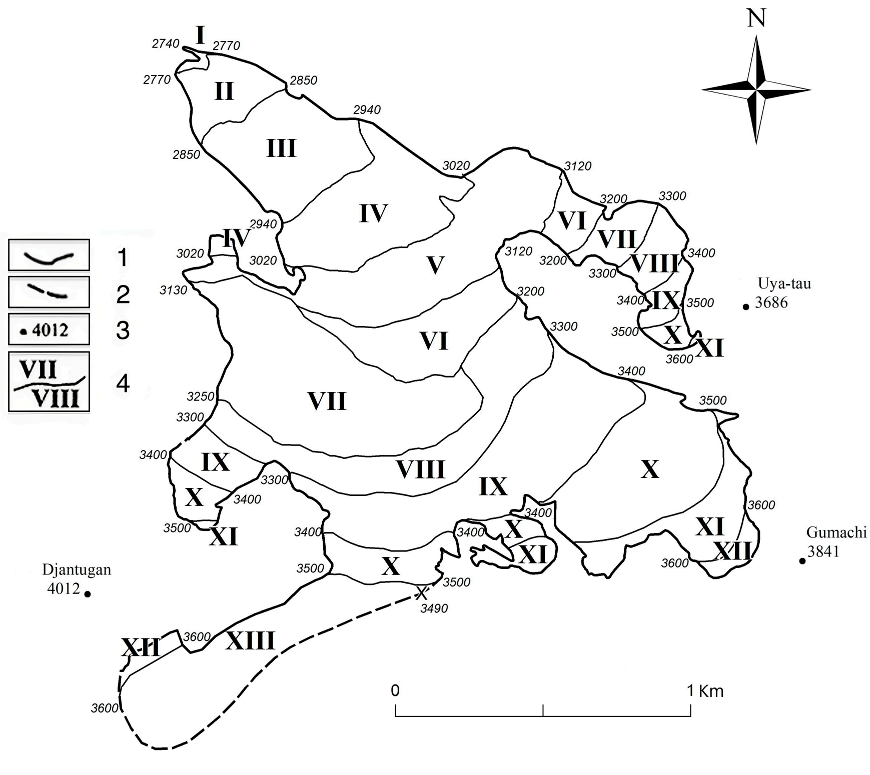



**Figure 4.** Alti-morphological zones of the Djankuat Glacier (topography of 2018): 1—glacier boundary; 2—ice divides; 3—main summits and their absolute height; 4—alti-morphological zones, their numbers and contours.

### 2.3. Meteorological Reasons That Predetermined the Mass-Balance Specifics of Recent Seasons

The current global warming is often stated (e.g., [22,23]) to be accompanied by an increase in the frequency and intensity of dangerous weather events and significant temperature anomalies in various regions of the planet. In temperate latitudes, the rise in the number of temperature and humidity anomalies is primarily associated with the warming in the Arctic. This results in a weakening of the western transport of air masses and an increase in the frequency of meridional blocking processes [24,25]. It is logical to expect that alpine glaciers, which are very sensitive to climatic trends, will inevitably respond to such disturbances with sharp changes in their external mass turnover parameters.

Tables 1–3 summarize the results of calculations of accumulation, ablation, and mass balance of the Djankuat Glacier for the past 4 balance years (2017/2018–2020/2021) and, on average, for all 54 years of direct instrumental observations. Along with the final values for the whole glacier (the middle rows of the tables), there are values systematized by alti-morphological (upper parts of the tables) and altitudinal 100 m (lower parts) zones. The tables clearly show how different and deviant from the average annual norms of mass balance and both its components the last 4 years have turned out, although they all have one thing in common: in none of them did the mass balance of Djankuat become positive.

**Table 1.** Accumulation, mm w.e., of the Djankuat Glacier and its alti-morphological and altitudinal zones in 2017/2018–2020/2021 and averaged over the whole monitoring period since 1967/1968.

| | | 2017/2018 | 2018/2019 | 2019/2020 | 2020/2021 | 54-Term Mean (1967/1968–2020/2021) |
|---|---|---|---|---|---|---|
| Alti-morphological zones | I | 1890 | 1240 | 1030 | 1620 | 1369 |
| | II | 2020 | 1480 | 1750 | 1770 | 1402 |
| | III | 2170 | 1490 | 1710 | 1680 | 1593 |
| | IV | 2610 | 1810 | 2010 | 2460 | 1868 |
| | V | 3120 | 2310 | 2340 | 2760 | 2308 |
| | VI | 3230 | 2310 | 2750 | 3130 | 2298 |
| | VII | 4260 | 2810 | 3370 | 3730 | 2818 |
| | VIII | 4330 | 2720 | 3590 | 4010 | 2781 |
| | IX | 4260 | 2840 | 3260 | 3650 | 2732 |
| | X | 4120 | 2590 | 3210 | 3420 | 2853 |
| | XI | 4080 | 2690 | 3330 | 3220 | 3075 |
| | XII | 3200 | 1650 | 2280 | 2540 | 1685 |
| | XIII | 5640 | 4050 | 3940 | 4200 | 3755 |
| **Glacier** | | **3760** | **2520** | **2990** | **3290** | **2508** |
| Altitudinal spans | 2700–2800 | 1950 | 1360 | 1600 | 1740 | 1392 |
| | 2800–2900 | 2100 | 1490 | 1720 | 1710 | 1502 |
| | 2900–3000 | 2410 | 1660 | 1910 | 2190 | 1767 |
| | 3000–3100 | 3030 | 2220 | 2320 | 2740 | 2191 |
| | 3100–3200 | 3570 | 2490 | 2940 | 3320 | 2451 |
| | 3200–3300 | 4300 | 2760 | 3500 | 3890 | 2789 |
| | 3300–3400 | 4260 | 2840 | 3260 | 3650 | 2732 |
| | 3400–3500 | 4120 | 2590 | 3280 | 3490 | 2856 |
| | 3500–3600 | 4950 | 3450 | 3660 | 3760 | 3353 |
| | >3600 | 3200 | 1650 | 2280 | 2540 | 1795 |

**Table 2.** Ablation, mm w.e., of the Djankuat Glacier and its alti-morphological and altitudinal zones in 2017/2018–2020/2021 and averaged over the whole monitoring period since 1967/1968.

| | | 2017/2018 | 2018/2019 | 2019/2020 | 2020/2021 | 54-Term Mean (1967/1968–2020/2021) |
|---|---|---|---|---|---|---|
| Alti-morphological zones | I | 4100 | 3760 | 7060 | 6090 | 4779 |
| | II | 5970 | 5040 | 7100 | 6020 | 5263 |
| | III | 6030 | 5130 | 6620 | 5330 | 4895 |
| | IV | 5010 | 4800 | 5800 | 4830 | 4411 |
| | V | 4120 | 3900 | 4700 | 3670 | 3310 |
| | VI | 3990 | 3360 | 4280 | 3330 | 2873 |
| | VII | 4020 | 3500 | 4770 | 3540 | 2632 |
| | VIII | 3680 | 2630 | 4290 | 3480 | 2352 |
| | IX | 3260 | 2570 | 3940 | 3240 | 2085 |
| | X | 2980 | 2250 | 3470 | 2590 | 1722 |
| | XI | 2190 | 1580 | 2710 | 2280 | 1335 |
| | XII | 2000 | 1210 | 2230 | 2040 | 1275 |
| | XIII | 2710 | 2050 | 3260 | 2490 | 1710 |
| **Glacier** | | **3800** | **3150** | **4360** | **3460** | **2711** |
| Altitudinal spans | 2700–2800 | 5010 | 4390 | 7090 | 6040 | 5004 |
| | 2800–2900 | 6000 | 5090 | 6790 | 5580 | 5018 |
| | 2900–3000 | 5480 | 4950 | 6080 | 5000 | 4567 |
| | 3000–3100 | 4270 | 4050 | 4880 | 3850 | 3501 |
| | 3100–3200 | 4020 | 3500 | 4530 | 3460 | 2862 |
| | 3200–3300 | 3820 | 2990 | 4490 | 3500 | 2445 |
| | 3300–3400 | 3260 | 2570 | 3940 | 3240 | 2085 |
| | 3400–3500 | 2980 | 2250 | 3450 | 2580 | 1721 |
| | 3500–3600 | 2480 | 1840 | 3010 | 2400 | 1456 |
| | >3600 | 2000 | 1210 | 2230 | 2040 | 1291 |

2017/2018. Accumulation this year was huge—1.5 times higher than the long-term average. This resulted from the mild and warm winter, when the seasonal positive air temperature anomaly in the cold half-year (November–March) reached +2 °C (Figure 5c). At the same time, an essential role in the glacier regime was played by advection of tropical air masses carrying sand from the Sahara. By the end of the accumulation season, the snow surface was painted yellowish and light brown. The dust on the glacier surface due to dry deposition and wet leaching reduced the surface albedo, contributing to an increase in ablation at the beginning of the summer season. The effect of increased dust aerosol content was observed over a vast area, and was called "the case of an extreme dust storm in the Mediterranean" [26].

According to the Main Weather and Environmental Centre of the USA [27], the 2018 ablation season was characterized by a stable positive temperature anomaly at the level of the 700 hPa isobaric surface (Figure 6c), averaging +1.5 °C. July turned out to be the warmest (anomaly +3.2 °C); in August, the temperature was close to normal (only 0.5 °C higher). The cause of temperature anomalies was the anticyclonic weather regime, most pronounced at the beginning of the season (May) and closer to its end (September). The most typical process was the formation of a blocking anticyclone over the European territory of Russia. This process disrupts western air transfer and causes positive temperature anomalies. In September, the Azores anticyclone was manifested, a spur stretching from the Mediterranean to the Caucasus and predetermined cloudy and very warm weather. In all zones (except the terminal one), 2017/2018 ablation significantly exceeded the long-term averages, and the resultant glacier ablation came in 3rd place in the entire 54-year series of direct instrumental observations. However, due to very high accumulation values, 2017/2018 was like no other in the last 16 years close to a positive mass balance value, and although its final value remained slightly negative (−40 mm w.e.), this year was definitely the most favorable for the glacier after 2004/2005.

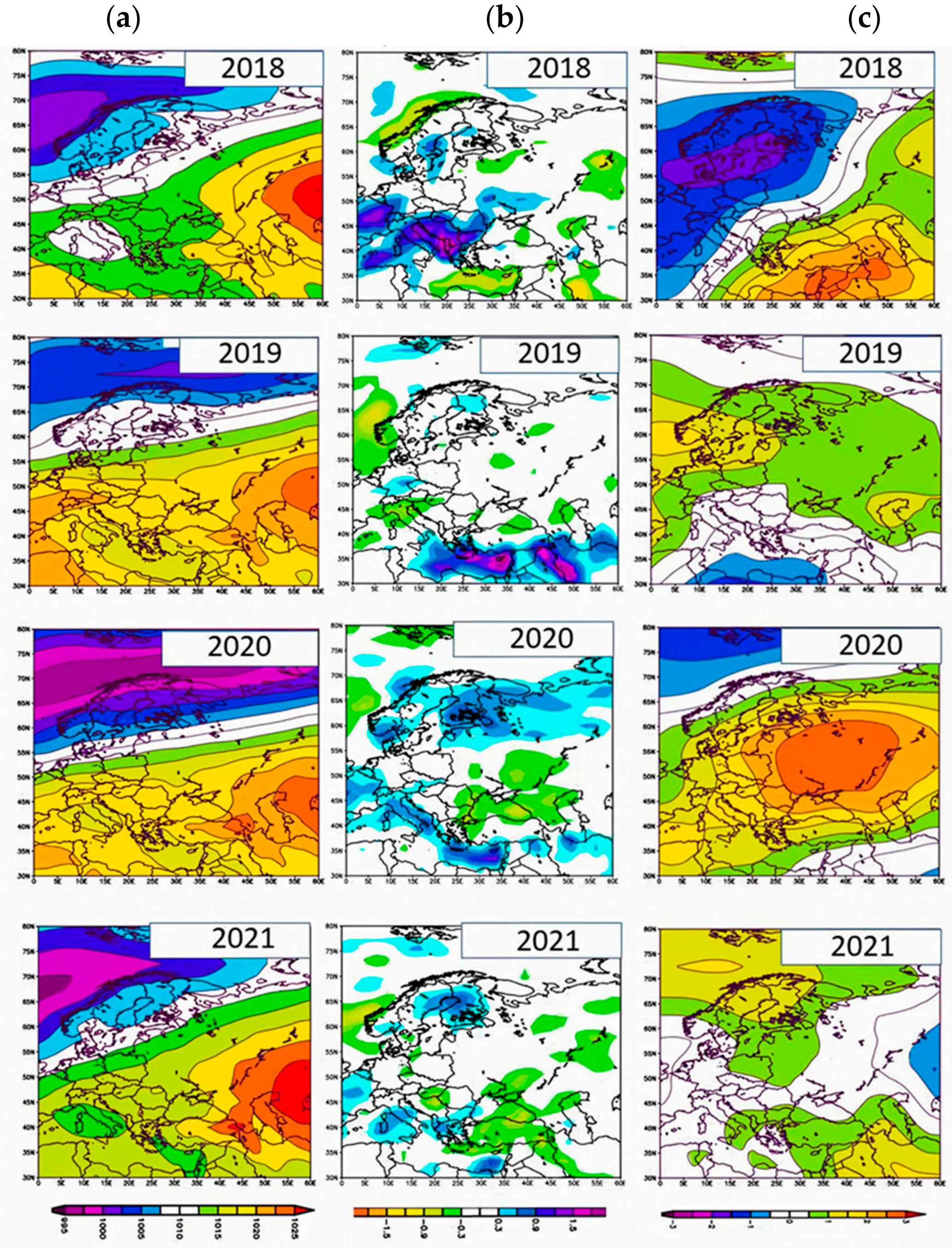



**Figure 5.** Atmospheric pressure at the sea level (**a**) as well as anomalies of precipitation (**b**) and air temperature (**c**) at the 700 hPa isobaric surface, averaged over the cold season (October–April), in 2017/2018–2020/2021 (mapped by the data of the Main Weather and Environmental Centre of the USA [27]).

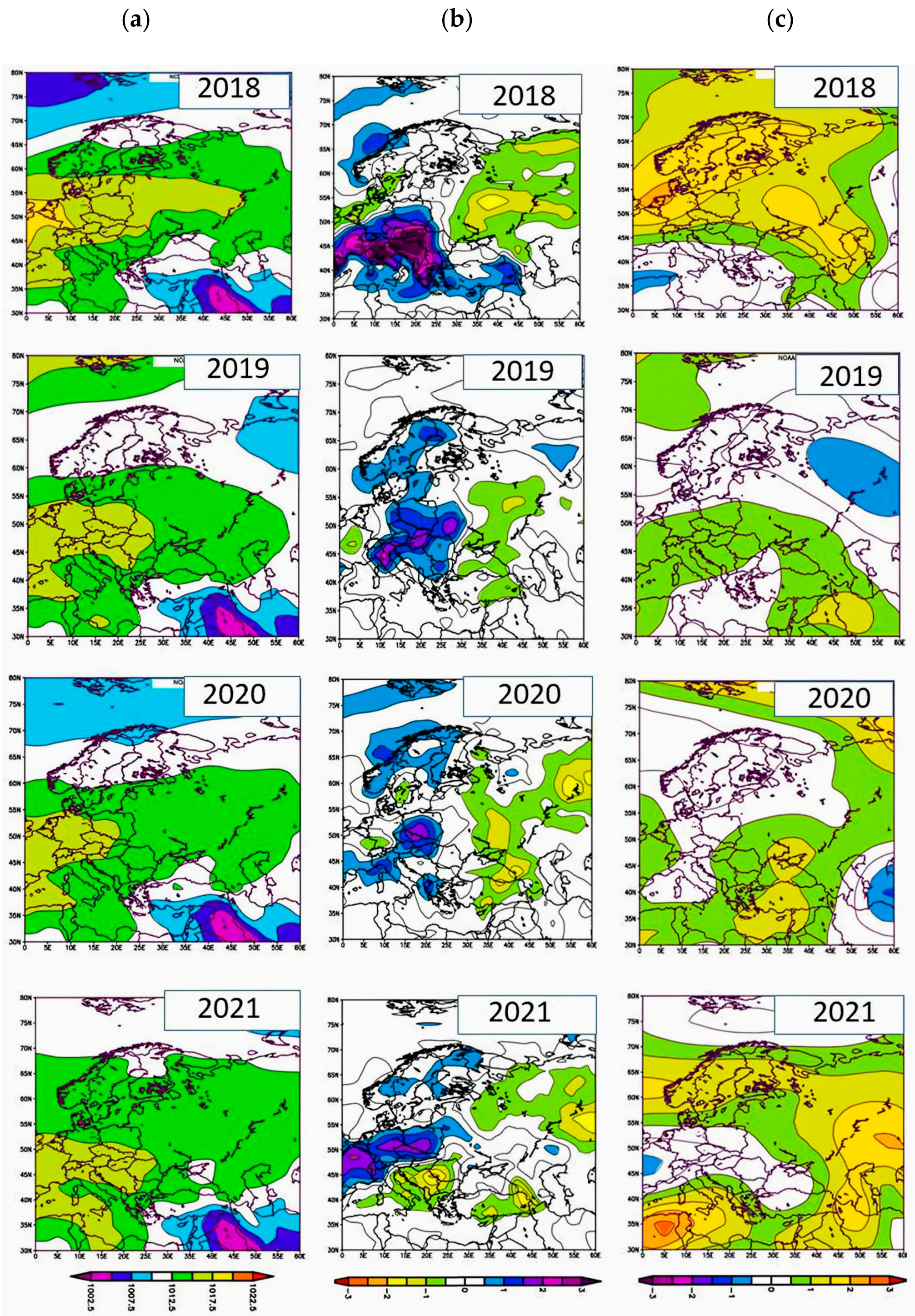



**Figure 6.** Atmospheric pressure at the sea level (**a**) as well as anomalies of precipitation (**b**) and air temperature (**c**) at the 700 hPa isobaric surface, averaged over the warm season (May–September), in 2017/2018–2020/2021 (mapped by the data of the Main Weather and Environmental Centre of the USA [27]).

2018/2019. According to the glacier budget conditions, this season was closer than the others over the past 4 years to the long-term average. It turned out to be the least snowy in the last 4 years, although even such an accumulation, albeit symbolically, exceeded its long-term mean by 2%.

**Table 3.** Mass balance, mm w.e., of the Djankuat Glacier and its alti-morphological and altitudinal zones in 2017/2018–2020/2021 and averaged over the whole monitoring period since 1967/1968.

| | | **2017/2018** | **2018/2019** | **2019/2020** | **2020/2021** | **54-Term Mean (1967/1968–2020/2021)** |
|---|---|---|---|---|---|---|
| Alti-morphological zones | I | –2210 | –2520 | –6030 | –4470 | –3410 |
| | II | –3950 | –3560 | –5350 | –4250 | –3870 |
| | III | –3860 | –3640 | –4910 | –3650 | –3302 |
| | IV | –2400 | –2990 | –3790 | –2370 | –2540 |
| | V | –1000 | –1590 | –2360 | –910 | –1015 |
| | VI | –760 | –1050 | –1530 | –200 | –575 |
| | VII | 240 | -690 | –1400 | 190 | 186 |
| | VIII | 650 | 90 | –700 | 530 | 421 |
| | IX | 1000 | 270 | –680 | 410 | 648 |
| | X | 1140 | 340 | –260 | 830 | 1131 |
| | XI | 1890 | 1110 | 620 | 940 | 1740 |
| | XII | 1200 | 440 | 50 | 500 | 410 |
| | XIII | 2930 | 2000 | 680 | 1710 | 2044 |
| **Glacier** | | **–40** | **–630** | **–1370** | **–170** | **–203** |
| Altitudinal spans | 2700–2800 | –3060 | –3030 | –5490 | –4300 | –3612 |
| | 2800–2900 | –3900 | –3600 | –5070 | –3870 | –3517 |
| | 2900–3000 | –3070 | –3290 | –4170 | –2810 | –2799 |
| | 3000–3100 | –1240 | –1830 | –2560 | –1110 | –1310 |
| | 3100–3200 | –450 | –1010 | –1590 | –140 | –411 |
| | 3200–3300 | 480 | –230 | –990 | 390 | 344 |
| | 3300–3400 | 1000 | 270 | –680 | 410 | 648 |
| | 3400–3500 | 1140 | 340 | –170 | 910 | 1135 |
| | 3500–3600 | 2470 | 1610 | 650 | 1360 | 1897 |
| | >3600 | 1200 | 440 | 50 | 500 | 504 |

Ablation also differed from the average for less than other years, but compared with the income component, the difference was more robust: mass loss was 16% higher than normal. The extremely hot weather in the first half of the melting season played a major role in this. In May-June, the regime of anticyclonic blocking of western transfer in the middle and upper troposphere prevailed over the European territory of Russia, including the Caucasus region. As a result, vast areas of positive temperature anomalies up to 1.5–2 °C were formed. Ablation started at least one month earlier than usual. By the end of May, it amounted to ca.1500 mm w.e. at the altitude of 3000 m a.s.l. on the upper part of the Djankuat snout—almost a third of the total mass loss at this altitude for the entire season (an unprecedented case for May ablation). The average monthly value of the heat balance for May was +190 W/m$^2$ (or 514.13 MJ in monthly equivalent), almost twice the average long-term value. According to the heat balance structure on the Djankuat Glacier, the main contribution to melting is traditionally made by the radiation balance, but, in addition to its anomaly in May 2018/2019, the turbulent heat flux was significantly increased too [28]—this was the reason for the extreme May melting. In early June, owing to the long ongoing melting, the average density of seasonal snow at an altitude of 3230 m rose to an all-time high value of 0.63 g/cm$^3$. By midsummer, the thermal regime entered its long-term norm, and the end of the ablation period turned out to be even colder than usual by 0.5 °C.

2019/2020. This season should definitely be attributed to the extreme unfavorability for Djankuat. This conclusion follows even though winter conditions of snow accumulation initially augured a favorable budget state of the glacier in this balance year: snow fell by 21% above the long-term norm. Like in 2017/2018, the reason for this can be seen in the high, about +2 °C, positive temperature anomaly in winter (Figure 5c), when relatively mild weather conditions in the glacial zone promoted sedimentation of abundant solid precipitation. This resulted from low pressure over the Mediterranean Sea, which indicated intensive cyclogenesis in the polar front zone. It is important to note that most of the solid precipitation fell in the springtime.

Summer conditions caused an unprecedentedly strong melting, which more than surpassed the positive effect of excessive accumulation. First, this was due to a pronounced positive temperature anomaly in May, which became even higher than its counterpart of the previous year. This anomaly of +2.5° was accompanied by a significant excess of the long-term average values of the radiation balance. During May, the glacier snout managed to lose 600–1000 mm w.e. Unlike in 2019, melting was no less intense in September as well, which was determined by the unusually northern and very stable position of the Azores anticyclone. At the same time, melting even in the uppermost hypsometric zones continued almost until the end of the month. Autumn snowfalls were not observed on the entire glacier until the very last pentad: at altitudes above 3500 m, the first stable snow cover was registered only on 26 September. The lower glacier belts continued melting until October 3. Such unique conditions led to the fact that in 2019/2020, an absolute record of ablation (4360 mm w.e.) was set since the very beginning of observations in 1967/1968. This was the only case when ablation exceeded the 4000 mm line. Additionally, only the fact that this year the accumulation was also very high did not allow 2019/2020 to become a record in terms of negative mass balance. This balance year stayed in second position, whereas 2006/2007 remained a negative extreme.

2020/2021. The meteorological situation in the final season of the period under review partly resembled 2017/2018. The winter, similarly, resulted in the accumulation of vast masses of snow on Djankuat, and the year, undeniably, became one of the snowiest since the beginning of regular monitoring, although the reasons for this most likely lie in another plane than three years ago. In contrast to the winter of 2017/2018, a certain precipitation deficit was even registered over the Caucasus, which reached an average of −0.5 mm/day; in the whole region, this led to a total amount of precipitation of 30% less than the long-term norm (Figure 5b). However, intense avalanches were observed in the highlands, which caused excessive feeding of the glacier with snow and formed an evident increased accumulation.

In summer, just like in 2017/2018, a positive temperature anomaly of approximately +1.5 ÷ +2° (Figure 6c) was observed almost the entire ablation season (except for September), and this manifested itself yet in spring. By the stage when the seasonal maximum of accumulation has been formed, the snow was already well warmed up and had very high density values, partially due to huge avalanches that consisted of wet heavy snow. Weather conditions warmer than usual in the first half of summer were associated with blocking processes. In September, the Caucasus turned out to be on the eastern periphery of the blocking anticyclone, so the winds of the north-easterly direction prevailed in the middle troposphere, which finally interrupted the prolonged heat anomaly. Because of this, melting at altitudes > 3100 m stopped after the establishment of the fresh snow cover already on September 1, so that the ablation season (and, hence, the entire balance year) of the whole glacier ended extremely early—on 23 September. However, the intense mass loss of the previous part of the summer could not help but affect the fact that the final ablation in 2020/2021 turned out to be significantly higher, almost a third, than the long-term average. As a result, like all 16 previous years, the mass balance turned out to be negative again, although very small in modulus. Therefore, despite the resultant mass loss, this balance year should be considered in general as relatively favorable for the glacier budget at the current evolutionary stage.

Thus, summarizing, the winter conditions of all four seasons under consideration were characterized by positive temperature anomalies (primarily in 2018 and 2020), although not as significant as in comparison with the ablation periods. Apparently, they were caused by highly intense cyclogenesis in the North Atlantic and over the northern regions of the European territory of Russia, and the trajectories of cyclones passed north of the average climatic storm tracks. The southern regions often found themselves either under the influence of the Azores anticyclone, which occupied an abnormally northern position in these years, or on the eastern periphery of the Asian anticyclone. The reason for such circulation features could be the positive phase of the North Atlantic Oscillation (NAO), which was just noted in these years [27].

The main similarity of summer (May–September) meteorological conditions was that positive temperature anomalies prevailed during the ablation periods (Figure 6c): of the total 20 analyzed warm months, 13 were warmer than the long-term mean values (anomalies $\triangle$T, compared to the 1981–2010 period, averaged +0.5 °C), and in 5 cases the monthly anomaly can be considered extreme ($\triangle T > 3$ °C). Only three cool summer months ($\triangle T < 0.5$ °C) were observed, and in no case did the negative average monthly anomaly exceed the $-1$ °C threshold. On average, the temperature of the ablation period for four years was 1.2 °C higher than its long-term mean. Analysis of atmospheric pressure fields and maps of absolute topography AT700 showed that the reason for the positive temperature anomaly and precipitation deficit was the high frequency of anticyclonic situations (Figure 6a). From May till July, inclusively, these were blocking processes, and in August–September it was owing to the abnormally northern and stable position of the Azores anticyclone. Not only (and not so much) did positive temperature anomalies contribute to the intense melting, but so did a slight decrease in the cloud cover degree in anticyclonic conditions, which caused an increase in the radiation balance. The positive trend of this process in the Caucasus was noted earlier [28].

The reason for negative mass balance anomalies in recent decades may be a statistically significant negative trend in the radiation balance, which in turn is associated with increased frequency of anticyclonic circulations over Northern Eurasia [29]. These pronounced changes in synoptic processes may respond to the so-called "expansion of the tropics", which consists of shifting the descending branch of the Hadley cell toward more northern latitudes; this may be one of the manifestations of modern warming [24]. Another reason may be a decrease in the aerosol optical thickness of the atmosphere, which leads to better transmission of solar radiation by the atmosphere [30]. Most likely, both effects play a significant role.

## 3. Results and Discussion

### *3.1. The Last 4 Years in the Long-Term Series of Mass Balance Observations*

The database on the Djankuat Glacier accumulated over 54 years of direct instrumental observations makes it possible to estimate the place of the 2017/2018–2020/2021 time span in this multi-year series according to all the most critical glaciological indicators. These conclusions partly follow from Tables 1–3, but they are more clearly demonstrated in the graphs of Figure 7.

The budgetary state of the glacier in the characterized period as a whole fits perfectly into the overall picture of the degradation of the mountain glaciation in the Caucasus over the recent decades. Nevertheless, the differences between the four balance years, as shown above, are rather significant. Regarding winter snow accumulation, three years were above average, and one was close to the norm; according to summer conditions, also, only in one season did the melting differ slightly from the average, but in the other three, melting was much more intensive; and as for mass balance, in one year the state of the glacier was close to normal, in the other the budget situation was much more favorable for Djankuat, and in the other two mass reduction seriously surpassed the average annual loss rate. However, 2018–2021 has not changed the long-term course of the evolution of Djankuat. The dominant trends have not undergone any new disturbances, but in some cases they have revealed some nuances of recent seasons.

Since 1967/1968, snow accumulation in the Caucasus has experienced a weak but persistent tendency to gradual growth, although the positive trend remained statistically insignificant. This trend has been repeatedly noticed in various former scientific publications [31,32] and has often been linked to an increase in the proportion of processes, typical for the zonal (western) form of atmospheric circulation [33–35]. The time series of accumulation $b_w$ at Djankuat looks like a response to these patterns (Figure 7a): it reveals an obvious positive linear trend with a 5.6 mm/year gradient.

Approximation of this series by a higher-order polynomial reveals two periods of apparent acceleration of this trend. The first tends to the late 1980s–early 1990s and the second coincides with the very last years in the second decade of the XXI century. At the same time, the second period is ahead of the 1980s–1990s stage in accelerating the increase in the average values of $b_w$.

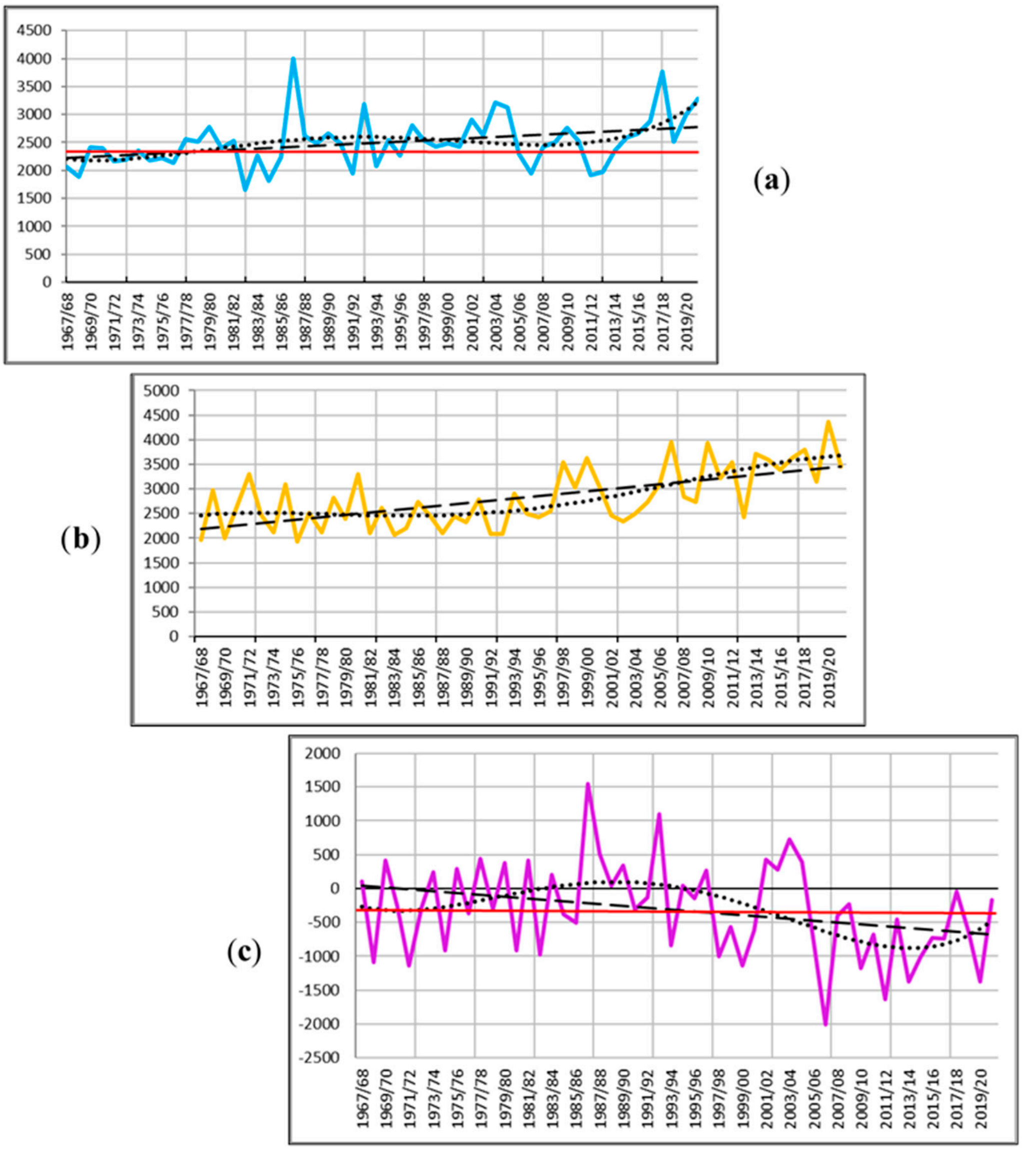



**Figure 7.** Shown are 54-year-long series of accumulation (**a**), ablation (**b**), and mass balance (**c**), mm w.e., of the Djankuat Glacier: annual values (solid lines), linear trends (dashed lines), and time series approximations by the 4th-order polynomial (dotted lines).

The absolute maximum of winter snow accumulation on the Djankuat Glacier over the past 54 years falls on 1986/87; it equals 4000 mm in the water layer. With variations of $b_w$ values over half a century in the range of 1650 $\div$ 4000 mm, the snow abundance in 1986/87 is evaluated by a statistical probability of about 1–1.5%. The second and third places in terms of snow accumulation for the entire monitoring period are occupied by the years of the last four–year period: 3760 mm w.e. accumulated on the glacier in 2017/2018 and 3290 mm in 2020/2021. One should note that accumulation at Djankuat exceeded the 3000-mm milestone only six times throughout all 54 years of observations. Considering that 2019/2020, with its $b_w$ value equal to 2990 mm, did not reach this mark purely symbolically, we can confidently interpret recent years as the stage of the sharpest increase in the snow amount over the past half-century.

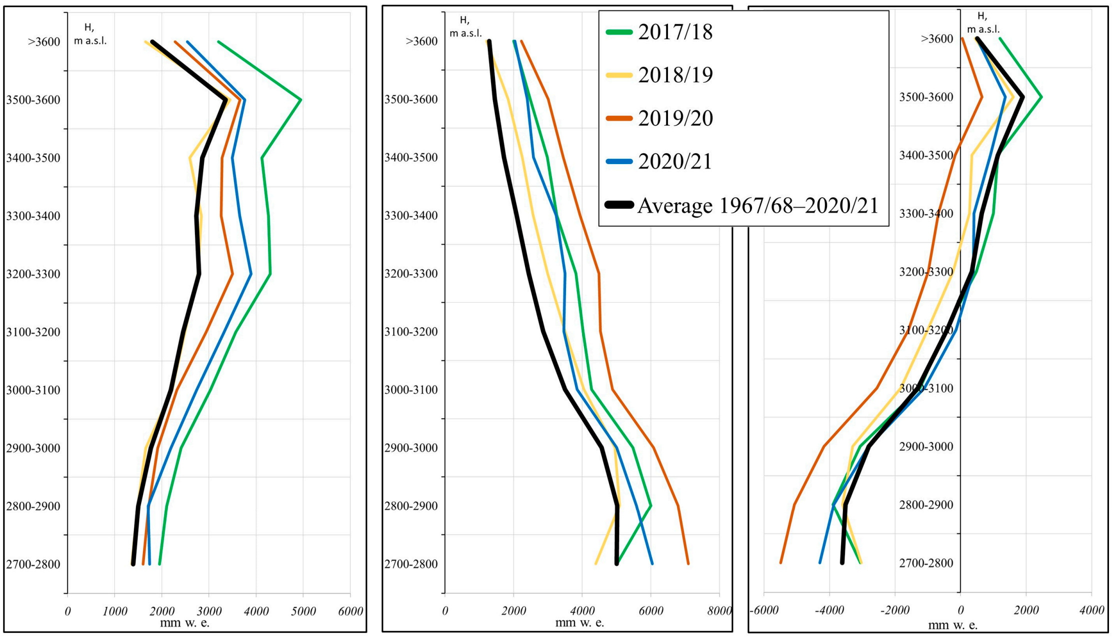
The ablation trend is routed in the opposite direction. Figure 7b shows a clear tendency to increase mass wastage at Djankuat. Until the 1990s, it was not statistically significant at all, but later there came a period with a pronounced negative budget effect for the glacier. The average long-term ablation value since the beginning of instrumental observations today is approximately 2800 mm, and ablation has never been less in the last four years. Of these, only one season, 2018/2019, with its value of 3150 mm w.e., slightly, by 12%, differs from the average. The rest represent pronounced positive (by modulus) anomalies: the glacier mass loss in these years exceeded the mean annual value by 650–1550 mm. Ablation in 2019/2020 (4360 mm w.e.) became an absolute record for more than 50 years of direct observations, surpassing the previous record of 2006/2007 by as much as 400 mm, i.e., by about 10%.

The trend towards accelerating the glacier mass loss would have been even more pronounced if in recent years there had not occurred an increasingly noticeable effect from both areal expansion and thickness growth, of debris cover. It slows down ablation due to the absorption of solar radiation and thermal insulation and, to some extent, compensates for the negative impact of climatic changes on the glacier state. Deglaciation leads to the exposure of the rock framing around firn basins from under the ice, which enhances denudation processes (landslides, rockfalls, desquamation) that supply lithogenic matter to the glacier surface. The thinning of the glacier and the gradual year-by-year rise of the equilibrium line into ever higher hypsometric belts leads to accelerated debris thawing off to the day surface. According to the results of repeated direct debris thickness surveys, the volume of the moraine cover has quadrupled over the past 40 years. The debris-covered area of Djankuat was estimated as early as 1968 at 2% of the total glacier area, and by 2022 this share increased by an order of magnitude and is already 20%. The average thickness of the superficial moraine cover has reached 60 cm today. Such a cover has an apparent sunlight-protective effect on the icy substrate and significantly weakens its ablation [19]. At the present stage, the evolution of debris cover has been proved to affect the glacier state commensurate with climate changes.

Even though all four years, as noted above, were characterized by negative mass balance, the polynomial approximation of the 54-year time series (Figure 7c) detects signs of some positive shifts for the glacier state in recent years since approximately the mid-2010s. They are only relative, because the glacier mass continues to decrease annually, but there is an apparent slowdown in the rate of these losses. A comparison of the graphs in Figure 7a,b reveals the reason for these relatively favorable changes: the increase in snow accumulation in recent years overrides the negative effect of the continued ablation growth. As a result, the mass balance in two of the four reported balance years shows minimally negative values for the period after 2005. The second decade of the 21$^{st}$ century should be recognized as the most unfavorable for the glacier for more than half a century of direct monitoring. At the same time, the inter-annual differentiation of the balance values remains very high; this is confirmed by the fact that even despite the emerged shifts towards improving the Djankuat budget, the negative anomaly of 2019/2020 is among the four extremes for the entire 54-year-long period.

### *3.2. Altitudinal Distribution of Mass Balance Parameters*

Over the past four years, a certain transformation has also been registered for the balance curves, i.e., distribution of mass balance components and their resultant value versus altitude (Figure 8). Nevertheless, a comparison of the shape of these curves for each year with the mean pattern of the multi-year distribution (highlighted with a bold black line in the graphs) does not refute the general congruence of balance curves in time—one of the basic glaciological laws for alpine glaciers [15]. The analytical type of similarity is believed to be determined by the dominant features of the local climate. For continental conditions, the multiplicative law is more peculiar: at each hypsometric level, any balance parameter $X$ in a year $i$ will be associated with its long-term average value $X_o$ at the same height by the coefficient inherent in this year ($X_i = k_i X_o$), whereas on marine-type glaciers, the additive law is more sustained, i.e., a free term instead of a coefficient figures in the relation ($X_i = X_o + C_i$). As follows from macro-climatic considerations, the Djankuat curves should be more likely characterized by the additive similarity type, although the accumulation curves (Figure 8a) disclose signs of multiplicativity. But, regardless of which similarity law is generally inherent for a particular balance indicator, it is possible to distinguish altitudinal zones where deviations from the long-term pattern are more pronounced.




(**a**) (**b**) (**c**)

**Figure 8.** Accumulation (**a**), ablation (**b**) and mass balance (**c**), mm w.e., of the Djankuat Glacier versus altitudinal belts in 2017/2018–2020/2021 and averaged over 54 years.

The income mass balance component in almost all belts and every four years differs from the long-term average: it is more prominent. However, the properties of congruence with the long-term pattern are violated by the configuration of the altitudinal curve (Figure 8a) most of all in the upper part of the glacier, above 3100–3200 m a.s.l.: an increase in accumulation here is disproportionately more significant than wherever within the snout.

The shape of the ablation vs. altitude curves in 2018–2021 (Figure 8b) is maximally inconsistent with the long-term distribution in those altitudinal spans, where the particularly dynamic thawing-off of the englacial moraine to the daytime surface has been observed in recent years; this process has seriously distorted both ablation fields and ablation–elevation dependences. First of all, this concerns the lowest Djankuat sectors, where the progressive debris piling up has long led to the morainic meso-relief losing its linear outlines along the flowlines, replacing them with a hummocky landscape. In the lower zones, discrete strips of still pure ice are rapidly replaced by debris-covered areas with widely varying thickness values of superficial moraine, and this transformation naturally causes dynamic changes in the melting regime. This is superimposed by the separation of peripheral snout segments from the main glacier body, which pass into the category of stagnant ice massifs, no longer mapped as parts of a glacier. Because of this, the lowest segments of the ablation curves look extremely inconsistent: in some years, the thermal insulation of the submerged ice by the lithogenic envelope only weakens melting and noticeably reduces the vertical ablation gradient in the lower belts, whereas in other years this shielding effect even leads to inversions of epures, causing a mass loss in the terminal zones more minor in comparison with those located higher. This protective function of debris cover for ablation, which progresses over time, manifests itself even within the analyzed short 4-year time interval: it is in the two most recent seasons when the inversions of the ablation curves in their lower parts in Figure 8b look especially evident. Another area where the congruence of curves is also obviously observed is the firn line migration belt in the middle course of the glacier. Here, the reason for the violation of the similarity law is colluvial material melting-out, whose emergence onto the day surface reached its highest intensity just in recent years. This matter has been incorporated inside the glacier firn basin after extremely bulky rock collapses [19] in 2001. The process of the recent formation of impressive longitudinal ramparts and isometric piles of the median moraine in the middle course of Djankuat is visually tracked when comparing glacier photos at different times in Figure 2, and the result is clearly visible in Figure 9. Therefore, the mass loss inhibiting effect rendered by debris cover in the altitude range of 3100–3300 m, similar to the lowest zones, also leads to a noticeable decrease in the natural vertical ablation gradient up to certain inversions in some years.

**Figure 9.** Debris cover in the middle course of the Djankuat Glacier (photo taken by V.A. Lisak in 2021).

The above-described properties of the height distribution are manifested in Figure 8c also for the curves of mass balance as the resulting parameter. Even though it is just in the balance curves where the properties of additive similarity are pronounced better than in others, their nuances are inherited primarily from the epures of the wastage component.

The distorting effect of the expanding debris cover on the shape of the curves (inversions at the bottom, decreasing vertical gradient near the firn line) is also reflected in the occurrence of zonal deviations in the distribution of the mass balance, and also, apparently, largely determines the relative improvement in the state of the Djankuat Glacier in recent years, which can be traced in Figure 7. Without denying the fact that the main reason explaining the recent improvement of the glacier budget is the climatic mechanisms of the circulatory nature, leading to an apparent increase in winter precipitation, a certain slowdown in the ablation growth rate, primarily associated with the shielding influence of the superficial moraine, also contributes.

### *3.3. Glacier Mass Turnover*

Finally, another characteristic feature of the long series of mass-balance observations at Djankuat is the revealed tendency to increase glacier turnover. Turnover is understood as [36] the annually calculated sum of accumulation and ablation values taken modulo. This parameter indicates the glaciation energy, which is the leading indicator characterizing the intensity of the external mass exchange of an alpine glacier. In quantitative terms, it is traditionally [37] calculated as the sum of vertical gradients of accumulation and ablation near the equilibrium line. Hence, the glacier turnover reflects the general climatic conditions in which the glacier exists. The final years of the monitoring series (Figure 10) are clearly distinguished by their increased mass exchange. The 2017/2018 balance year with its absolute turnover record of 7560 mm w.e. became the undisputed leader among all other years of the 54-year-long series, and the values of 2019/2020 and 2020/2021 (7350 and 6750 mm, respectively) occupy honorable second and third places in this series.

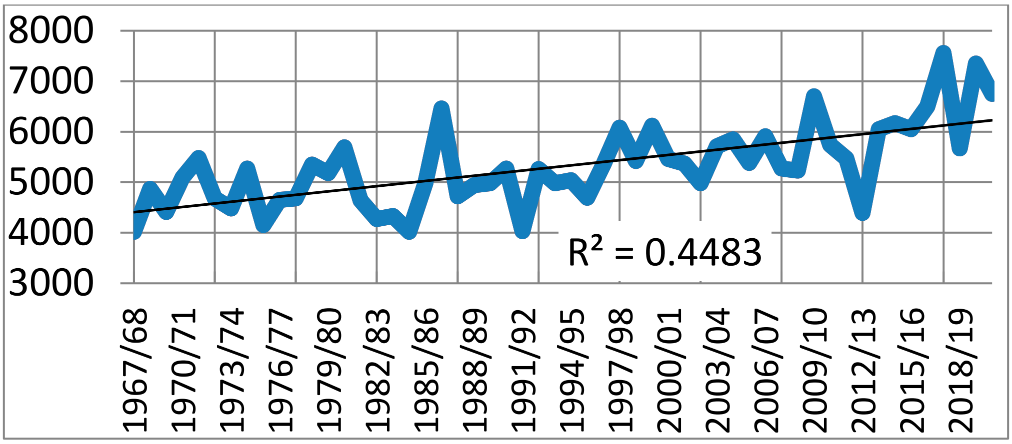



**Figure 10.** Djankuat Glacier annual mass turnover, mm w.e., in 1967/1968–2020/2021.

The mass turnovers of recent years, for all years, go beyond the natural inter-annual variability, which is rarely recorded even in a rapidly changing climate. The determination coefficient of the graph in Figure 10, equal to 0.45, characterizes the statistical significance of the trend towards more intensive mass exchange, and it, in turn, indirectly indicates a certain weakening of continentality in the regime of the local glacial belt. Although the Caucasus is located far inside the Eurasian continent and is too remote from the Atlantic as the primary oceanic source of precipitation, its climate has traditionally been characterized as moderately maritime due to the proximity of the inland Black Sea (Figure 1). Judging by Figure 10, the trend towards climate mitigation continues to progress over the past half-century, causing corresponding shifts in the mass turnover of the Caucasian glaciers. It is possible, however, to see some contradiction of this conclusion with the fact that the accumulation vs. altitude curves (Figure 8a) over the studied four years tend more likely to reveal a multiplicative type of similarity, characteristic primarily for glaciers of continental regions. It seems that either the multiplicativity of the accumulation curves reflects only the specifics of 2018–2021, or the final transition to additivity has simply not yet happened. Anyway, the dependence of the similar types of balance curves on the degree of continentality has not yet lost its controversy and still remains far from strictly functional.

## 4. Conclusions

According to many articles, the 2017/2018–2020/2021 seasons were very abnormal for the state of the Djankuat Glacier, considered representative of the Caucasus. Notwithstanding the fact that the active deglaciation is still peculiar for the present evolutionary stage in the Caucasus and that the mass of its ice resources does not stop decreasing, sure signs of slowing down these negative trends for glaciers began to be revealed recently. This relative budgetary improvement is mainly due to a progressive increase in winter snow accumulation, overlapping thereby the effect of an increase in ablation recorded alongside due to ongoing warming and growth of the radiation balance; the latter is caused by cloudiness reduction induced by the enhancement of anticyclonic circulations.

A peculiar feature of present global climate changes is the increasing frequency of anomalies in the indices of external mass turnover of alpine glaciers. The mass income in two seasons (2018 and 2021) was extremely large, taking second and third places in a long-term series of instrumental observations. The wastage in two seasons (2018 and 2020) was also among the top five since the beginning of monitoring in 1967/1968, and 2019/2020 with its value of 4360 mm w.e. became the absolute record holder for the last 54 years. As a result, this year's sharply negative mass balance was inferior in absolute value to only three years for the entire period. On the contrary, the increased differentiation of inter-annual values led to the fact that in the other two seasons (2018 and 2021) of the 4 years under consideration the moduli of the negative balance were the smallest for 16 years since 2004/2005, after which positive values have been never recorded at Djankuat. Hence, the assumption about a slight relative improvement in the budgetary condition of the reference glacier in recent years was based on this result.

Anomalies in the configuration of the curves, reflecting the distribution of mass balance parameters versus altitude, are primarily associated with the intensive growth (both in area and thickness) of debris cover on the glacier, which plays a vital thermophysical role in inhibiting ablative processes. This process also contributes to reducing the rate of glacier mass loss in recent years.

The increased moduli of mass balance components mean intensifying glacier turnover—a trend that has manifested itself over all 54 years of observations, but has significantly accelerated recently. In terms of this parameter, 2017/2018 became the absolute leader, and 2020/2021 and 2019/2020 occupy the second and third places in the rating, respectively, for the entire half-century of monitoring. Indirectly, such an increase in the energy of glaciation may indicate a weakening of the degree of continentality in the highlands of the Caucasus.

**Author Contributions:** Conceptualization, V.P.; methodology, V.P., P.T.; formal analysis, all authors; investigation, V.P., A.G., V.L.; data curation, A.G., V.L., P.T.; writing—original draft, writing—review and editing, V.P.; visualization, A.G., V.L.; supervision, project administration and funding acquisition, V.P. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

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