Earth`s Cryosphere, 2018, vol. XXII, No. 4, pp. 37–48 **http://earthcryosphere.ru/**

DOI: 10.21782/EC2541-9994-2018-4(37-48)

EVALUATION OF THE COMPONENTS OF THE HEAT BALANCE OF THE DJANKUAT GLACIER (CENTRAL CAUCASUS) DURING THE PERIOD OF ABLATION IN 2007–2015

P.A. Toropov[1,2], A.A. Shestakova[3], A.M. Smirnov[1], V.V. Popovnin[1]

[1] *Lomonosov Moscow State University, 1, Leninskie Gory, Moscow, 119991, Russia*
[2] *Institute of Geography, RAS, 29, Staromonetny per., 119017, Moscow, Russia*
[3] *Obukhov Institute of Atmospheric Physics, RAS, 3, Pyzhevsky per., 119017, Moscow, Russia; tormet@inbox.ru*

Analysis of mass-balance data monitoring of the Djankuat Glacier has demonstrated that the severe deglaciation over the past 20 years is associated with the ablation anomaly. We have analyzed the main components of the heat balance during the ablation seasons of 2007–2015 on the basis of meteorological measurements. The quantitative estimates of the accuracy of calculating turbulent heat fluxes using different methods have been presented. It has been revealed that the 'eddy covariance' technique can be used as a reference method. The assessment of the temporal variability of the basic components of heat balance has been carried out. The bulk formulas method seems to be the most accurate among other methods. The contribution of various factors to the formation of the melt layer has been estimated: the fraction of the radiation balance is 50–80 %, and that of turbulent heat exchange is 20–40 %. It has been found for the first time for a Caucasus glacier that turbulent heat-moisture exchange plays a more significant role in the formation of the heat balance than it had been previously. Partly, this can be explained by transformation of the heat balance structure associated with climate change.

Glacio-climatology, Djankuat Glacier, glacier heat balance, turbulent flux

INTRODUCTION

The Djankuat Glacier is one of the objects of the World Glacier Monitoring Service WGMS (http://wgms.ch/) and is considered to be representative of Central Caucasus (Fig. 1) [*Golubev et al., 1978*]. Annual observations over the mass-balance components have been conducted there since 1969. Since the beginning of the 21st century, the mass balance of the Djankuat Glacier has been negative, with a statistically significant trend noted. For example, over the recent 15 years, the mean value of the mass balance has been −500 (±25) mm of the water equivalent, with the value of the standard deviation of the mass balance (σ), calculated for the entire series of observations, being 350 mm for its module, i.e., the mean value of the mass balance for the period of 2000–2015 goes beyond the limits of natural variability. It can be seen from Fig. 2, *b* that intensive ablation is the main cause of the glacier's degradation in the 21st century. The accumulated layer became reduced by approximately 160 mm (Fig. 2, *a*), and the value of the anomaly did not go beyond the limits of natural variability (in 1967–2015 $|\sigma|$ = 200 mm).

The equation of the heat balance of the glacial surface is the main equation in most of the algorithms of evaluating ablation of mountain glaciers. On many glaciers represented in the database of WGMS (http://wgms.ch/latest-glacier-mass-balance-data), complete meteorological measurements are made, with which the components of the heat balance equation are evaluated, allowing the researchers finally to calculate the melting layer, comparing the calculated values with the ablation measurement data. In some studies, evaluations are made exclusively on the basis of the observation data, and only certain parameters (for example, resistance factors in formulae for calculating turbulent heat and moisture fluxes) are determined empirically [*Voloshina, 2001; Mölg and Hardy, 2004; Cullen et al., 2007; Mölg et al., 2008*]. Other researchers take efforts to parametrize the fluxes of direct and dissipated radiation and the level of glacier surface roughness, considering the microrelief specifics [*Hock and Holmgren, 2005; MacDougall and Flowers, 2011*]; dissipated radiation, albedo depending on temperature and intervals between snowstorms in the season of ablation, etc. [*Munro, 1989; Anslow et al., 2008*].

An extensive program of meteorological and hydrological observations was carried out at the stationary base of the Djankuat Glacier in the 1970s [*Voloshina, 2001*]. In 2007, there emerged a possibility of making measurements using modern meteorological equipment, which allowed highly discreet series of meteorological data relating to the Djankuat Glacier to be obtained. In this study, accuracy of calculations of turbulent heat exchange is assessed on the basis of the Djankuat Glacier measurement data by different methods. The contribution of all the components of the heat balance is evaluated, and attempts are made physically to interpret the mechanisms of intense glacier melting observed over the recent decades.

Copyright © 2018 P.A. Toropov, A.A. Shestakova, A.M. Smirnov, V.V. Popovnin, All rights reserved.

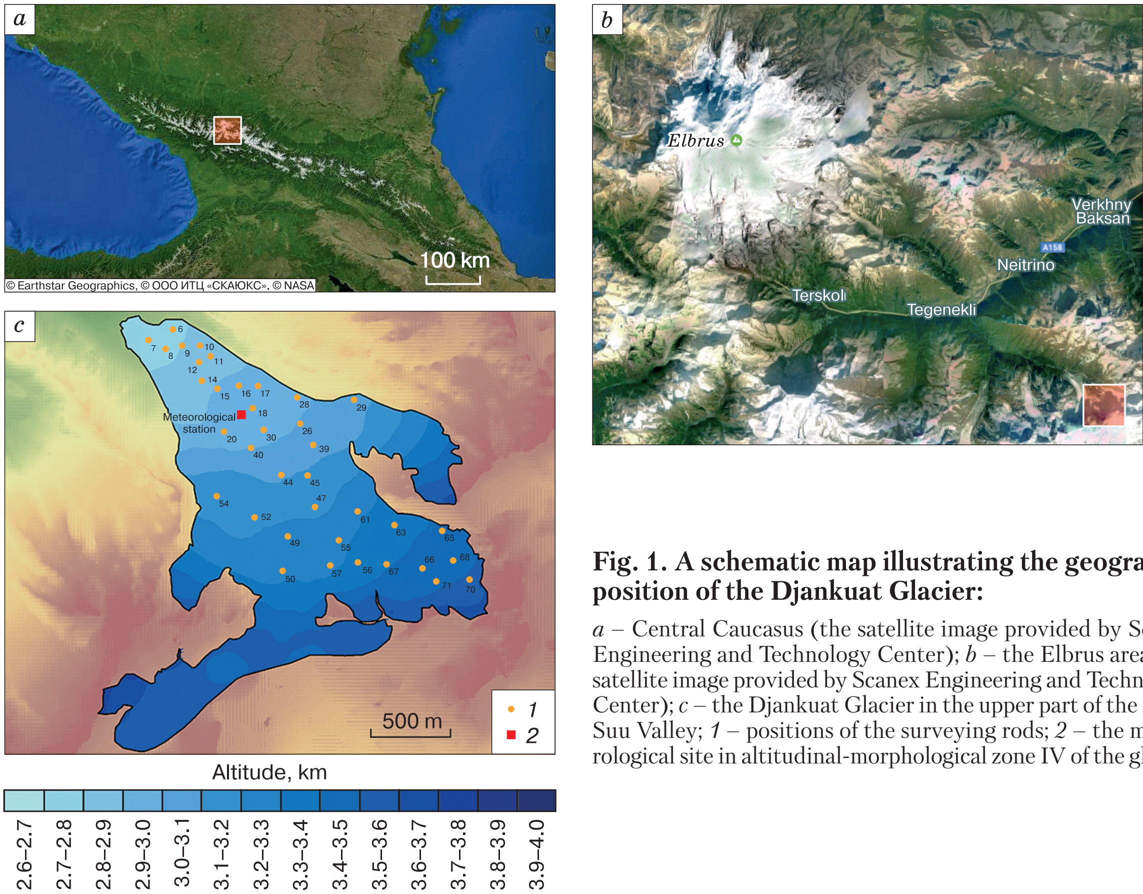

Fig. 1. A schematic map illustrating the geographic position of the Djankuat Glacier:

a – Central Caucasus (the satellite image provided by Scanex Engineering and Technology Center); *b* – the Elbrus area (the satellite image provided by Scanex Engineering and Technology Center); *c* – the Djankuat Glacier in the upper part of the Adyl-Suu Valley; *1* – positions of the surveying rods; *2* – the meteorological site in altitudinal-morphological zone IV of the glacier.

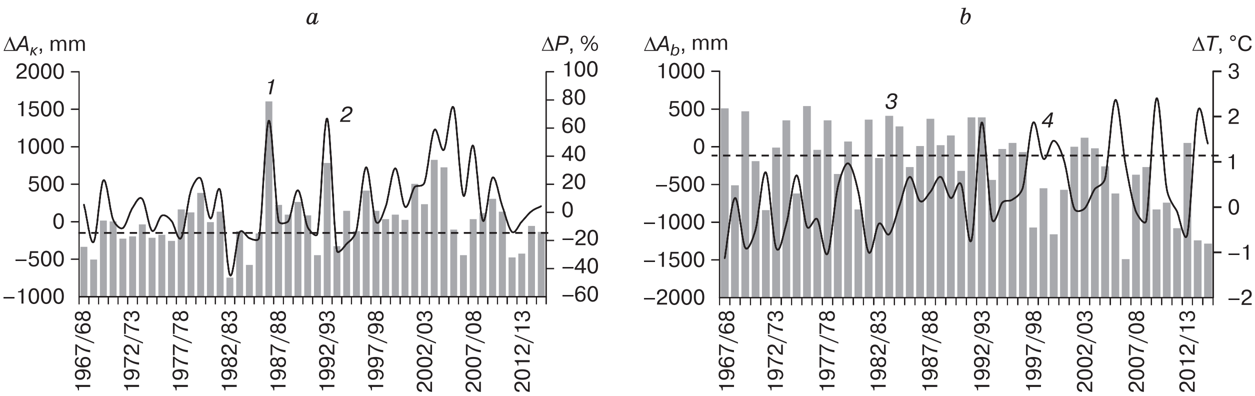

Fig. 2. The time course of the accumulation ΔA_k (*1*) and ablation ΔA_b anomalies (*3*) on the Djankuat Glacier and of respective anomalies of winter precipitation ΔP (*2*) and of summer temperature ΔT (*4*) at the Terskol meteorological station compared to the mean values of the period of 1967–2015.

a – the correlation coefficient is significant and is equal to 0.7; *b* – the correlation coefficient is significant and is equal to 0.64; dashed lines – zero anomalies of accumulation and ablation.

THE DATA AND METHODS OF INVESTIGATION

Description of glaciological and meteorological measurements

The geographic position of the Djankuat Glacier is shown in Fig. 1. The glacier is referred to valley-type glaciers characteristic of Central Caucasus and has stepwise morphology. The orthogonal area of the Djankuat Glacier is 2.688 km^2, and its physical area is 2.93 km^2. The mean surface slope is 23° (on average 15–16° on the glacier tongue, 25–27° in the area of the central icefalls, and 7–8° on the Djantugan Plateau). The glacier facing is mostly north-north-western; the glacier is situated in the altitudinal belt at the altitude of 2700–3700 m. The glacier length in the direction of the main ice flow from the Djantugan Plateau is 3.1 km, its width varies from 500 m on the glacier tongue to 1.5 km in the middle altitudinal-morphological zones. The hosting relief of the glacier, the Greater Caucasus Mountain Range and the Kurmychi Spur, is characterized by alpine rock shapes and the heights of 3800–4100 m.

Every year, mass-balance works are carried out at the glaciological camp of the Moscow State University located on the Djankuat Glacier, including measurements of the maximum thickness of the snow cover before the beginning of the ablation season with the accuracy of 3–7 % (depending on the number of the snow measuring points), density of the snow cover in the base snow pits, and the layer of snow and ice melting measured by surveying rods in the period from the last ten days of May through the last ten days of September [*Popovnin, 1989*]. The average accuracy of assessing daily ablation by surveyor rods is 7 %, and that of seasonal melting is 3 % [*Golubev et al., 1978*].

Meteorological measurements are conducted from mid-June to mid-September, covering the greater part of the ablation season. In some years, due to severe weather conditions or due to a tense political situation in the region, the period of observations proves to be much shorter. In this study, meteorological data are used, obtained by the authors on the Djankuat Glacier in the ablation seasons of 2007–2015 (Table 1). Their brief description is provided below.

1. The main meteorological observations included measurements of the air temperature, relative humidity, wind velocity and direction at the level of 2 m above the glacier surface; actinometric measurements at the level of 1 m above the glacier surface, and measurements of the glacier surface level. The measurements were made in the automatic mode using respective gauges (Table 1), which were connected to the CPU of the CAMPBELL automatic meteorological station (AMS).

2. The DAVIS automatic gradient mast (AGM) included 4 temperature and humidity and 4 wind gauges mounted at the levels of 0.25, 0.5, 1.0 and 2.0 m above the glacier surface. These measurements were conducted only in 2015 in order to obtain profiles of temperature, relative humidity and wind velocity in the near-surface atmospheric layer, required for assessing the turbulent flows of heat and moisture by the Monin–Obukhov method.

3. Measurements of pulsations of three components of the wind velocity and air temperature were made, using a three-component ultrasonic anemometer GILL WindMaster, in order to assess turbulent heat exchange between the glacier and the atmosphere by a direct method.

Table 1. **Types and accuracy of meteorological measurements made on the Djankuat Glacier in 2007–2015**

<table>
<tr><th rowspan="2">Equipment</th><th colspan="5">Accuracy of measured values (by module)</th><th rowspan="2">Period of observations**</th><th rowspan="2">Measurement rate/ frequency</th></tr>
<tr><th>Temperature, °C</th><th>Relative humidity, %</th><th>Wind velocity, m/s</th><th>Components of radiation balance*, W/m²</th><th>Distance to ice surface H, m</th></tr>
<tr><td>VAISALA MT300</td><td>0.2</td><td>5</td><td>–</td><td>–</td><td>–</td><td rowspan="4">15.06.07–30.09.07 (107)
17.06.08–30.09.08 (105)
01.07.09–30.09.09 (91)
09.07.10–29.09.10 (82)
10.07.12–05.08.12 (26)
07.07.13–09.09.13 (64)
19.06.14–30.09.14 (103)
07.07.15–04.09.15 (59)</td><td rowspan="4">15 minutes</td></tr>
<tr><td>CAMPBELL</td><td>–</td><td>–</td><td>0.5–2.0</td><td>–</td><td>–</td></tr>
<tr><td>KEEP&ZONNEN 1</td><td>–</td><td>–</td><td>–</td><td>15</td><td>–</td></tr>
<tr><td>SONIC RANGER</td><td>–</td><td>–</td><td>–</td><td>–</td><td>0.04–0.06</td></tr>
<tr><td>DAVIS AGM***</td><td>0.4</td><td>10</td><td>0.5–2.0</td><td>–</td><td>–</td><td>05.07.15–15.08.15 (41)</td><td>15 minutes</td></tr>
<tr><td>Assmann–Fuss GM****</td><td>0.2</td><td>5</td><td>0.1–0.5</td><td>–</td><td>–</td><td>05.08.10–13.08.10 (9)
12.07.12–15.07.12
21.07.12–25.07.12 (9)</td><td>30 minutes</td></tr>
<tr><td>GILL acoustic anemometer</td><td>0.05–0.10</td><td>–</td><td>0.01–0.05</td><td>–</td><td>–</td><td>12.07.13–03.08.13
09.08.13–16.08.13
26.08.13–06.09.13 (42)
30.06.14–30.07.14 (30)</td><td>10 Hz</td></tr>
</table>

* Fluxes of incoming and reflected shortwave radiation, fluxes of longwave radiation from the atmosphere and the glacier surface.

** Indicated in brackets is the number of days when measurements were made.

*** An automatic gradient mast (AGM), with mounted temperature and humidity and wind gauges DAVIS, the measurements were made at the levels of 0.25, 0.5, 1 and 2 m above the glacier surface.

**** A gradient mast (GM) equipped with Assmann psychrometers and Fuss anemometers; the measurements were made at the levels of 0.25, 0.5, 1 and 2 m above the glacier surface.

The methods of calculating the components of the heat balance

Analysis of the equation of the heat balance and its reduction. In general terms, the equation of the glacier's heat balance is written as follows:

$$c_i \rho_i h \frac{\partial T_h}{\partial t} + L_i \rho_i \frac{\partial h}{\partial t} = \left(SW^- - SW^+\right) - \left(LW^+ - LW^-\right) + $$
$$+ H + LE - Q_D + P_{liq} + F_{liq}. \quad (1)$$

Here T_h is the temperature of the ice layer (K) with thickness h (m); c_i – heat capacity of ice, J/(kg·K); ρ_i – ice density, kg/m^3; L_i – specific heat of ice melting–freezing, J/kg; components of the radiation balance (W/m^2): SW^- – incoming shortwave (solar) radiation, SW^+ – reflected shortwave radiation, LW^+ – upward longwave radiation flux (from the glacier surface), LW^- – downward longwave radiation flux (from the atmosphere); sensible heat turbulent flux $H = c_p \rho k \frac{\partial T}{\partial z}$ (W/m^2) and latent heat turbulent flux $LE = \rho k \frac{\partial q}{\partial z}$ (W/m^2) (where T – temperature, q – mass fraction of water vapor, measured at the levels z = 0.25, 0.5, 1, 2 m (Table 1); k – coefficient of turbulent heat exchange, m^2/s; c_p – heat capacity of air, J/(kg·K); ρ – air density, kg/m^3; L – specific heat of evaporation/condensation, J/kg; E – rate of evaporation/condensation, kg/(m^2·s)); $Q_D = \frac{\partial}{\partial \xi} \lambda_i \frac{\partial T_i}{\partial \xi}$ – heat flux due to molecular diffusion in the glacier mass (T_i – ice temperature at different depths ξ, m; λ_i – coefficient of heat capacity of ice, W/(m·K)); P_{lig} – heat flux due to liquid precipitation, W/m^2; F_{lig} – heat brought by waterflows formed on the glacier surface, W/m^2.

Applying equation (1) to the Djankuat Glacier (and to most glaciers of Northern Caucasus), certain reductions may be made. In summer, the temperature stratification of warm glaciers of the temperate latitudes is, as a rule, close to indifferent, with its value in the ice mass assumed to be invariant and close to 0 °C [*Kotlyakov, 1994*]. Therefore, the first term in equation (1) and the value Q_D may be neglected. We can evaluate the heat flux from liquid precipitation:

$$P_{liq} = \rho C_w \Delta T h,$$

where ρ – water density, kg/m^3; C_w – its heat capacity (4220 J/kg); ΔT – difference of temperatures between a rain drop and ice, °C.

Let us assume that 10 mm of liquid precipitation fell on the glacier during a day, and the temperature pf the raindrops at the moment of touching the ice was equal to the mean surface air temperature for the ablation season (7 °C). Then the daily heat flux from the 10-mm layer of liquid precipitation will be approximately 0.3 mJ/m^2, or about 1 % of the entire energy of daily melting. The contribution of this value may be significant only in case of extreme rainfall in the melting season (more than 50 mm per day) observed at these altitudes approximately once every ten years. Similar evaluations of the heat flux with rain P_{lig} and water flows F_{lig} (about 2 % of the sum of the radiation balance [*Poggi, 1977; Voloshina, 2001; MacDougall and Flowers, 2011*]. Based on this, in the problem of daily and seasonal assessments of the components of the heat balance, the values P_{lig} and F_{lig} may be neglected.

Finally, equation (1) may be reduced to the following:

$$L_i \rho_i \frac{\partial h}{\partial t} = \left(SW^+ - SW^-\right) + \left(LW^+ - LW^-\right) + H + LE. \quad (2)$$

Introducing the value of albedo $A = SW^- / SW^+$, equation (2) may be written as:

$$L_i \rho_i \frac{\partial h}{\partial t} = SW^+(1 - A) + \left(LW^+ - LW^-\right) + H + LE. \quad (3)$$

If we indicate the value $L_i \rho_i \frac{\partial h}{\partial t}$ as Q_{melt} (the quantity of heat required for ice melting), and expression $SW^+(1 - A) - (LW^+ - LW^-)$ – as R (radiation balance), equation (3) may be written in the general form:

$$Q_{melt} = R + H + LE. \quad (4)$$

The components of equation (4) were evaluated by many researchers [*Ohmura, 2001; Hock, 2003; Mölg and Hardy, 2004; Mölg et al., 2008; Wheler et al., 2014*]. In most cases, the radiation balance R (50–85 %) makes the maximum contribution, followed by turbulent heat exchange H (10–50 %). The flux of heat produced during condensation of water vapor on the glacier surface proves to be least significant; yet, its contribution is sizable (2–10 %).

At the stationary gauging station of the Djankuat Glacier, the components of the radiation balance are measured with modern radiometers KEEP&ZONNEN rather precisely (Table 1). However, additional errors occur due to deviation of the position of the radiometers from the horizontal level on the melting ice surface and due to moisture condensing on the gauges' working surfaces. Therefore, during procession of the data, about 10 % of the measured values have to be discarded, and the final accuracy of the measurements of radiation fluxes is taken to be equal to ±25 W/m^2.

Consider the main methods of evaluating turbulent heat and water exchange between the glacier and the atmosphere, which were used in this study. It is to be noted that the differentials used in determining the fluxes are replaced with the end differences due to inevitable spatial-temporal discreteness of measurements.

The heat balance method is based on analysis of the terms of equation (4). The value of radiation balance R is known from the measurements. The quantity of heat spent on ice melting Q_{melt} during a certain time span (hours, days) is evaluated as the product of multiplication of the melted ice layer Δh measured with the Sonic Ranger by the value $L_i \rho_I$. To evaluate turbulent heat fluxes and quantities of heat on evaporation, let us introduce the Bowen ratio:

$$\mathrm{Bo} = \frac{H}{LE} = \frac{c_p}{L}\frac{\Delta T}{\Delta q},$$

which is determined by the measured vertical temperature gradients and by the mass fraction of water vapor over ice. In case of the absence of gradient measurements, the difference is evaluated between the air temperature measured at the level of 2 m above ice and the temperature in the layer of air directly adjacent to the glacial surface (the viscous laminar sublayer), which under conditions of ablation is taken to be equal to 0 °C. In the same way, the water vapor gradient is evaluated: it is measured at the level of 2 m, while in the viscous laminar sublayer it corresponds to the state of saturation at the temperature 0 °C (in the case of the conditions of the Djankuat Glacier, it is equal to 5.6 GPa). Using the Bowen ratio, we can determine turbulent fluxes of heat and water vapor from transformed equation (4):

$$LE = \frac{Q_{melt} - R}{\mathrm{Bo} + 1}, \; H = LE \cdot \mathrm{Bo}.$$

In case of technical problems with the Sonic Ranger, we used an empirical formula, which allowed calculation of the ice melting layer h by meteorological parameters [*Rets et al., 2011*]

$$h = \frac{R + H + LE}{L}.$$

In this case, the turbulent fluxes of heat and water vapor were calculated by the ratios proposed in [*Kuzmin, 1961*]:

$$H = (\alpha_1 + \beta_1 u_2)(T_2 - T_0),$$

$$LE = (\alpha_2 + \beta_2 u_2)(e_2 - e_0).$$

Here u_2, T_2, e_2 are the wind velocity, the temperature and the partial pressure of the water vapor at the height of 2 m above the glacier surface: T_0 is the temperature of the glacier surface taken to be equal to 0 °C under conditions of ablation; e_0 is the corresponding value of the saturation pressure, equal to 6.1 GPa; α_1 = 3.37, β_1 = 1.83, α_2 = 0.7, β_2 = 0.38 are empirical coefficients considering the contribution of thermal convection and the turbulent exchange above the ice and snow surface. Hereinafter the used application of the heat balance method is stated as 'the Kuzmin method' [*Kuzmin, 1961*].

The Monin–Obukhov method is one of the most advanced methods in geophysical hydrodynamics, in particular, in atmospheric physics, and is based on dimensional analysis [*Monin and Yaglom, 1965*]. The essence of the method consists in strict expression of the turbulent fluxes of heat, moisture and impulse through universal dimensionless functions, first of all depending on temperature stratification. This method works on condition of horizontal homogeneity of the underlying surface, in supposition of stationarity of meteorological conditions during a given period of time (in our case, 15 minutes), as well as of stability of turbulent flows by height in the near-surface layer. The latter condition allows constant scales for the friction velocity u_*, temperature T_* and specific humidity q_* to be introduced, which are then used for developing dimensionless functions:

$$u_* = \sqrt{\frac{\tau}{\rho}}, \quad T_* = -\frac{H}{\kappa c_p \rho u}, \quad q_* = -\frac{E}{\kappa \rho u_*}. \qquad (5)$$

Here τ is the wind friction stress, N/m^2; κ is the Karman constant, equal to 0.4; the remaining variables and constants are determined above. In addition to these dimensionless parameters, parameter of flotation $\beta = g/T$ (g is acceleration due to gravity) is an important value determining intensity of turbulent heat exchange.

Dimensionless vertical profiles of the wind velocity u/u_*, temperature T/T_* and specific humidity q/q_* in the near-surface layer of air, determining turbulent air fluxes, are described by universal functions f, dependent on the dimensionless variable z/L, where z – the height above the glacier surface, and L_{MO} is the so-called scale of the Monin–Obukhov length, which is the only combination of the above mentioned parameters u_*, T_*, β:

$$L_{\mathrm{MO}} = \frac{u_*^2}{\kappa^2 \beta T_*}.$$

The asymptomatic behavior of universal functions at indifferent, extremely stable or extremely unstable stratification has been studied rather thoroughly [*Monin and Yaglom, 1965; Zilitinkevich, 1970*] and is written as follows:

$$f = \begin{cases} \ln(z/L) + \dfrac{10z}{L} & \text{with} \quad z/L > 0, \\ \ln(|z/L|) & \text{with} \quad -0.07 \le z/L \le 0, \\ 0.25 + 1.2(z/L)^{-1/3} & \text{with} \quad z/L < -0.07. \end{cases} \qquad (6)$$

Positive values of the argument z/L_{MO} correspond to stable stratification, the interval $-0.07 \leqslant z/L_{\mathrm{MO}} \leqslant 0$ corresponds to indifferent stratification, the values of $z/L_{\mathrm{MO}} < -0.07$ correspond to unstable stratification (thermal convection regime). Above the glacier surface, stable stratification prevails in summer; therefore, in most cases $f = \ln\left(\frac{z}{L_{\mathrm{MO}}}\right) + \frac{10z}{L_{\mathrm{MO}}}$. We took the level of ice roughness to be constant (considering relative inhomogeneity of the ice surface near the measurement point), equal to 0.01 m, and the fluxes of heat and water vapor were calculated every 15 minutes, in accordance with the above:

$$H = c_p \rho u_* T_*, \quad LE = L\rho u_* q_*. \tag{7}$$

The problem of calculating the fluxes consisted in the search for the scales of velocity u_*, temperature T_* and humidity q_*. In [*Zilitinkevich, 1970*] the principle of calculating u_*, T_*, q_* for an arbitrary number of measurement levels is presented, which we used:

$$a_* = \frac{N_a \sum_{n=1}^{N_a} a_n f(z_n/L) - \sum_{n=1}^{N_a} a_n \sum_{n=1}^{N_a} f(z_n/L)}{N_a \sum_{n=1}^{N_a} f^2(z_n/L) - \left[\sum_{n=1}^{N_a} f(z_n/L)\right]^2}.$$

Here a_*, a_n and f_a are determined depending on the flux of which physical substance is recovered: $a_* = T_*$, $a = T$ for turbulent heat flux; $a_* = q_*$, $a = q$ for the turbulent flux of water vapor; N_a – the number of measurement levels; f – the universal function determined by ratios (6).

Combining the equations for u_* and T_* (5) and one of the equations for the universal function (6) (dependence on stratification), we obtain a system of three трех equations with three unknown variables – u_*, T_*, L. Solving transcendent equations for u_* and T_* by the method of selecting the root, we find all the unknown variables, and for the obtained value of L we calculate the value of q_*. Then it will not be difficult to calculate the turbulent fluxes of heat and water vapor by formulae (7).

The aerodynamic method. In the general form, the formulae for calculating turbulent fluxes and heat and water vapor in the framework of the aerodynamic method are presented as

$$H = c_p k\rho(T_2 - T_0), \; LE = Lk\rho(q_2 - q_0).$$

As in the framework of the method temperature T and water quantity q are measured at two levels (2 m above and near the glacier surface), the only unknown variable is the turbulent heat exchange factor k, which is usually determined as follows:

$$k = \frac{\kappa^2 u}{\left(\ln(z_2/z_0)\right)^2} f(\mathrm{Ri}_b),$$

where z_0 – parameter of surface roughness, which varies for different glaciers from 0.5 to 3 mm, in our case, z_0 = 1 mm; $f(\mathrm{Ri}_b)$ – the function of the Richardson volume number, considering stratification in the near-surface layer of the Earth's atmosphere:

$$f(\mathrm{Ri}_b) = \begin{cases} (1 - 5\mathrm{Ri}_b)^2, & \mathrm{Ri}_b > 0, \\ (1 - 16\mathrm{Ri}_b)^{0.75}, & \mathrm{Ri}_b < 0, \end{cases} \quad \mathrm{Ri}_b = \frac{g}{T}\frac{dT/dz}{(du/dz)^2}.$$

The method of turbulent pulsations (the direct method) presupposes measuring pulsations of three components of the wind velocity (vertical and two horizontal components) u', v', w', temperature T', specific humidity q' in the layer of constant fluxes (the near-surface layer) by using highly sensitive acoustic anemometers, based on the Doppler effect. The fluxes of heat and of water vapor are calculated also by covariances between them:

$$H = c_p \rho_0 \overline{w'T'}, \quad LE = \rho_0 L\overline{w'q'}.$$

(It is possible to read about the calculation technique in more detail in, for example, [*Kaimal and Gairon, 1991; Andreas et al., 2005*].)

The optimal rate of measurements corresponds to the frequency of the lowest pulsations in the atmosphere and constitutes 10–20 Hz. The time of averaging the obtained data is selected in such a way as to ensure statistical stability of the results [*Kaimal and Gairon, 1991*]. As shown by special studies published back in [*Volkov, 1968*], the optimal averaging time is 30 minutes.

RESULTS AND DISCUSSION

Evaluating the methods for calculating ablation

Direct measurements of ice melting with Sonic Ranger, which allowed estimation of the value Q_{melt} in equation (3), in combination with rather precise measurements of the radiation balance R, enabled us to select an optimal method for calculating turbulent fluxes. In other words, the daily sum of the radiation balance R in equation (4) was set by the measurement data and remained invariable, while the values H and LE varied depending on the method of calculation used. The final calculated value of the ice melting layer was compared to the measured value. In order to exclude random errors, noise and statistical overshoots, pentade (five days') evaluations were made.

Consider the results of comparing the methods used shown in Fig. 3. It can be seen that the accuracy of evaluating the ablation layer much depends on the choice of the method of calculating turbulent heat fluxes. The determination factor R^2 demonstrates the accuracy of approximation of the obtained linear dependences. However, the accuracy of the methods themselves should be assessed by the obtained regression equations, which for all the four methods look like the function $Y = kX + b$. It is noteworthy that for all the cases the value b, characterizing systematic overestimation of the melting layer, was 0.10–0.16 m over 5 days. We can assume the error to be related to possible underestimation of the flux of reflected radiation in a specific point of measurement: the albedo of an elementary glacier site with the area of 100 × 100 m, selected in the ablation zone, is a rather variable value, and, as the measurements showed,

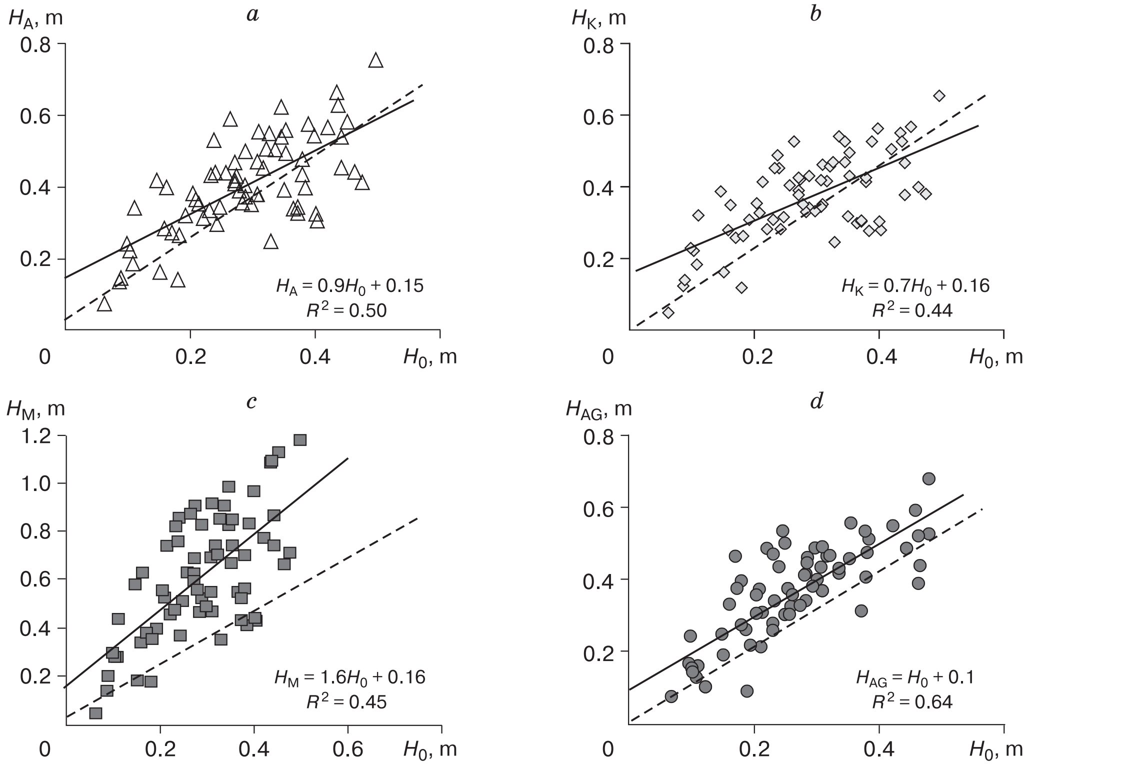

Fig. 3. Dissipation diagrams for comparing the measured thickness of the five days' ablation layer H_0 with the calculated value based on the heat balance equation (3) using different plans of calculating turbulent heat exchange:

a – the method of aerodynamic formulae (H_A); *b* – the Kuzmin method (H_K); *c* – the Monin–Obukhov method (H_M); *d* – the direct method (H_{AG}). Dashed lines – bisecting lines corresponding to ideal matching of the measured values with the calculated ones.

may vary from 0.2 to 0.4. Another cause of overestimation of the total melting layer compared to the measured one may be an assumption that the temperature on the glacier surface and in the roughness layer are equal (0 °C). In reality, this value may be higher than 0 °C, as the glacier surface is a mixture of melting ice with small fragments of moraine material and water. In this situation, the temperature gradient in the near-surface air layer will prove to be less, and hence, the real value of the turbulent heat flux will be somewhat less than the measured value.

Coefficient k in the considered linear relations between the calculated and measured melting layers varies from 0.7 to 1.6. For the method of turbulent pulsations, its value is 1 (Fig. 3, *d*). This means that the calculation of the turbulent flux on the basis of the data obtained with the acoustic anemometer GILL may be considered as model calculation. The operational margin of this method is related only to general overestimation of the melting layer (see the above). The Monin–Obukhov method (Fig. 3, *c*) proved to be the least accurate one: its application to assessment of the turbulent heat flux resulted in over-

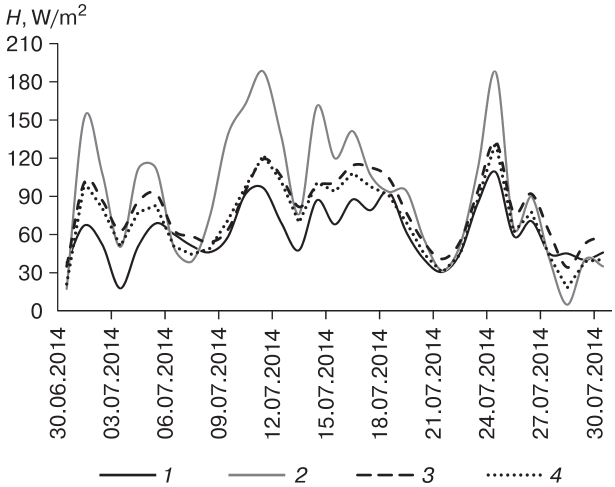

Fig. 4. Comparison of the mean daily values of turbulent heat fluxes H, calculated for July 2014 by the following methods:

1 – the method of turbulent pulsations, *2* – the Monin–Obukhov method, *3* – the Kuzmin method, *4* – the method of aerodynamic formulae.

estimation of the calculated five days' layer of melting compared to the measured one by a factor of 2–2.5, i.e. by 100–150 %. The Kuzmin method was not very successful, either, for which maximum (compared to the other methods) variance of errors is characteristic, which determined the lowest determination factor (0.44). On average, this method underestimates the flux values by 30 % (Fig. 3, *b*). The method of aerodynamic formulae proved to be the most successful one: the mean error without systematic overestimation was 10 %.

Figure 4 is an example of comparing mean daily values of turbulent heat fluxes calculated by using all the methods mentioned in 2014. All the schematics, except for the Monin–Obukhov method, reproduce the day-from-day variation of the turbulent heat exchange quite well. Maximum errors are noted for days with little clouds, and on the days with fohns, when the conditions of stationarity are essentially disturbed.

Temporal variability of the heat balance components

Shown in Fig. 5 are examples of day-to-day variation of the heat balance components in morphological zone IV of the Djankuat Glacier, which were calculated by the method of aerodynamic formulae, which proved to be most precise. In all the selected cases, 3–7 days' periodicity is observed in the temporal variability of the heat balance components, corresponding to the period of meteorological variability, which under conditions of the alpine region of Caucasus is primarily manifested in the situation of cloudiness, and hence, of the radiation balance. In the year with significant repeatability of days with little clouds (for example, in 2014), the correlation coefficient between the mean daily quantities of heat spent on melting and the radiation balance was –0.94 (Fig. 5, *d*), whereas under conditions of the cloudiest season of ablation (2008), it was only –0.6. In the remaining years, the correlation coefficient varied from

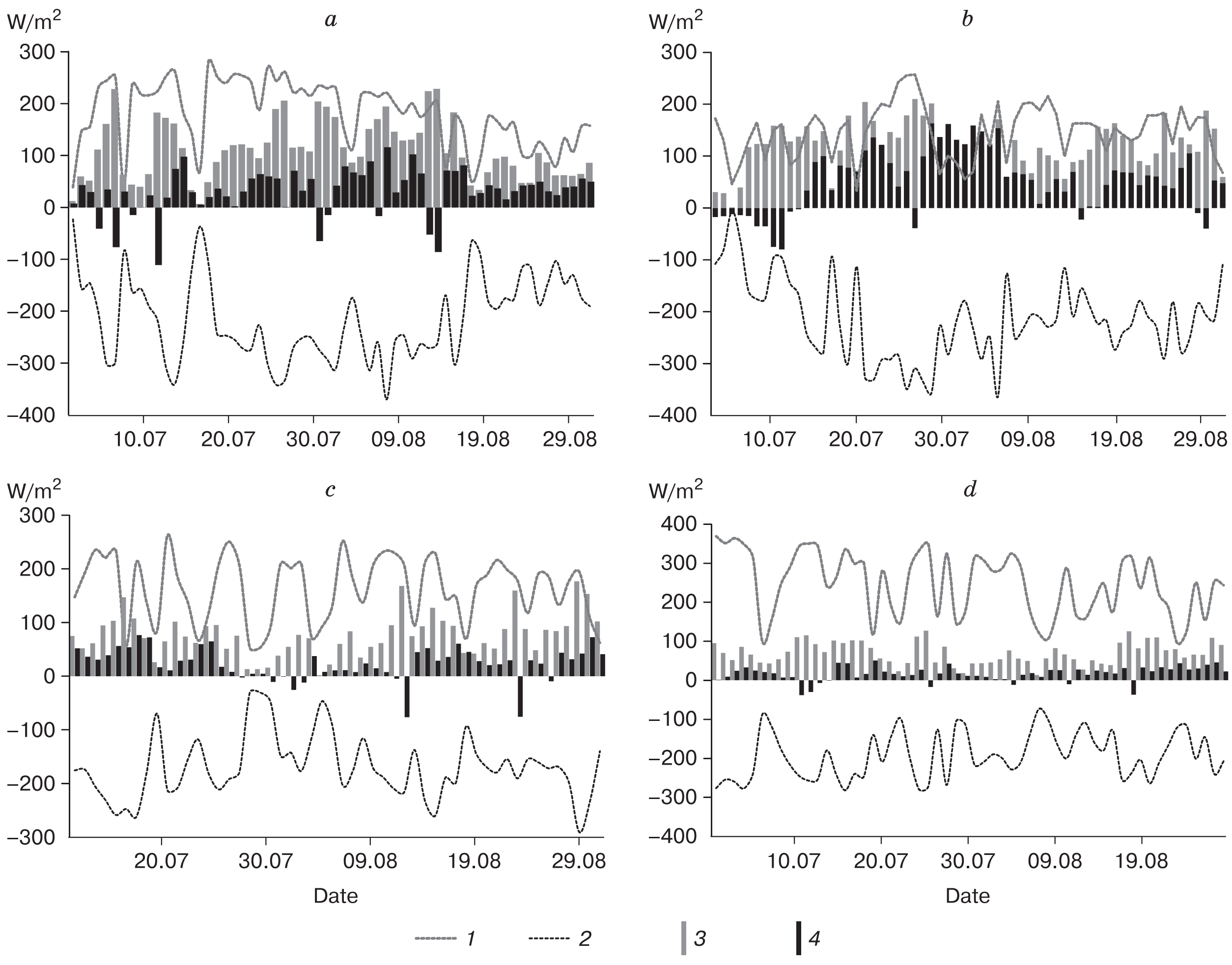

Fig. 5. The time course of the heat balance components on the Djankuat Glacier in the active ablation period (July–August).

a – 2007, *b* – 2008, *c* – 2013, *d* – 2014; *1* – radiation balance; *2* – quantity of heat spent on ice melting; *3* – turbulent heat exchange; *4* – quantity of heat spent on evaporation.

Table 2. **Mean daily meteorological values on the Djankuat Glacier in 2007–2015, averaged for the ablation season (July–August)**

Year	Main meteorological parameters							Radiation balance components*, W/m^2				Melting characteristics**	
	Air temperature T, °C			Relative humidity F, %		Wind velocity U, m/s							
	mean	min	max	mean	min	mean	max	SW^+	SW^-	LW^+	LW^-	M, W/m^2	H, mm
2007	8.0 (±2.6)	0.4	13.5	66 (±19)	13	3.8 (±1.7)	8.4	247 (±99)	68 (±39)	280 (±27)	314 (±3)	–302 (±130)	–3960
2008	8.1 (±2.1)	2.3	13.9	72 (±15)	24	4.2 (±1.8)	9.3	237 (±105)	88 (±58)	291 (±26)	315 (±4)	–276 (±105)	–2840
2009	6.0 (±2.5)	–0.5	14.2	76 (±13)	36	3.8 (±1.7)	9.0	225 (±88)	71 (±48)	286 (±29)	313 (±8)	–234 (±110)	–2740
2010	8.3 (±2.2)	2.9	15.2	68 (±14)	31	4.2 (±1.3)	8.5	265 (±84)	43 (±15)	293 (±21)	317 (±5)	–300 (±100)	–3300
2012	7.7 (±2.0)	1.7	15.2	71 (±15)	31	3.9 (±1.6)	7.9	267 (±104)	57 (±25)	290 (±19)	323 (±3)	–290 (±117)	–3550
2013	5.0 (±2.2)	–0.7	10.7	77 (±12)	40	3.5 (±2.0)	10.5	225 (±98)	53 (±30)	300 (±22)	325 (±4)	–235 (±121)	–2420
2014	7.6 (±2.1)	2.4	14.7	67 (±16)	18	3.6 (±1.6)	8.3	274 (±111)	47 (±18)	306 (±18)	293 (±6)	–308 (±133)	–3710
2015	8.8 (±2.8)	–0.1	17.9	65 (±17)	15	4.0 (±1.8)	8.9	308 (±78)	75 (±22)	357 (±10)	332 (±5)	–322 (±120)	–3754
Mean value	7.5 (±2.3)	1.1	14.4	70 (±17)	25	3.9 (±1.7)	8.9	231 (±94)	63 (±25)	300 (±10)	317 (±5)	–283 (±116)	–3276

Note. Shown in brackets are standard deviations of the respective values.

* SW^+ – incoming shortwave (solar) radiation; SW^- – reflected shortwave radiation; LW^+ – longwave (thermal) radiation of the atmosphere; LW^- – longwave radiation of the glacier surface.

** M – mean daily heat spent on ice melting; H – total yearly ablation.

–0.65 to –0.81. Less variable relation is observed between the quantities of heat spent on melting and turbulent heat exchange: the rated correlation coefficient varies in the range of –0.74...–0.85. The statistically significant relation between the value of the heat flux due to condensation of water vapor on the glacier surface and the quantities of heat spent on melting was found only for 2008 to constitute –0.64.

The mean values of the radiation balance components and of the respective meteorological values in the period of 2007–2015 are shown in Table 2. On the Djankuat Glacier, the wind velocity is characterized by the lowest year-to-year and day-to-day variability: year-to-year variability does not exceed 1 m/s. This stability is explained by the prevalence of the glacial wind, which blows in the ablation zone of the Djankuat Glacier in 80 % cases. Relative humidity (about 10 %) is characterized by comparatively low year-to-year variability, although day-to-day variability of this value may be significant (its minimum values during fohns reach 13–18 %). The air temperature at the level of 2 m above the glacier surface is more variable: on average for the season of ablation, it is +7.5 °C; however, the mean-square deviation reaches 2.3 °C. Year-to-year variability is closely connected with variability of incoming shortwave radiation, and hence with the quantity of heat spent on melting (Table 2).

Table 3 demonstrates sums of the components of the radiation balance in the period of maximum ablation. Maximum values of incoming shortwave radiation and of the radiation balance as such are demonstrated in 2009 and in 2013. As shown in Table 2, negative anomalies of temperature averaged for the period correspond to this period. An interesting exception is the year of 2008, characterized by the minimum sum of the radiation balance (13.2 mJ/m^2), with the air temperature being +8.1 °C, which is higher than the mean annual value by 0.6 °C. This is connected with the role of meteorological processes in formation of the temperature regime: the cyclonic character of the weather in the ablation season of 2008 accounted for the high repeatability of cloudy days and frequent advection of warm air from tropical latitudes. Significant variability of albedo is noted for the observation point within the ablation zone: with the mean value of 23 %, the mean seasonal values vary from 18 to 32 %. Evaluation of the spatial-temporal variability of albedo, related to snowfalls of different intensity in the beginning and end periods of the ablation season [*Voloshina, 2001*], as well as evaluation of the precipitated atmospheric aerosol [*Lim et al., 2017*], are important issues of the heat balance problems of glaciology. Measurements in one point analyzed in this study have a physical meaning; however, they do not fully demonstrate the flux of reflected radiation.

Table 3 and Fig. 6, *a* demonstrate year-to-year variability of the structure of the heat balance of the Djankuat Glacier. Maximum values of the ablation layer even on the basis of such a small sample are not always related to the mean air temperature. Two types of distribution of the contribution of different factors are identified. The first type is characterized by the dominant role of the radiation balance (up to 70–80 %), while the second type is related to the commensurable contribution of the radiation balance to ice melting (50–65 %) and the turbulent heat flux (30–40 %). This type is always found against the background of the positive temperature anomaly in

Table 3. **Total components of the heat balance (mJ/m^2) on the Djankuat Glacier in the period of the highest ablation in 2007–2015**

Year	SW^+	SW^-	LW^+	LW^-	A, %	R	H	LE	Q_{melt}	Q^0_{melt}
2007	26.1	4.9	24.6	27.3	19	18.5 (57–71)	11.3 (35)	2.6 (8)	–32.4	–26.2
2008	21.8	7.1	26.0	27.5	32	13.2 (48–58)	11.2 (41)	3.0 (11)	–27.4	–23.9
2009	20.2	4.7	26.1	27.3	23	14.3 (58–71)	7.6 (31)	2.9 (12)	–24.8	–20.2
2010	22.5	4.0	25.6	27.4	18	16.7 (54–65)	11.5 (37)	3.0 (10)	–31.2	–25.8
2012	22.9	4.9	25.1	27.9	21	15.2 (51–60)	11.5 (39)	3.0 (10)	–29.7	–25.2
2013	20.7	4.9	26.2	27.9	24	14.1 (61–70)	6.2 (27)	2.9 (12)	–23.2	–20.2
2014	24.2	4.5	26.4	25.3	19	20.8 (73–78)	5.1 (18)	2.6 (9)	–28.5	–26.6
2015	26.6	6.4	28.9	26.7	24	22.4 (69–80)	7.4 (23)	2.7 (8)	–32.5	–27.9
Mean value	23.1	5.2	26.1	27.2	23	16.9 (59–69)	9.0 (31)	2.8 (10)	–28.7	–24.5

Note. A – glacier surface albedo, R – radiation balance (shown in brackets is its contribution to melting in accordance with the calculations (the first value) and on the basis of measurements (the second value), %); H, LE – turbulent fluxes of heat and moisture, respectively (shown in brackets are their contributions to melting in accordance with the calculations, %); Q_{melt} – calculated quantity of heat spent on melting; Q^0_{melt} – quantity of heat spent on melting obtained on the basis of measurement data.

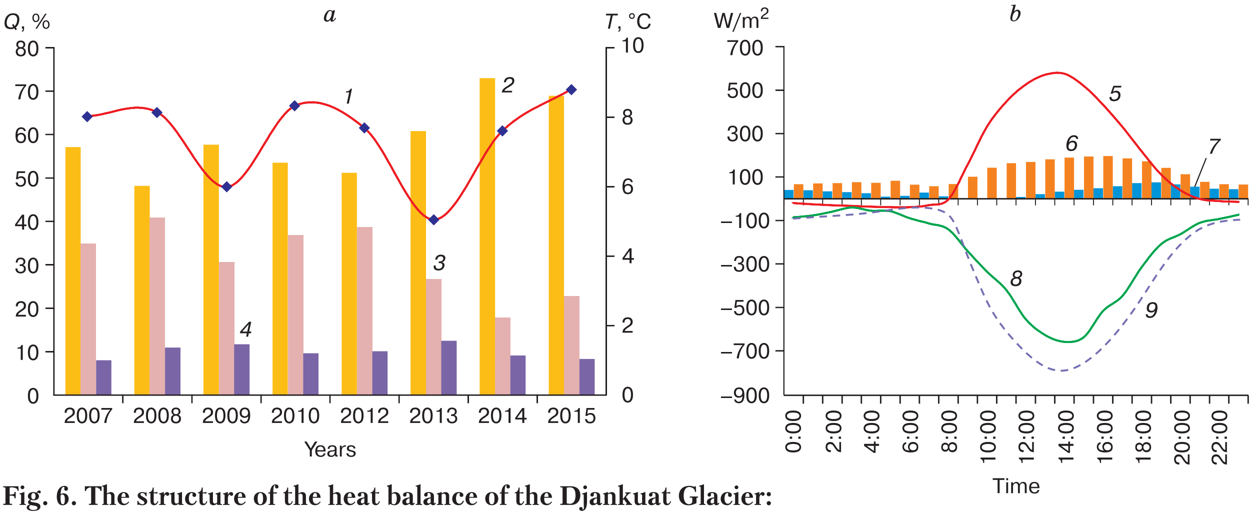

Fig. 6. The structure of the heat balance of the Djankuat Glacier:

a – on average for the periods of intense ablation in 2007–2015 (*1* – mean daily air temperature, *2* – contribution of the radiation balance, *3* – contribution of the turbulent heat flux, *4* – contribution of the condensation heat); *b* – the daily course of the heat balance components averaged for all the ablation seasons (*5* – radiation balance, *6* – turbulent heat flux, *7* – heat of condensation deposited on the glacier surface, *8* – quantity of heat spent on ice melting according to measurements, *9* – calculated quantity of heat spent on ice melting).

the period of active ablation, while the former type may be observed both amid an anomalously warm season (2007, 2015) and amid an anomalously cold season (2009, 2013). This is explained by the fact that the contribution of the radiation factor to ice melting is primarily determined by incoming shortwave radiation, which depends on cloudiness. The high fraction of the turbulent heat flux is recorded in those years when the air temperature is consistently higher than average; therefore, the temperature gradient in the near-surface layer of air is higher than average. Such a situation may be observed under any meteorological conditions.

Table 4 shows a comparison of results obtained in this study with the data provided by other authors on the mountain glaciers of the temperate climatic zone [*Poggi, 1977; Takeuchi et al., 1999; Ohmura, 2001; Voloshina, 2001*]. The prevailing role of the radiation balance is typical of glaciers in the range of altitudes 2200–3200 m above sea level, while for the glaciers located at the altitudinal levels below 1000 m, the contribution of the turbulent heat exchange (due to greater difference between the temperature of the glacier surface and of the near-surface air, compared to the mountainous regions) is no less important. Generally, it is typical of the glaciation of Central Caucasus, by the example of the Garabashi Glacier and the Djankuat Glacier, that the contribution of the radiation component to ice melting is 70–80 %, that of the turbulent heat flux is 20–30 %,

Table 4. **The mean contribution of the main components of the heat balance and melting of glaciers at temperate latitudes (Q_{melt}) compared to the Djankuat Glacier**

Glacier	Height, m	*R*	*H*	*LE*	Q_{melt}	Δ	Source
Kesselwandferner (Alps)	3240	54	62	−8	−100	−8	[*Ohmura, 2001*]
Ewigshneefeld (Alps)	3366	93	9	−4	−98	0	Ibid.
Aletsgletsher (Alps)	2220	71	21	8	−100	0	»
Medvezhiy (Pamir)	3050	95	5	−3	−97	3	[*Voloshina, 2001*]
Maliy Aktru (Altay)	2340	82	15	3	−100	0	Ibid.
Marukh (Caucasus)	2910	98	1	1	−100	−1	»
Garabashi (Caucasus)	3500	82	18	−9	−91	−9	»
Djankuat (Caucasus)	2950	69	31	10	−100	−10	This study
Ampere glacier (Kerguelen Island)	550	58	25	16	−99	−1	[*Poggi, 1977*]
Moreno (Andes)	480	47	50	1	−98	−2	[*Takeuchi et al., 1999*]
Tyndall (Andes)	620	60	34	5	−99	−1	Ibid.

N o t e. *R* – radiation balance; *H* – turbulent heat exchange; *LE* – heat equivalent of condensation (with the “+” sign) and quantity of heat spent on evaporation (with the “–” sign); Δ – disparity between Q_{melt} and $R + H + LE$, arising to measurement errors and underestimation of values Q_D, P_{lig}, F_{lig} in equation (1). Maximum disparity Δ was obtained by the authors for the Djankuat Glacier. The cause of the disparity is consistent overestimation of the turbulent heat flux (see the above), related to underestimation of the temperature of the ice surface due to the presence of liquid water and of moraine fragments.

whereas the value of *LE* may be both positive and negative (on the Garabashi Glacier the quantities of heat spent on melting prevail, while on the Djankuat Glacier, the condensation heat seems to prevail). The data on the Marukh Glacier are rather difficult to be interpreted: absolute prevalence of the radiation balance (98 %) should be stressed, which is not commented in [*Voloshina, 2001*]. It is likely that such an unusual structure of the heat balance is related to the prevalence of daily measurements and to the insufficient size of the sample.

Figure 6, *b* shows the daily course of the heat balance components averaged for the period of observation on the Djankuat Glacier. In the night hours, ice melting is fully determined by turbulent heat exchange, which is especially high in the case of fohns. This is a well-known effect, the so-called ‘katabatic contribution’, which is described, for example, in [*Broeke, 1997*]. The calculation methods essentially overestimate the quantities of heat spent on ice melting in the day hours. The possible causes of this effect are considered above.

CONCLUSIONS

Analysis of the data of mass-balance observations conducted on the Djankuat Glacier in the period of 1969–2015 has shown that intense degradation of the glacier over the recent 20 years is mostly related to ablation anomalies, and hence to the specific features of the meteorological regime in the summer season.

Based on the results of meteorological measurements, the main components of the heat balance have been calculated for the ablation season from 2007 to 2015. Quantifications of the accuracy of calculating the turbulent heat fluxes by different methods on the basis of comparison with the measured ablation layer have been obtained. It has been demonstrated that the direct pulsation method, based on measurements made with a three-component acoustic anemometer may be used as a model method. Among the calculation methods of evaluating turbulent heat exchange, the method of aerodynamic formulae is the most precise one: the error module does not exceed 10 %.

Temporal variability of the main components of the heat balance and of the contribution of different factors to formation of the melting layer has been evaluated: the contribution of the radiation balance is 50–80 %, and that of the turbulent heat exchange is 20–40 %. Such a result has been obtained first for the glaciers of Caucasus: the data published in [*Voloshina, 2001*] testify to the much smaller role of the turbulent heat- and moisture exchange in the 60–80s of the 20th century (not more than 20 %). In addition to differences in the techniques and timelines of measurements, the variations revealed may be related to the change in the structure of the heat balance over the recent 15–20 years. In particular, statistically significant increase in the air temperature in the summer season could entail increase in the turbulent heat exchange between glaciers and the near-surface air. The growth of the temperature in the troposphere due to the Clausius–Clapeyron relation could cause the increase in the moisture concentration, which resulted in the increase of the flux of water from the atmosphere to the glacier surface and hence to the growth of the condensation heat.

Considering the IPCC scenarios, in accordance with which global warming will continue in the 21st century (http://www.ipcc.ch/report/graphics/index.php), we may suppose the energy of turbulent heat fluxes to the mountainous glaciers of Caucasus to increase. In addition, the rise of temperature and moisture content of the troposphere will result in the increase of the downward flux of longwave radiation over glacial regions, shown, in particular, in [*Philipona, 2012; Toropov et al., 2016*] and will contribute to the growth of summer ablation.

The study has been conducted with the financial support of RFBR (projects # 17-05-00771 and 15-05-00599).

References

Andreas, E.L., Jordan, R.E., Makshtas, A.P., 2005. Parameterizing turbulent exchange over sea ice: the ice station Weddell results. Boundary-Layer Meteorology 114, 439–460.

Anslow, F.S., Hostetler, S., Bidlake, W.R., Clark, P.U., 2008. Distributed energy balance modeling of South Cascade Glacier, Washington and assessment of model uncertainty. J. Geophys. Res. 113, F02019, DOI: 10.1029/2007JF000850.

Broeke, M.R., 1997. Momentum, heat and moisture budgets of katabatic wind layer over midlatitude glacier in summer. J. Appl. Meteorology 36 (6), 763–774.

Cullen, N.J., Mölg, T., Kaser, J., Steffen, K.l., Hardy, D.R., 2007. Energy balance model validation on the top of Kilimanjaro, Tanzania, using eddy covariance data. Annals of Glaciology 46, 227–233.

Golubev, G.N., Durgerov, M.B., Markin, V.A., Vari, L.B., et al., 1978. The Djankuat Glacier (Central Caucasus). Gidrometeoizdat, Leningrad, 184 pp. (in Russian)

Hock, R., 2003. Temperature index melt modelling in mountain areas. J. Hydrology 282, 104–115.

Hock, R., Holmgren, B., 2005. A distributed surface energy-balance model for complex topography and its application to Storglaciären, Sweden. J. Glaciology 51 (172), 25–36.

Kaimal, J.C., Gairon, J.E., 1991. Another Look at Sonic Thermometer. Boundary-Layer Meteorology 56, 401–410.

Kotlyakov, V.M., 1994. The World of Snow and Ice. Nauka, Moscow, 286 pp. (in Russian)

Kuzmin, P.P., 1961. The Process of Snow Cover Melting. Gidrometeoizdat, Leningrad, 346 pp. (in Russian)

Lim, S., Faïn, X., Ginot, P., Mikhalenko, V., Kutuzov, S., Paris, J.D., Kozachek, A., Laj, P., 2017. Black carbon variability since preindustrial times in Eastern part of Europe reconstructed from Mt Elbrus, Caucasus, ice cores. Atmospheric Chemistry and Physics, European. Geophysical Society (Germany) 17, 3489–3505.

MacDougall, A.H., Flowers, G.E., 2011. Spatial and temporal transferability of a distributed energy-balance glacier melt-model. J. Clim. 24 (5), 1480–1498.

Monin, A.S., Yaglom, A.M., 1965. Statistical Hydromechanics. Part I. Nauka, Moscow, 641 pp. (in Russian)

Mölg, T., Hardy, D.R., 2004. Ablation and associated energy balance of a horizontal glacier surface on Kilimanjaro. J. Geophysical Research, 109, pp. 1–13, D16104, DOI: 10.1029/2003JD004338, 2004.

Mölg, T., Cullen, N.J., Hardy, D.R., Kaser, G., Klok, L., 2008. Mass balance of a slope glacier on Kilimanjaro and its sensitivity to climate. Intern. J. Climatology 28 (7), 881–892.

Munro, D., 1989. Comparison of melt energy computations and albatometer measurements on melting ice and snow. Arctic, Antarctic, and Alpine Research 22, 153–162.

Ohmura, A., 2001. Physical basis for the temperature-based melt-index method. J. Applied Meteorology 40, 753–761.

Philipona, R., 2012. Greenhouse warming and solar brightening in and around the Alps. Intern. J. Climatology 33, 1530–1537.

Poggi, A., 1977. Heat balance in the ablation area of the Ampere Glacier (Kergelen islands). J. Applied Meteorology 16, 48–55.

Popovnin, V.V., 1989. The budget evolution of the representative Djankuat Glacier. Candidate thesis (geography). Moscow, 309 pp. (in Russian)

Rets, E.P., Frolova, N.L., Popovnin, V.V., 2011. Modeling melting of the alpine glacier surface. Led i Sneg 116 (4), 24–31.

Takeuchi, Y., Naruse, R., Satow, K., Ishikawa, N., 1999. Comparison of heat balance characteristics at five glaciers in southern hemisphere. Global and Planetary Change 22, 201–208.

Toropov, P.A., Mikhalenko, V.N., Kutuzov, S.S., Morozova, P.A., Shestakova, A.A., 2016. Temperature and radiation regime of glaciers on slopes of the Mount Elbrus in the ablation period over last 65 years. Led i Sneg 56 (1), 5–19.

Volkov, Yu.A., 1968. Analysis of the spectra of sea disturbance developing under the influence of a turbulent wind. Izv. AN SSSR, physics of atmosphere and ocean, vol. 4, 957–968.

Voloshina, A.P., 2001. The meteorology of mountain glaciers. Materialy Glatsiol. Issled., issue 92, 3–138.

Wheler, B.A., MacDougall, A.H., Flowers, G.E., Petersen, E.I., et al., 2014. Effects of Temperature Forcing Provenance and Extrapolation on the Performance of an Empirical Glacier-Melt Model. Arctic, Antarctic, and Alpine Research 46 (2), 379–393.

Zilitinkevich, S.S., 1970. Dynamics of the Marginal Stratum of the Atmosphere. Gidrometeoizdat, Leningrad, 290 pp. (in Russian)

URL: http://www.ipcc.ch/report/graphics/index.php (submittal date: 14.12.2017).

URL: http://wgms.ch/ (submittal date: 30.11.2017).

Received June 13, 2017