Bulletin of Glaciological Research 22 (2005) *121–133*

A 34-year-long record of mass balance and geometric changes of the Djankuat Glacier, Caucasus

Victor V.Popovnin[1] and Renji Naruse[2]

1 Cryolithology & Glaciology Dept., Geographical Faculty, Moscow State University, Leninskiye Gory, Moscow, 119992, Russia
2 Institute of Low Temperature Science, Hokkaido University, Sapporo, 060-0819 Japan

(Received October 15, 2004; Revised manuscript received November 30, 2004)

Abstract

Dynamics of mass balance and its components of the Djankuat Glacier, representative for the Central Caucasus, during the 34-year-long period of direct measurements are analyzed. Mean mass balance is slightly negative (−160 mm w.e.), with average accumulation and ablation values coming to 2410 and −2570 mm w.e., correspondingly. As a result, orthogonal projection of the Djankuat Glacier area on the northern macro-slope of the Main Caucasus Ridge decreased by 12% in the period 1968–1999, while its surface lowered slightly less than 6 m (in water equivalent). Variability of both mass balance components is practically the same at the Djankuat Glacier. Mass balance extremes coincide with the years of maxima of its components. The whole 34-year-long observation period is marked by weak trends towards increase of both balance constituents. Dominant tendency towards the improvement of the Djankuat Glacier budget conditions changed to the contrary (or, at least, was interrupted) since 1998. It is not clear whether this pattern indicates the beginning of the new stage of glacier degradation in the Caucasus or it should be regarded only as a natural fluctuation of atmospheric processes.

1. Introduction

The Djankuat Glacier, located in the Caucasus, is currently the most widely investigated glacier in Russia. The World Glacier Monitoring Service has selected it as one of the 10 reference glaciers of the Earth for the global mass-balance programme. Direct observations here have lasted continuously for 34 years up to present. This is the longest time series in Russia and the second in the ex-USSR territory, yielding only to the Tuyuksu Glacier; besides, Djankuat has one of the longest records all over the world. This mass balance series is the only one in the Caucasus suitable for tracing present evolutionary tendencies. Conclusions, derived here, could be extended to the entire central section of the Great Caucasus, because initially Djankuat has been the representative glacier for this region since the International Hydrological Decade (IHD) (The Djankuat Glacier, 1978).

2. General characteristics of the Djankuat Glacier

Djankuat (Fig. 1) is situated in the axial part of the Main Caucasus Ridge, in the upper reaches of the Adylsu valley, engrafted into the northern macro-slope of the meganticlinorium. The Adylsu River, in its turn, is an important tributary of the Baksan River, which belongs to the Caspian Sea basin. The uppermost part of the valley, together with the studied glacier, faces NW. It has a typical alpine appearance, with a lot of surrounding peaks exceeding 4000 m a.s.l. The extensive glaciation (Fig. 2) is the characteristic feature of the region.

Morphometrically, the Djankuat Glacier has much in common with a hypothetical pattern of the typical Caucasian valley glacier. It lies within the altitudinal span 2700–3750 m a.s.l. and it is 3.5 km long, being characterized by a step-like longitudinal profile. Its physical area is 3.009 km^2, status 1999. In general, its ablation and accumulation areas occupy the 2700–3020 m and 3300–3600 m elevation ranges correspondingly, and the firnline migration belt lies in between. Steep slopes above 3600 m a.s.l. are mainly represented by firn/ice revetment around the nourishment basin.

Djankuat is a typical simple valley glacier, consisting of 4 adjacent ice streams: two principal streams originate from under Mt.Gumachi and from the Djantugan firn plateau, and two secondary ones flow down from the slopes of Mt.Uya-tau and Mt.Djantugan. The individual peculiarity of the Djankuat Gla-

A)

Fig. 1. A) The Djankuat Glacier: general view of the glacier (photo taken by A. A. Aleynikov in 2000).

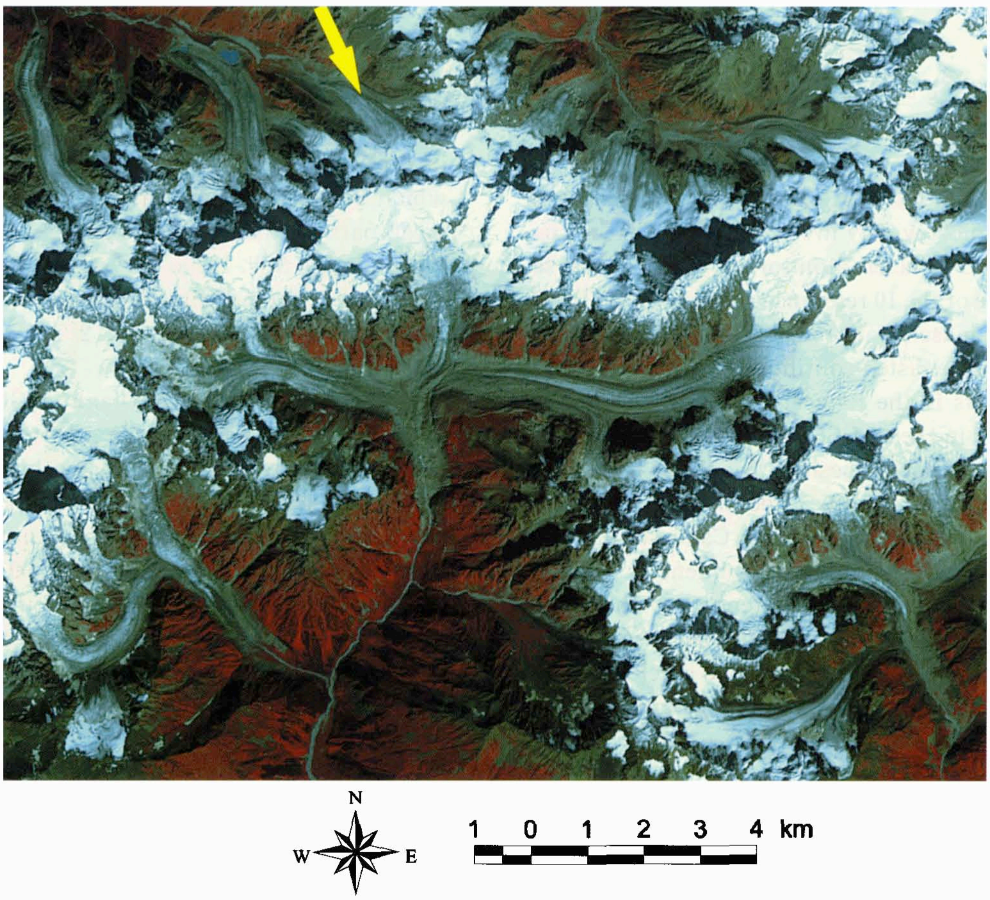

Fig. 2. Glaciers of the investigation area (Central Caucasus). ASTER satellite image of 16.09.2001. The Djankuat Glacier is shown by arrow.

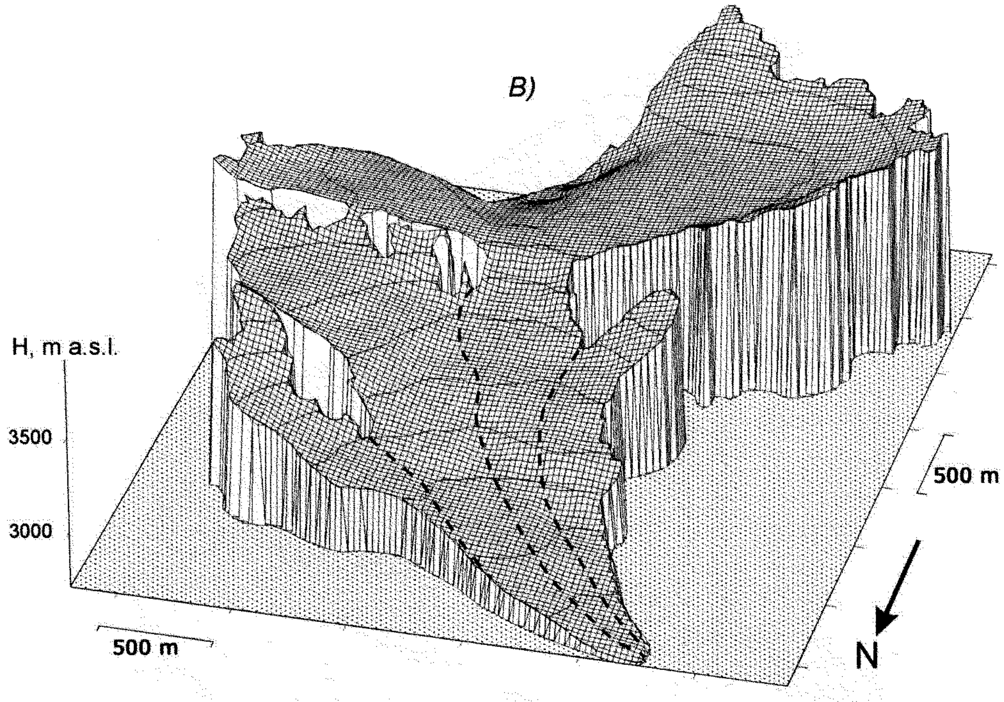

Fig. 1. B) Digital terrain model of the Djankuat Glacier.

cier morphology is the initiation of one of the most prominent and significant central ice streams from the crestal firn plateau, distributing mass fluxes towards both northern and southern macro-slopes of the Great Caucasus. The ice divide location on the plateau surface is quite indefinite, it is not clearly pronounced in the glacial relief and continuously migrates along the flat plateau. A special investigation by Aleynikov *et al.* (2002) revealed the Djankuat catchment area on the plateau continuously changing throughout the entire 34-year-long observation period, averaging from 0.300 km^2 in 1968–1984, 0.223 km^2 in 1984–1992, 0.243 km^2 in 1992–1998 and 0.387 km^2 since 1999.

Djankuat is a temperate glacier, and the dominant ice formation mechanism is the temperate firn one (Shumskii, 1964). Its location within the zone of relatively humid climate determines the intensive mass turnover, with the order of magnitude of several thousand millimeters of water equivalent per year.

3. Mass balance calculation scheme

From the very onset of the continuous monitoring at the Djankuat Glacier, mass balance b_n and its components were calculated in accordance with the stratigraphic reporting system, accumulation being represented by winter balance b_w and ablation by summer balance b_s. Since the late 1980s this scheme turned to be closer and closer to the most sophisticated system - the combined system, which requires much more detailed (frequent) measurements in transitional periods, separating balance years or their seasons when accumulation and ablation processes can proceed simultaneously in different altitudinal spans. This allowed to submit mass balance calculation results not only in accordance with the traditional stratigraphic reporting system, but with the fixed-date system as well. Approximately at the same time a principle of drawing accumulation, ablation and mass balance fields was introduced into practice of glaciological research at the Djankuat Glacier. These fields were subsequently digitized in a 50×50 m rectangular grid in order to compute external mass turnover parameters for the entire glacier. Introduction of the digitizing scheme and other slight innovations didn't affect the statistical uniformity of the balance time series. Comparison of mass balance values, calculated for the same year by the former and the new schemes, showed that the difference didn't exceed 4% as an average. That's why all conclusions about the observed changes seem to be climate-related and not caused by difference in methods.

The accumulation field at the Djankuat Glacier is drawn on the basis of data obtained at 300–400 (sometimes more than 500) measurement points of direct snow depth survey, distributed more or less evenly over the whole accessible area, covering *ca.* 90% of the glacier's surface (Fig. 3a). Snow density is estimated in 4–5 snow pits, dug both on the snout and in the firn basin, and extrapolated later over the entire area of the correspondent glacier belt. Snow depth survey is carried out in May-June, coinciding with the time of snow maximum. However, dates of maximum snow accumulation in the lower and upper parts of the glacier usually differ by 1.5–2 months. That is why special amendments, counting for accumulation after the survey or ablation prior to it, are also inserted. Seasonal snow accumulation on inaccessible zones is calculated with the help of geographical indices (such

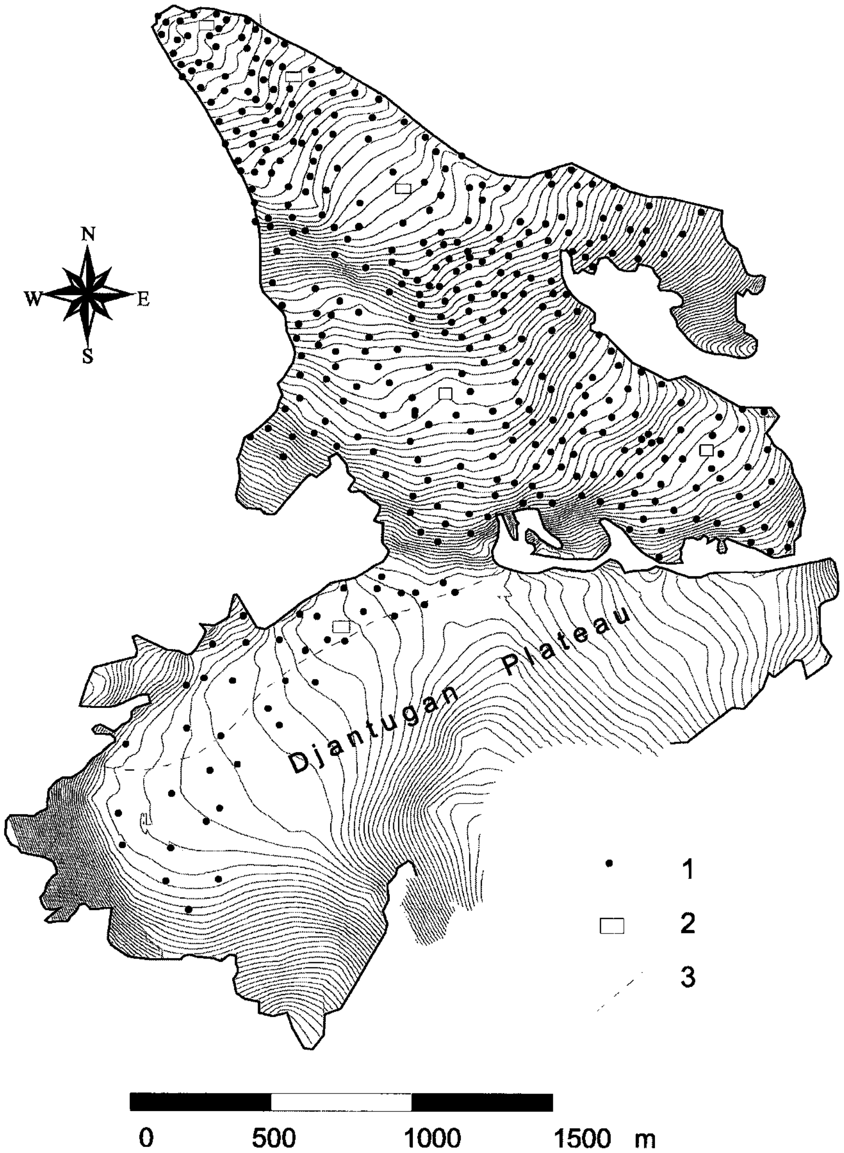

Fig. 3. a) Mass balance observational network at the Djankuat Glacier (status 1999 as an example), for accumulation measurements: 1 - measurement points of snow depth survey; 2 - snow pits for densimetry; 3 - border of the Djankuat Glacier catchment area on the Djantugan Plateau.

as absolute elevation, slope, surface geometry, aspect, dynamics of the seasonal snow melt-off, etc.) and statistical correlations between the grid nodes, looking rather stable in time due to temporal conformity of the accumulation pattern over the glacier surface.

Ablation at the Djankuat Glacier is measured by means of the well-known method of stakes and pits. The usual ablation network consists of 50–80 stakes (Fig. 3b), meeting the requirements of the first class of regime observations. Besides, melting in the nourishment area is estimated as a difference between snowpack water equivalents, measured in spring and in autumn. When drawing the ablation field, the influence of debris cover on thawing rate (Popovnin and Rozova, 2002) is also taken into account as well as en- and subglacial melting, ablation in crevasses and "internal feeding" (or ablation decrement), being based on simulation results or indirect considerations and evaluated after a thorough examination, introduced in former publications (*e.g.* The Djankuat Glacier, 1978).

Mass balance field results from the sum of accumulation and ablation fields, corrected by mapping of snowline dynamics and data of autumn (August-September) snow depth survey. The three fields are strictly correlated with each other, so that consequently the equation

$$b_w + b_s = b_n$$

is kept valid in each node of the regular grid.

The final calculation of overall glacier budget parameters is carried out by averaging values not obtained directly in measurement points but digitized

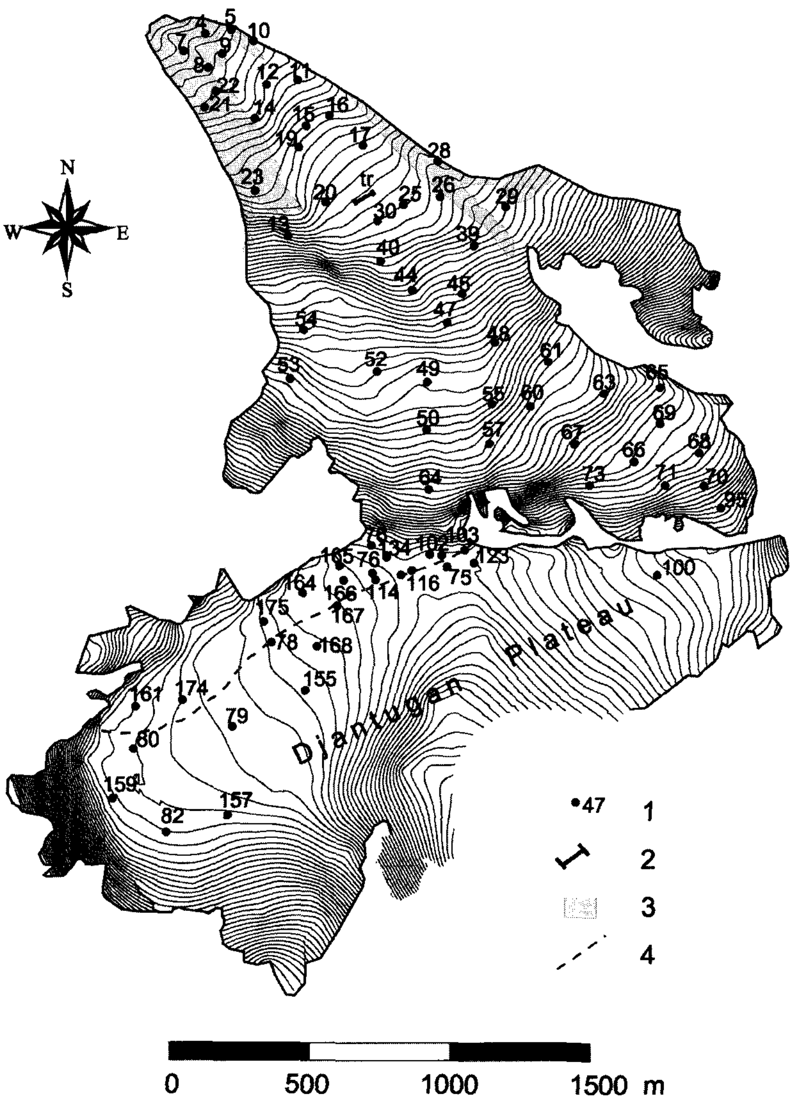

Fig. 3. b) Mass balance observational network at the Djankuat Glacier, for ablation measurements: 1 - ablation stakes and its numbers; 2 - reference cable; 3 - border of the debris cover on the glacier snout; 4 - border of the Djankuat Glacier catchment area on the Djantugan Plateau.

in the grid nodes. Hereby, the influence of subjective arrangement of any direct measurement is eliminated, and the resultant data set becomes statistically significant and independent.

4. Statistical structure of mass balance time series

Results of accumulation, ablation and mass balance calculation over the instrumental observation period are summarized in Table 1 and depicted on Fig. 4.

The dynamics of mass-balance features of the Djankuat Glacier throughout 34 years of direct measurements has not yet been analyzed before. Previously published summaries (*e.g.* Baume and Popovnin, 1994) concerned the observation period between 1968 and the early 1990s, whereas time series exceeding 30 years can disclose present tendencies in external mass and energy turnover more reliably. This duration reflects an important quantitative threshold in statistics, in general: if a time series contains >30 items, its variability can be evaluated by non-shifted dispersion.

Negative mass balance values prevailed during the 34-year-long observation period, and are registered in 19 years. The mean long-term mean values of accumulation and ablation are 2410 and 2570 mm w.e., correspondingly, making up an average mass balance value of −160 mm w.e. The range in accumulation values is 2350 mm, with a standard deviation of 420 mm. The range in ablation values is about 1.5 times

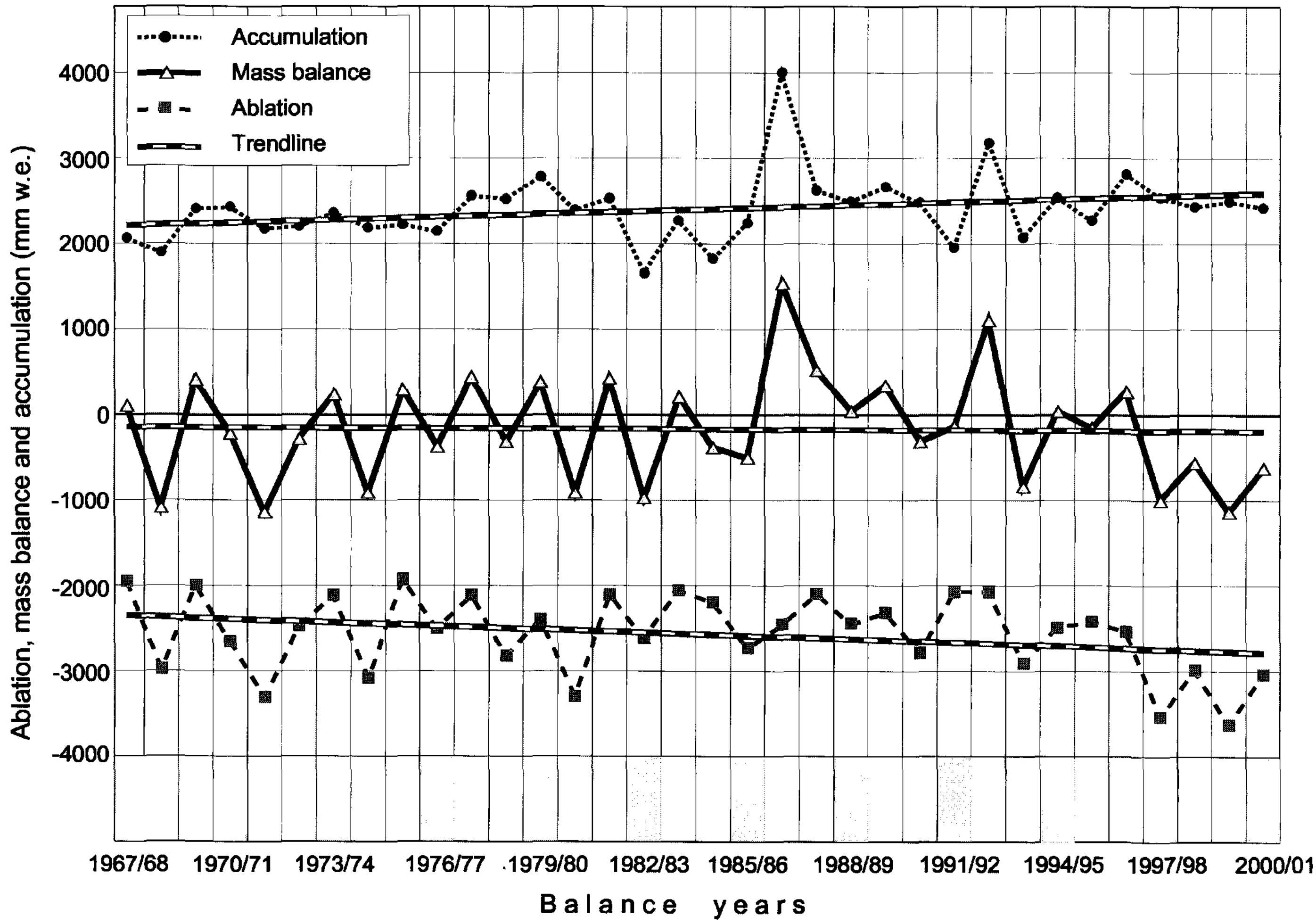

Fig. 4. Accumulation, ablation and mass balance fluctuations of the Djankuat Glacier during the 34-year-long period of direct measurements.

smaller (1670 mm), with a strongly higher standard deviation of 470 mm. Variation coefficient c_v of accumulation (calculated as standard deviation divided by the mean) is also slightly less than that of ablation -0.17 against 0.18. During the 1968-1974 (IHD) period c_v of accumulation was 0.10, whereas c_v of ablation was twice as high (0.21). Later, however, the 20-year-long time series revealed already a quite different relationship: c_v of accumulation became 0.20 and c_v of ablation became 0.18 (Popovnin, 1989). Hence, the tendency towards leveling of accumulation and ablation variation with time can be easily traced. Apparently, variation of mass balance components would remain approximately the same in the long-term time scale.

Formerly, when analyzing 10- and 20-year-long time series (Chizhov, 1982; Popovnin, 1989), the balance effect caused by accumulation and ablation anomalies was revealed to coincide: for example, a year, marked by favourable conditions for the glacier health, was often characterized by both increased accumulation and reduced ablation. Nevertheless, analysis of the 34-year-long series leads to the opposite conclusion: low correlation coefficient between annual values of accumulation and ablation $r\,(b_w, b_s)=0.07$ testify to almost complete lack of correlation between them. In other words, the amount of winter snow is found out not to influence the summer thawing. All this demonstrates the special importance of the observation period duration: short time spans lead sometimes to unreliable conclusions, not corroborated later on.

Mass balance variation is much higher than that of any of its constituents: the range of its annual values is 2680 mm w.e. and the standard deviation is 650 mm. The latter is somewhat higher than for the IHD period (580 mm), though it yields to that of the first 20 years (680 mm). It is peculiar that mass balance value is mostly predetermined by ablation: its correlation with accumulation $r\,(b_w, b_n)=0.70$ is slightly smaller than that with ablation $r\,(b_s, b_n)=0.77$. Balance extremes coincide with maxima of its components: the highest accumulation, observed in 1986/87 (4000 mm w.e.) answers the balance maximum (+1540 mm), whereas the highest ablation in 1999/2000 (3630 mm) corresponds to the most negative mass balance value (-1140 mm).

The high degree of temporal steadiness of the external mass/energy turnover fields results in the peculiar pattern: local accumulation, ablation and

Table 1. Results of the Djankuat Glacier mass balance monitoring (in mm of water equivalent) during the period of direct observations.

Balance year	Winter balance (accumulation), b_w mm w.e.	Summer balance (ablation), b_s mm w.e.	Mass balance, b_n mm w.e.	Glacier-derived run-off, $10^6\,m^3\,a^{-1}$
1967/68	2060	−1960	+ 100	5.65
1968/69	1890	−2980	−1090	10.79
1969/70	2410	−2000	+ 410	8.90
1970/71	2400	−2660	−260	8.91
1971/72	2170	−3310	−1140	12.26
1972/73	2200	−2480	−280	9.23
1973/74	2360	−2120	+ 240	7.52
1974/75	2180	−3090	−910	10.24
1975/76	2220	−1930	+ 290	7.12
1976/77	2140	−2510	−370	9.15
1977/78	2560	−2120	+ 440	7.00
1978/79	2520	−2830	−310	9.42
1979/80	2780	−2400	+ 380	8.02
1980/81	2390	−3300	−910	11.12
1981/82	2530	−2110	+ 420	7.11
1982/83	1650	−2620	−970	8.90
1983/84	2270	−2060	+ 210	7.05
1984/85	1820	−2200	−380	7.53
1985/86	2240	−2740	−500	9.38
1986/87	4000	−2460	+1540	8.42
1987/88	2620	−2100	+ 520	7.17
1988/89	2490	−2450	+ 40	8.36
1989/90	2660	−2320	+ 340	7.91
1990/91	2480	−2790	−310	9.47
1991/92	1950	−2080	−130	7.04
1992/93	3180	−2080	+1100	7.04
1993/94	2070	−2910	−840	9.85
1994/95	2540	−2500	+ 40	8.46
1995/96	2270	−2420	−150	8.19
1996/97	2810	−2540	+ 270	8.60
1997/98	2540	−3540	−1000	11.16
1998/99	2430	−2990	−560	9.43
1999/2000	2490	−3630	−1140	10.92
2000/01	2420	−3040	−620	9.15
Average	2410	−2570	−160	8.72

mass balance extremes are every year observed almost at the same sites of the glacier surface irrespective of the absolute values of corresponding parameters for the whole glacier. The only exceptions are the belt of steep firn/ice slopes, where accumulation values are correlated weakly with the background due to the active gravitational redistribution of the matter, and the lowermost part of the snout, where annual ablation depends primarily on winter snow amount that determines the duration of the part of the summer season when the exposed supraglacial debris cover plays its screening role.

5. Trends in mass balance

Each of 34-year-long time series of budget parameters (accumulation, ablation, mass balance) has its own peculiar features throughout the entire period of direct observations.

A weak linearly increasing trend can be detected on Fig. 4 for the accumulation series. It is not very well pronounced, judging by its R^2-criterion value (0.0783). The same is valid also for ablation (or summer balance), revealing a very slight trend towards increase of its absolute value ($R^2=0.0776$). Dominant tendency in mass balance series in 1968–2001 is practically non-pronounced at all ($R^2=0.0005$, that is statistically insignificant): weak increase of accumulation is almost compensated by weak increase of ablation.

The accumulation time series can be subdivided into a number of stages:

- Stage 1 (1968–1977): Accumulation is almost stable ($c_v=0.07$), and it averages 2200 mm;

- Stage 2 (1978–1982): Mean accumulation value increases abruptly up to 2560 mm w.e., the low variation remaining at the same level ($c_v=0.07$);

- Stage 3 (1983-1986): Accumulation values are the lowest of the whole observation period (2000 mm at an average), its inter-annual variation grew rapidly ($c_v=0.15$);

- Stage 4 (1987-1993): This is a time span of the highest accumulation (the mean value coming to 2770 mm) and the greatest variation ($c_v=0.24$);

- Stage 5 (1994-2001): The final stage is characterized by the reduction of both accumulation and its variation.

A similar subdivision of the ablation time series into stages looks as follows:

- Stage 1 (1968-1981): Ablation slightly exceeds its long-term average (2560 vs. 2570 mm), and its variation is high ($c_v=0.19$); only two episodes of considerably increased ablation take place in the early 1970s and early 1980s;

- Stage 2 (1982-1993): Both absolute ablation values and their variation become smaller (2330 mm and $c_v=0.12$, correspondingly);

- Stage 3 (1994-2001): The final period is the most peculiar, because ablation reaches its absolute maximum (averaging 2590 mm), accompanied by the growth of inter-annual variation ($c_v=0.16$); the very last 4 years, 1998-2001, were the most outstanding, since this was the only time span throughout the entire observation period at the Djankuat Glacier, when ablation practically exceeded 3000 mm w.e. during 4 consecutive years.

Fluctuations of glacier-derived bulk run-off (Table 1), that is, mass loss (in water equivalent) multiplied with the glacier area, naturally inherit features, peculiar for the ablation time series. However, they were influenced to a certain degree by areal reduction of the glacier of more than 10%. Therefore, the general decreasing tendency for the run-off is expressed quite definitely. The only exception occurred in 1998-2001, when considerably increased ablation caused the increase of the running mean to 10.2×10^6 m^{3}a^{-1}, whereas the average for the whole 34-year-long period was evaluated as 8.7×10^6 m^{3}a^{-1}.

The mass balance time series is predetermined by tendencies, revealed separately for each of its components, but has its own peculiarities as well, since at different stages it is influenced mainly by either accumulation or ablation. In 1968-1975 the mean mass balance value was considerably negative (-370 mm w.e.). Between 1976 and 1986 the budget conditions of the glacier relatively improved at the expense of accumulation growth, though its average value remained negative (-150 mm). Much more pronounced was this improvement in 1987-1997: the average value obviously moved into the field of positive values (+220 mm w.e.). However, this stage was followed by the extraordinarily unfavourable period, and in 1998-2001 the mean mass balance value suddenly decreased down to -830 mm.

Signs of 5-6 year cyclic recurrence can be detected for accumulation records within the 34-year-long period under investigation. The most vivid feature of the ablation series is biannual harmonic, expressed best of all in 1968-1985 and attenuated afterwards; 7-8 year cycles can be traced also. Biannual cyclicity stands out also for the mass balance series, pronounced even better than for the ablation series.

6. Discussion of mass balance trends

Let us discuss now the reasons of mass balance fluctuations in a more detailed way, paying attention to the most general climatic prerequisites during the past periods.

In 1968-1986 mass balance was influenced mostly by ablation and not by accumulation: $r\ (b_s,\ b_n)=0.87$, whereas $r\ (b_w,\ b_n)=0.60$. As a whole, this time interval was characterized by moderate amount of winter snow that increased a little during the last half of the period. Summer temperature did not disclose any pronounced trend over this time span.

The 1987-1997 stage was quite inverse: $r\ (b_s,\ b_n)=0.53$ and $r\ (b_w,\ b_n)=0.91$, meaning that mass balance was determined mainly by accumulation. The main feature of this stage was the growth of winter snow amount. Simultaneously, summer air temperature increased also, notwithstanding the fact that ablation period used to start somewhat later than in previous years.

Since 1998 practically functional dependence between mass balance and ablation $r\ (b_s,\ b_n)=0.99$ is observed, though apparently one cannot speak of any statistically significant trend for such a short, 4-year-long time interval. Nevertheless, at the same time some noteworthy features of this short stage should be noted. For instance, a unique phenomenon is traced: interrelationship between mass balance and accumulation became inverse $-r\ (b_w, b_n)=-0.76$ - that is patently atypical not only for the Djankuat Glacier but for the Earth's glacierization entirely as well (*e.g.* Chizhov, 1982). Directly observed alterations in macrocirculation patterns over the Great Caucasus since the beginning of 1998 led to the certain decrease of winter snow amount and sharp summer air temperature rise. The absolute air temperature maximum, ever recorded at the Campsite weather station 800 m below the Djankuat Glacier terminus, increased by more than 2℃ after early 1990s. Summer precipitation reduced considerably: *e.g.* only 2 short periods of rain were registered in August 1998, bringing 15 mm in total, which is only *ca.* 20% of the long-term climatic mean.

However, in spite of the evident peculiarities of the last 4 years, the mass balance of the Djankuat

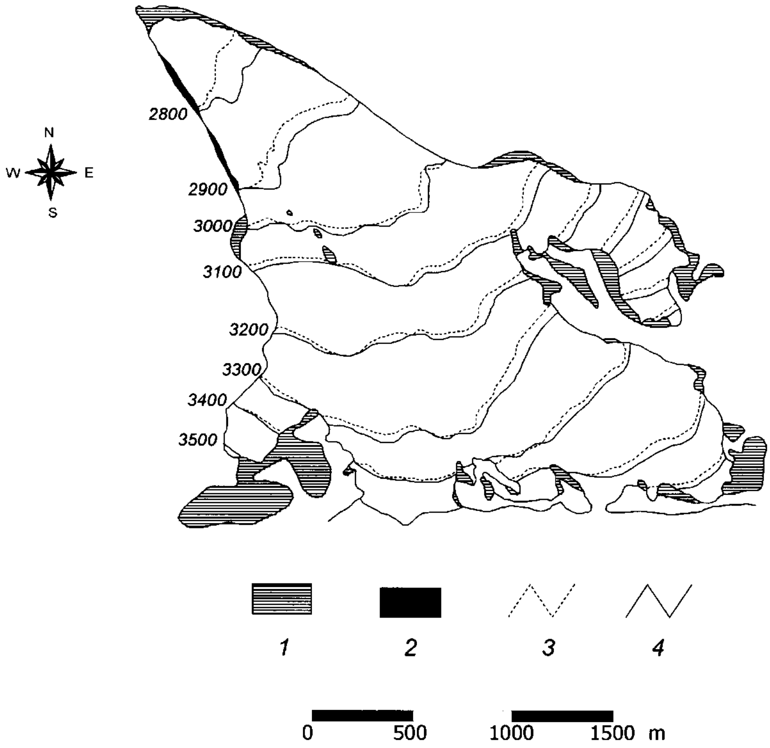

Fig. 5. Changes in the Djankuat Glacier 100 m interval contour lines and its boundaries in 1968–1999: 1 - areal loss; 2 - areal expansion; 3 - contour lines in 1968; 4 - contour lines in 1999.

Glacier seems to reveal no decreasing trend over the whole 34-year-long period of direct monitoring. Trend-lines, depicted on Fig. 4, demonstrate evidently that the glacier can be considered quasi-stationary throughout the whole period under investigation. At the same time the slight increase of both balance components by absolute value mean the gradual increase of the total mass turnover and of the glacier energy. The glacier regime tends to the pattern, answering more maritime conditions. Future measurements will clarify whether the final post-1997 stage signifies a change into an increasingly more negative mass balance trend or if it is a normal (casual) short-term fluctuation. Anyway, the most recent years (after 2001) of mass balance estimates have not yet been calculated (raw field data are still being processed), but preliminary observations seem to testify in favour of the latter suggestion, because the weather conditions became profitable for the glacier again, and summers 2002 and 2004, in particular, were extremely cool and humid for the entire alpine belt of the Caucasus.

7. Changes of the glacier geometry

The main consequence of a glacier mass turnover is always the change of its areal and spatial extent as well as altitudinal alteration of its surface. In order to obtain the detailed and thorough estimation of changes in glacier geometry, six large-scale 1: 10,000 maps of the Djankuat Glacier with the relief depiction by means of 10 m isohypses were compiled as a result of terrestrial photo-theodolite surveys, undertaken in 1968, 1974, 1984, 1992, 1996 and 1999. Areas were estimated, and mean slope values were derived by averaging measured distances between a pair of adjacent 10-m isolines in every node of the regular 50×50 m grid. The monitoring programme also included annual determination of frontal fluctuations along 8 longitudinal transects. At the same time the stereophotogrammetrical method provided an independent accuracy control of mass balance calculations. Table 2 and Fig. 5 show how the spatial position of the Djankuat Glacier has changed between 1968 and 1999.

In order to understand the character of the glacier response to the climatic signal it is better to exclude Djankuat catchment area on the Djantugan firn plateau, whose dynamics is predetermined largely by a complicated mechanics of divergent ice flow. Then the orthogonal projection area of the glacier only on the northern macro-slope of the Main Caucasus Ridge turns out to have decreased by 0.323 km^2, or a bit less than 12%, during this period. The most extensive area reduction occurred between 1968 and 1974, then its rate gradually decreased and accelerated again after 1992. Changes of the total Djankuat Glacier area, including ice catchment area on the plateau, are largely influenced by the process of ice divide migration, described in Section 2. From time to time this process either causes the intensified reduction of the total area or, vice versa, compensates areal losses on the north-

Table 2. Areal reduction of the Djankuat Glacier (excluding the Djantugan firn plateau) during 1968–1999.

Parameter	1968	1974	1984	1992	1996	1999
Physical area of the glacier, km^2	3.034	3.039	2.913	2.816	2.767	2.740
Mean slope, degrees	23.1	28.3	24.4	25.1	25.4	25.8
Orthogonal projection area, km^2	2.790	2.676	2.653	2.549	2.499	2.467
Reduction of orthogonal projection area, km^2		0.114	0.079	0.048	0.050	0.032
Annual rate of orthogonal projection area reduction, $km^2 a^{-1}$		0.019	0.008	0.006	0.012	0.011

ern macro-slope. Nevertheless, the general resultant effect over 34 years of direct monitoring is the decrease of the total glacier area from 3.234 to 3.009 km^2, or by 9.3 per cent.

Changes of a glacier area at progressive or regressive stages of its evolution are traditionally considered to occur mainly at the expense of frontal variations. The undertaken research shows that this statement is incorrect for brief time spans (from years to first decades). The largest changes during the period of direct observations took place just near the uppermost boundaries of the Djankuat Glacier. More than 75 per cent of areal reduction of the glacier falls on the region of firn/ice revetment around the nourishment basin. This is explained by the fact that ice thickness here is too small, it rarely exceeds 10 m. At the deglaciation stage the prevalence of negative mass balance values rapidly compels this thin ice envelope to melt off completely. This process became especially active since 1998, and consequently, tremendous rockfalls and stones collapsed from the crestal section of surrounding mountains with an increased occurrence. Ice surface on the revetment above the firn basin of the Djankuat Glacier diminished during 1968–1999 by a factor of 7. A similar situation, by the way, is reported (Panov, 1993) to have taken place between the end of the 19th century and the 1970s on most of the glaciers in the Central Caucasus.

Fluctuations of Djankuat's snout boundaries during the period under investigation were not so dynamic: the contribution of areal losses around the snout contour into the total reduction of the glacier area comes to only 15 per cent. Usually, variation of the snout boundary is characterized first of all by its terminal fluctuations. Its total recession between 1968 and 2000 was 105 m, but this process was extremely uneven. During the IHD, in 1968–1974, the Djankuat Glacier terminus retreated by 60 m, corresponding to a mean annual rate of 10 m a^{-1} (Golubev *et al.*, 1979). Later this velocity decreased: by the early 1980s the glacier retreated 28 m more and subsequently it remained nearly stationary during a number of years. This pause resulted in formation of the fresh terminal moraine looking like a rampart with a height of about 3–5 m (Zolotaryov and Popovnin, 1993). In 1985 the terminus retreated 2 m more, but after the stable position in 1986 it re-advanced by 3 m in 1987, rumpling and destroying the new-born moraine. Then it remained in a quasi-stationary position until 1993 (*e.g.* in 1991 it retreated by 1 m and in 1993 re-advanced by 1 m), but it resumed its retreat since 1994. The frontal recession reached 9 m during the next 3 years and 17 m more during 1996–1999.

In these years the terminal retreat took place predominantly at the expense of its orographically right periphery. Recession of the left and the central parts of the snout was restrained by the thick debris cover. However, later the glacier's meltwater tunnel shifted towards the central part of the front that washed away the morainic deposits, exposed the substrate ice onto the day surface and, consequently, led to terminal retreat along the whole front. In 2000 this exceeded 10 m. Evolution of debris cover on the snout turns out to be a very important process regulating the dynamics of areal changes in ablation zone of the glacier. During the regressive phase of the glacier evolution the debris cover expands, and it is this expansion that governs primarily the migration not only of terminal but of lateral glacier boundaries as well. If the lateral boundary is represented by bare ice, it shifts inwards with time in accordance with the dominant glacier degradation tendencies. But if marginal parts of the snout are screened by a thick layer of morainic material that reduces ablation, a lateral advance of the snout boundary can take place. This expansion is engendered by the ice influx from the upper glacier belts due to its viscous flow, which is not here compensated by ablation anymore. For instance, the only part of the Djankuat snout boundary, where areal expansion was observed during the period of direct monitoring, is situated along the left periphery of the glacier at an elevation of 2710–2880 m a.s.l. The new rampart of modern lateral moraine with a height of *ca.* 1.5–2 m was formed just along this section of the glacier contour.

Another significant peculiarity of glacio-morphological evolution of the Djankuat Glacier snout during the period of direct observation is the steadfast growth

Table 3. Changes in the Djankuat Glacier surface elevation in 1968–1999 (after Golubev *et al.*, 1979; Zolotaryov *et al.*, 1997; Aleynikov, 2001).

	1968–1974	1974–1984	1984–1992	1992–1999
Mean surface elevation change, m w.e.	−1.90	−0.88	−0.36	−2.77
Share of glacier area with hypsometrical rise, %	12	40	48	12

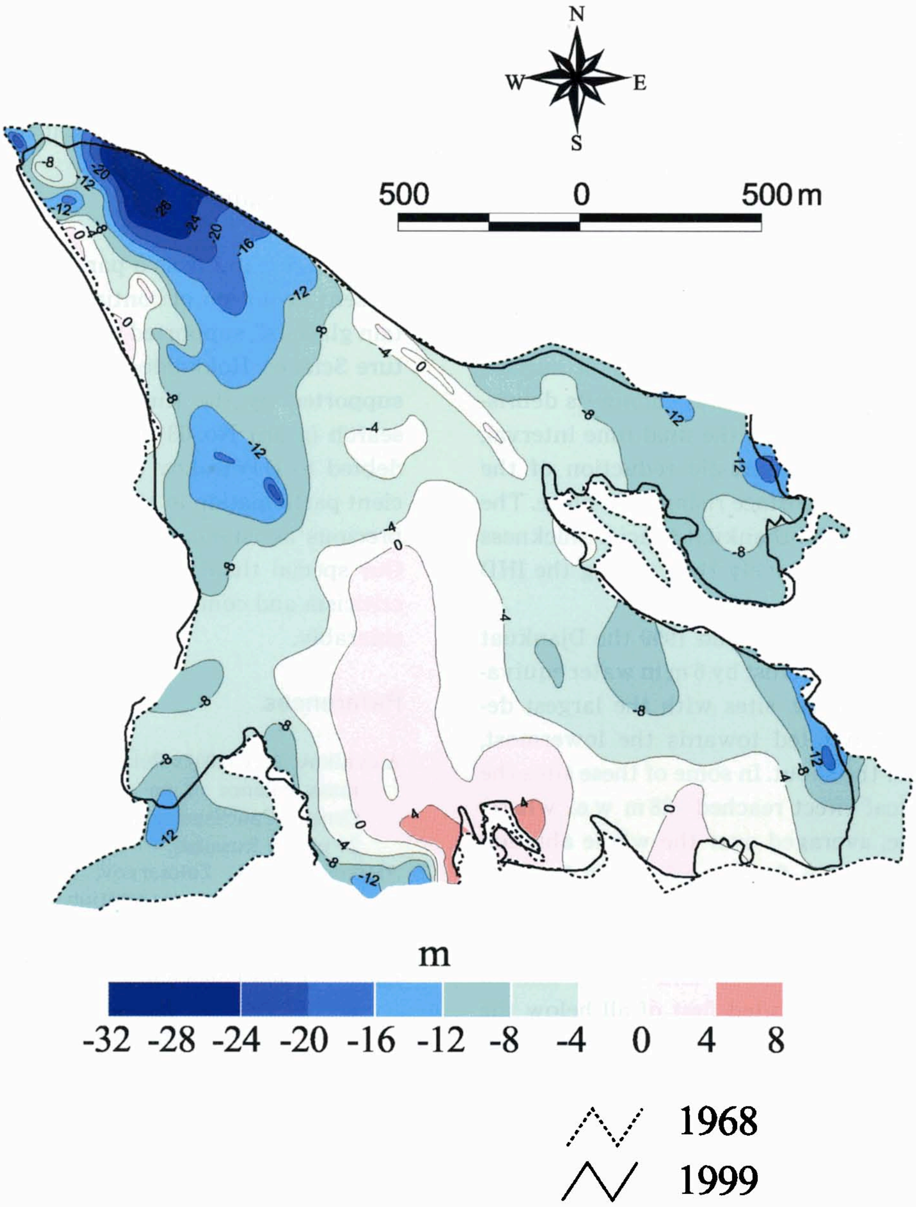

Fig. 6. Elevation changes of the Djankuat Glacier surface in 1968–1999.

not only of the supraglacial moraine area but of debris thickness too. In 1968 the supraglacial moraine covered 0.104 km^2, or 3 per cent of the glacier area, and by 1999 these values increased approximately thrice - up to 0.293 km^2, or 10 per cent of the glacier. In general, debris cover expansion rate is inversely proportional to mass balance: the least areal increment occurred during the prevalence of positive mass balance values. Comparison of a pair of debris thickness surveys, held in 1983 and 1994 over the entire debris-covered part of the Djankuat Glacier and mapped minutely (Popovnin and Rozova, 2002), reveals the increase of both average debris thickness (26 cm in 1983 and 39 cm in 1994) and values of its local maxima (183 and 280 cm, correspondingly). Such thicknesses of lithogenic envelope promote attenuation of sub-debris thawing, and this process is particularly significant (reduction up to 25%) for the lowermost zones of the snout. The growth of supraglacial moraine, including the above-mentioned effect of recent intensification of rockfalls and stone collapses from the revetment of the firn basin, leads to hypsometrical differentiation of the snout surface. Nowadays, for instance, the left, debris-covered stream of the snout, whose substrate ice is insulated from the exterior energy fluxes, towers *ca.* 20-25 m above the adjacent streams of the clean ice.

Alongside with areal changes and terminal fluctuations, a reliable indicator of the glacier state is alteration of its surface elevation (Table 3). During the IHD the predominant lowering of the glacier surface was registered. Afterwards, in 1974-1984 and 1984-1992, differentiation of the Djankuat Glacier area by the resultant hypsometrical effect increased essentially: surface rising began to be detected on considerable parts of the accumulation area and firnline migration belt. In 1984-1992, parts of the glacier area where surface rise and surface lowering were observed became approximately equal. A local zone of surface rising was also formed on the snout - along its debris-covered left margin. However, the final time interval, 1992-1999, was marked by drastic reduction of the glacier area share where surface rising took place. The registered decrease of the Djankuat Glacier thickness occurred even more intensively than during the IHD period.

As a whole, between 1968 and 1999 the Djankuat Glacier surface lowered almost by 6 m in water equivalent. Its local maxima, *i.e.* sites with the largest depression values, gravitated towards the lowermost, debris-free, part of the snout. In some of these sites the total hypsometrical effect reached -28 m w.e., whereas its mean value, averaged over the whole ablation area, came to -10.5 m. In firnline migration belt the surface became *ca.* 5 m lower as well as in the nourishment area and on firn/ice revetment -4 and 5.3 m, correspondingly (Fig. 6). Discrete and areally limited plots of surface rising are sited first of all below the Djantugan Pass in the nourishment area and in the zones of continuous debris cover. The share of the glacier area with the resultant surface rising after the whole 34-year-long period is less than 13 per cent.

8. Conclusion

In spite of the fact that the period of direct observations at the Djankuat Glacier lasts no more than a third of a century by now (that is too small in comparison with the glaciation life in the Caucasus), this time span embraces different phases of the present glacier evolution. The stage of active deglaciation, dominant up to the late 1970s, was followed by a period much more favourable for the glaciers in the Caucasus, during which many glaciers considerably decelerated their retreat rate and some, including the Djankuat Glacier, came to the quasi-stationary position, complicated even by episodes of re-advance. This period seems to have ceased in 1997, because climate in consequent years hardly promoted conservation of ice and water resources, stored in the glaciers of the Caucasus. It is not obvious still whether the recent years signify the new whorl of resumed glacier degradation in the Caucasus or if they represent only casual fluctuation of the natural dynamics of atmospheric processes. All the more, it is particularly important now to continue the complex monitoring of the representative glacier, uninterrupted since 1960s, as a reliable basis of judgements concerning evolution of the entire glacial system in the Caucasus.

Acknowledgments

The research was a part of a project "Features of present evolution of continental and maritime mountain glaciers", supported by Institute of Low Temperature Science, Hokkaido University, Japan. It was also supported by the Russian Foundation of Basic Research (grant No. 03-05-64973a). The authors are indebted to D.Petrakov and A.Aleynikov for their efficient participation in the fieldwork as well as for their precious assistance when preparing the manuscript. Our special thanks are to H. Jiskoot for her fruitful criticism and comments that improved the paper considerably.

References

Aleynikov, A. A. (2001): Relationship between the motion and mass balance of an alpine glacier (Djankuat Glacier, Central Caucasus, as an example). RhD thesis. Moscow, 24 pp. (in Russian).

Aleynikov, A. A., Zolotaryov, Ye. A. and Popovnin, V. V. (2002): Ice divide recognition on twinned glaciers: a case of the Djantugan firn plateau in the Caucasus. Moscow Univ. Herald, ser. 5 "Geography" (3), 36-43 (in Russian).

Baume, O. and Popovnin, V. V. (1994): Langzeituntersuchungen zur Budgetentwicklung des Reprasentativgletschers Dshankuat im Zentralen Kaukasus. In: "Petermanns Geographische Mitteilungen", Gotha, Germany, **138** (5), 273-286.

Chizhov, O. P. (1982): Results of analyzing long-term glacier mass-balance time series. Data of Glaciological Studies, **42**, 170-176 (in Russian).

Djankuat Glacier (1978): Leningrad, Gidrometeoizdat, 184 p. (in Russian).

Golubev, G. N., Dyurgerov, M. B. and Zolotaryov, Ye. A. (1979): Problems of external mass turnover of alpine glaciers at deglaciation stage (a pilot study of the Djankuat Glacier). Data of Glaciological Studies, **36**, 25-33 (in Russian).

Panov, V. D. (1993): Present glacier evolution in the Caucasus. Saint-Petersburg, Gidrometeoizdat, 430 p. (in Russian).

Popovnin, V. V. (1989): The budget evolution of the Djankuat Glacier, representative for the Central Caucasus. PhD thesis. Moscow, 24 pp. (in Russian).

Popovnin, V. V. and Rozova, A. V. (2002): Influence of sub-debris thawing on ablation and runoff of the Djankuat Glacier in the Caucasus. Nordic Hydrology, **33** (1), Lyngby, Denmark, p. 95-110.

Shumskii, P. A. (1964): Principles of structural glaciology. New York, Dover Publications.

Zolotaryov, Ye. A. and Popovnin, V. V. (1993): Hypsometrical changes of the Djankuat Glacier after I.H.D. (1968-1984). Data of Glaciological Studies, **77**, 177-183 (in Russian).
Zolotaryov, Ye. A., Popovnin, V. V., Goretskiy, A. S. and Kharkovets, Ye. G. (1997): The Djankuat Glacier during the last 25 years. Moscow Univ. Herald, ser. 5 "Geography" (1), 24-30 (in Russian).