Methodological aspects of heat balance components estimation on mountain glaciers

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Abstract. In this paper we present estimations of heat balance components (primarily, turbulent heat transfer) on the mountain glacier Djankuat calculated using different methods. The estimations are compared with the observations of turbulent fluctuations of wind speed and air temperature derived from sonic anemometer, as well as the automatic meteorological, actinometric and glaciological measurements in the ablation zone of the glacier. It is shown that the method of aerodynamic formulas is the most adequate method for estimating turbulent fluxes over mountain glacier. An attempt was also made to physically interpret a systematic overestimation of the calculated ablation.

1. Introduction

Intensive decrease of mountain glaciation in the last 20 years is associated with both a decrease of solid precipitation in the glacier accumulation zones and an increase in the ablation layer during the warm seasons. For many glacial regions, such as the Alps, the Caucasus, the Altai, as well as North American glacial regions, the ablation seems to play the prevailing role in deglaciation. This hypothesis has a clear climatic interpretation. Winter warming, generally, has little effect on the amount of solid precipitation in the areas of glaciation. Despite the current global warming, the air temperature at altitudes higher than 2500 m meters above sea level (AMSL) remains steadily negative. At the same time, growth of summer temperature entails an increase in the moisture content of the atmosphere and an increase in the greenhouse effect, which leads to further warming. In classical climatology this effect is called "direct feedback" [$Kislov$, 2001].

An example of the Djankuat glacier in the North Caucasus can clearly illustrate the role of ablation. According to the mass-balance observations on this glacier since 1967 [$Popovnin$, 1989], the accumulation layer in the period 2005–2015 decreased by approximately

160 mm (compared with the whole period of observations), and the magnitude of anomaly did not exceed the limits of natural variability, characterized by the standard deviation (RMS) $|\sigma| = 180$ mm. On the contrary, the ablation layer increased by 700 mm in modulus (with $|\sigma| = 220$ mm) over the same decade the magnitude of the anomaly exceeded 3σ and reached extreme values. This means that the mechanism of degradation of mountain glaciers in midlatitudes is directly related to intensive ablation.

Most algorithms of ablation estimation are based on the heat balance equation of the ice surface. In some studies [*Mölg and Hardy*, 2004; *Voloshina*, 2001], estimatimations of the heat balance components are performed almost entirely on the basis of observational data, and only some parameters are determined empirically. Other studies are dedicated to parameterization of the incoming short-wave radiation and the roughness level, taking into account the features of the glacier's microrelief, as well as the flux of reflected radiation as a function of temperature and solid precipitation during the ablation season [*Hock and Holmgren*, 2005; *Wheler and Flowers*, 2011]. Such algorithms take into the account physical mechanisms of melting, but,

as a rule, are "tuned" to a particular glacier. Therefore, another approach to evaluating ablation, called the "temperature index method", is being developed in parallel. It is based on a statistical relationship between the accumulated temperature and the ablation layer [*Krenke and Hodakov*, 1966; *Ohmura*, 2001; *Wheler et al.*, 2014]. In such correlations, various empirical values ("temperature melting factor", "radiation factor of melting" [*Wheler et al.*, 2014]) can be used as a regression coefficients. An obvious advantage of this method is its algorithmic and computational simplicity, and a significant disadvantage is disregarding impossibility of taking into account the spatial variability of the heat balance components of individual glacier.

The idea of current study is closer to the first approach, in which the radiation fluxes are measured quite accurately, and the turbulent heat and moisture fluxes are calculated on the basis of observational data. In this study, calculation of turbulent heat fluxes is performed by different methods. The most accurate method is revealed by a comparison with the direct measurements of turbulent pulsations in the conditions of mountain glaciation using the example of the Djankuat glacier. A physical interpretation of the errors in calculating the heat balance components is also given.

2. Data and Methods

2.1. Observational Data

Mass-balance observations at the glaciological station of the Moscow State University on Djankuat glacier are carried out every year and include measurements of the maximum thickness of the snow cover before the beginning of ablation season. The density of the snow cover in the reference snow pits, and also the measurement of the ice and snow melting using the network of ablation stakes [*Popovnin*, 1989] in the period from the last decade of May to the last decade of September in all morphological zones of the glacier (Figure 1a). An extensive program of meteorological observations was conducted on the Djankuat glacier in the 1970s [*Voloshina*, 2001]. Since 2007, measurements are also carried out with the help of modern meteorological equipment that allows obtaining series of meteorological and actinometric data automatically and with high temporal resolution. In the last 10 years, meteorological measurements are usually conducted from mid-June to mid-September, covering most of the ablation season.

The current program of meteorological measurements on the Djankuat glacier (Table 1) consists of the following parts:
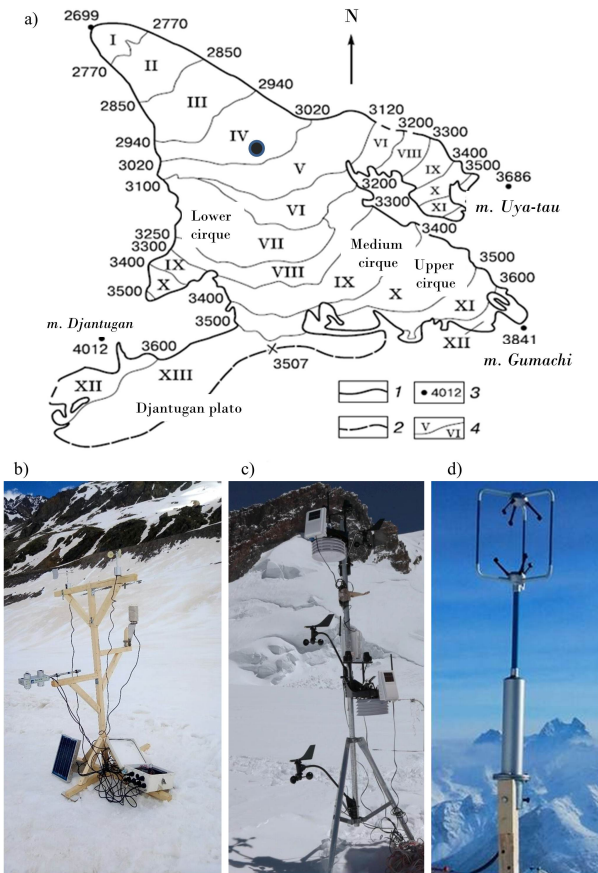
Figure 1. a) Scheme of the Djankuat glacier [*Popovnin et al.*, 2015]: 1 – glacier boundaries, 2 – ice divides, 3 – mountain peaks and their altitudes, 4 – numbers of morphological zones. Black point indicates the location of meteorological site where the following observations are carried out: radiation fluxes and basic meteorological variables from the AWS CAMPBELL (b); basic meteorological variables from gradient mast DAVIS (c); turbulent pulsations of wind and temperature from sonic anemometer GILL (d).

Table 1. Meteorological measurements on Djankuat glacier in 2007–2016 and their accuracy

Data source	Measured value and its accuracy (modulus)					Period of measurements (with number of days in brackets)	Sampling interval
	Air temperature T, °C	Relative humidity F, %	Wind speed V, m/s	Components of radiation balance B, W/m²	Distance "sensor-surface" H, m		
AWS CAMPBELL	0.2	5	0.5–2	15	0.04–0.06	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) 20.06.16–05.09.16 (77) 05.07.15–15.08.15 (41)	15 min
Gradient mast DAVIS	0.4	10	0.5–2	–	–	12.07.13–03.08.13 09.08.13–16.08.13	15 min
Sonic anemometer GILL	0.05–0.1	–	0.01–0.05	–	–	26.08.13–06.09.13 (42) 30.06.14–30.07.14 (30) 17.06.16–01.08.16 (45)	0.1 s

1. Meteorological and actinometric measurements using an automatic weather station (AWS) CAMPBELL (Figure 1b), including measurements of air temperature and relative humidity (Vaisala MT300 sensor), wind speed and direction (Campbell wind sensor) at 2 m AGL; radiation fluxes (KEEP & ZONNEN radiometers – two of them measure an upward and downward short-wave radiation, another two – an upward and downward long-wave radiation); measurements of ablation layer with the Sonic Ranger sensor (the sensor is located on a construction, that is drilled into the body of the glacier, and measures the distance from the sensor to the ice (snow) surface). These automatic measurements were made with interval of 15 min.

2. Gradient mast DAVIS (Figure 2c) includes 4 temperature and humidity sensors and 4 wind sensors located at 0.25, 0.5, 1 and 2 m AGL. These measurements were carried out only in 2015 with the aim of obtaining long time meteorological data series in the surface layer, which are necessary for the turbulent heat fluxes estimation with the Monin-Obukhov method [*Zilitinkevich*, 1972]. These automatic measurements also have record interval of 15 min.
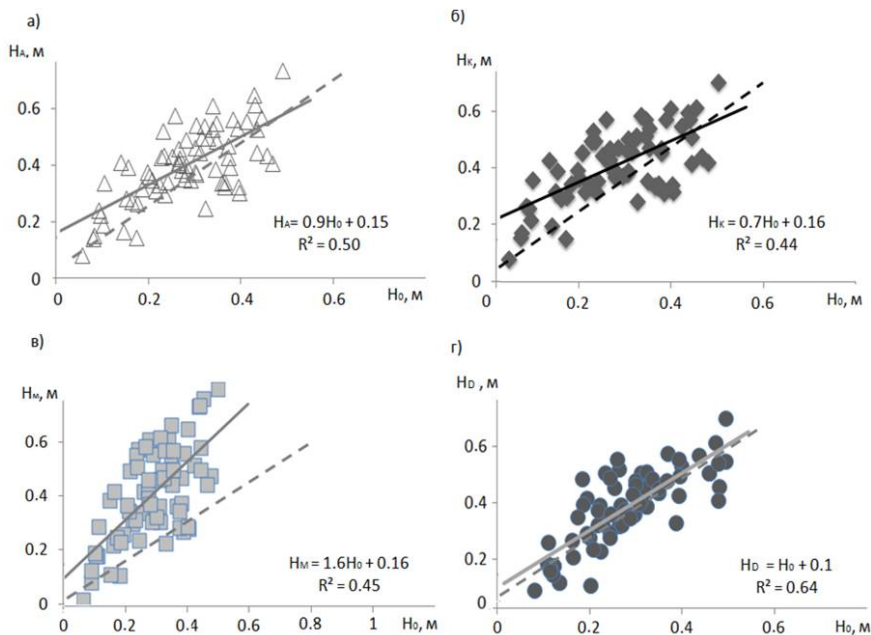
Figure 2. Scatter diagrams of 5-day ablation layer from observations H_0 and calculated from the equation of heat balance using different methods of turbulent heat fluxes calculation: a) aerodynamic formulas method H_A, b) Kuzmin's method h_K, c) Monin-Obukhov method H_M, d) direct method H_D. Dashed lines show bisectors, solid lines – regression curves. There are also regression equations on the plot.

3. Measurements of turbulent pulsations of wind and acoustic temperature with the 3-axis sonic anemometer GILL WindMaster. The measurement frequency is 10 Hz.

Averaged over the ablation periods 2007–2016 values of meteorological variables and radiation balance components on Djankuat glacier are shown in Table 2. It is noteworthy that the interannual variability of averaged over the ablation seasons air temperature is relatively low and in most cases its modulus does not exceed $1°C$. An exception is the negative anomaly of 2009 and 2013, as well as the positive anomaly in 2015. The interannual variability of temperature is in good agreement with that for incoming shortwave radiation, which indicates that the thermal conditions over the glaciers of the North Caucasus are primarily determined by the cloud regime. The wind speed variability is extremely small, due to the absolute predominance (75–80% of cases) of the katabatic glacier wind during the ablation season, whose speed (from average to gusts) varies in the range 4–9 m/s.

Table 2. Daily averaged meteorological variables on Djankuat glacier in 2007–2016 (with RMS in brackets)

Year	Air temperature, °C			Relative humidity, %		Wind speed, m/s		Components of radiation balance, W/m² Albedo A, %				A, %
	Mean	Min	Max	Mean	Min	Mean	Max	SW^+	SW^-	LW^+	LW^-	
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)	19
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)	32
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)	23
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)	18
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)	21
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)	24
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)	19
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)	24
2016	7.6(±2.8)	0.2	15.1	69(±16)	24	3.8(±1.9)	9.0	235(±92)	65(±23)	305(±15)	315(±6)	23
Mean	7.5(±2.3)	1.1	14.5	70(±17)	25	3.9(±1.7)	8.9	231(±94)	63(±25)	300(±10)	317(±5)	23

2.2 Heat Balance Estimation Methods

In general, the equation for the heat balance of a glacier is written as follows:

$$c_i \rho_i h \frac{\partial T_h}{\partial t} + L_i \rho_i \frac{\partial h}{\partial t} = (SW^- - SW^+) -$$

$$(LW^+ - LW^-) + H + LE - Q_m + P_{liq} + F_{liq} \quad (1)$$

Here T_h – temperature (K) of ice layer of thickness h, c_i – heat capacity of ice (J/kg K), ρ_i – density of ice (kg/m^3); L_i – specific heat of fusion (J/kg); SW^- – incoming short-wave radiation (W/m^2); SW^+ – outgoing short-wave radiation (W/m^2); LW^+ – upward long-wave radiation (W/m^2); LW^- – downward long-wave radiation (W/m^2); $H = c_p \rho k (\partial T / \partial z)$ – sensible heat flux (W/m^2), where T – air temperature, k – turbulence coefficient (m^2/s), c_p – air heat capacity (J/kg K), ρ – air density (kg/m^3); $LE = \rho k (\partial q / \partial z)$ – latent heat flux (W/m^2), where q – specific humidity (g/kg), L – specific heat of vaporization-condensation (J/kg), E – evaporation rate (mm/s); $Q_m = (\partial / \partial \xi) \lambda_i (\partial T_i / \partial \xi)$ – molecular diffusion of heat into glacier body (W/m^2), where T_i – ice temperature at levels ξ; λ_i – coefficient of thermal conductivity of ice (W/m K); P_{liq} – heat flux, related to liquid precipitations and freezing of water in the glacier body (W/m^2);

F_{liq} – heat flux, related to watercourses forming on the glacier surface in the ablation zone (W/m^2).

Equation (1) describes ablation process as completely as possible, taking into account most of the factors. For application to the Djankuat glacier (and to most glaciers of "alpine type"), some simplifications could be introduced. For so-called "warm" glaciers ice temperature of near-surface layer of finite thickness is assumed to be unchanged and close to 0°C in the summer, therefore it is often assumed that the first term in equation (1) can be neglected. This type of glacier is also characterized by intensive washing with melt waters into the glacier in the ablation zone, so the temperature distribution in glacial thickness is close to isothermal [$Kotlyakov$, 1994]. This condition can be violated only at the very beginning of the ablation season, when even at comparatively small depths (about 1 m) the ice temperature can be sufficiently lower than 0°C. This is especially true in the case of an abnormally cold winter preceding the ablation season. This assumption may also not be fulfilled in the case of an

abnormal radiative cooling of the glacier surface during the night hours at the end of the ablation season (mainly in September). That is the reason for including the molecular heat flux in some models [*Wheler and Flowers*, 2011]. It should also be noted that the contribution of the so-called submerged melting, or the transfer of heat due to molecular diffusion from the moraine material to the ice surface, can reach significant values – especially with a sharp increase in the amount of moraine material on the surface of the glacier [*Popovnin et al.*, 2015]. Heat flux related to liquid precipitations P_{liq} can play a significant role in the case of heavy rains during ablation season [*Voloshina*, 2001]. The same applies to the heat and mechanical effects of watercourses F_{liq}. However, it is not possible to correctly measure these fluxes. In addition, a number of works [e.g. *MacDougall and Flowers*, 2011; *Voloshina*, 2001] shows that the values of the heat flux of rains and watercourses, as well as the molecular diffusion of heat in the ice column, together do not exceed 2% of the radiation balance, that is, they are within the limits of error of heat fluxes measurement and are negligibly small.

Using these assumptions, equation (1) can be rewrit-

ten in a simplified form:

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

Or, using albedo, $A = SW^-/SW^+$,

$$L_i\rho_i\frac{\partial h}{\partial t} = SW^+ - (1 - A) + (LW^+ - LW^-) + H + LE \tag{2}$$

The equation of heat balance of glacier in the form (2) is used for ablation estimates by many researchers [*Kuzmin*, 1961; *Voloshina*, 2001; *Rets et al.*, 2011]. The first two terms (the radiation balance) are the most important (50–85%), sensible heat flux is on the second place (5–50%), latent heat fluxes is on the third place (less than 5%) [*Hock and Holmgren*, 2005; *Ohmura*, 2001; *Wheler and Flowers*, 2011]. At the Djankuat glacier, components of the radiation balance are measured quite accurately (Table 1). However, an additional unavoidable error is introduced by the deviation of the radiometers position from the horizontal level due to the tilting of weather station on the melting ice surface, and also because of the condensate on the working surfaces of the sensors. After data processing, about 10% of the measured values have to be rejected, and the final accuracy of the measurements of radiation fluxes due to these errors is assumed to be ± 25 W/m^2.

Turbulent heat fluxes can be evaluated in numerous ways, most of which reduces to the following.

Heat balance method.

In equation (2), we denote the quantity $L_i \rho_i (\partial h / \partial t)$ as Q_{melt} (heat consumption for ice melting) and the expression $SW^+(1 - A) - (LW^+ - LW^-)$ as R (radiation balance). Both values are known from observations: the components of the radiation balance are measured by radiometers (Table 1), the ablation layer h_0 for a time interval Δt is measured by Sonic Ranger sensor (multiplying this by $L_i \rho_i$ we get the heat consumption for melting). We introduce the Bowen ratio $B_0 = (H/LE) = (C_p/L)(dT/dq)$, which is derived from measured gradients of temperature and humidity. Using it, we can determine the turbulent heat fluxes from the modified equation (2):

$$LE = \frac{Q_{\text{melt}} - R}{B_0 + 1}, \qquad H = LE \times B_0$$

In cases with no data or erroneous data from Sonic Ranger an empirical formula is used [$Rets\ et\ al.$, 2011; $Volkov\ et\ al.$, 1968]:

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

In this paper sensible H and latent LE heat fluxes are calculated from the relationships proposed in [$Kuzmin$, 1961] (here and below, this application of the heat balance method is called "Kuzmin's method"):

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

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

Here u_2, T_2, e_2 – wind speed, temperature and partial pressure of water vapor at 2 m AGL, T_0 – surface temperature, which is assumed to be $0°$C (this assumption is correct in the absolute majority of cases); e_0 – saturation pressure at the surface (in our case equal to 6.1 hPa); $\alpha_1 = 3.37$, $\beta_1 = 1.83$, $\alpha_2 = 0.7$, $\beta_2 = 0.38$ – empirical coefficients, describing the contribution of thermal convection and turbulent exchange over the ice-snow surface.

Monin-Obukhov method.

This method is one of the most developed in the theory of the surface layer, however, it has a number of limita-

tions, among which is the homogeneity of the underlying surface in a radius ~ 100 m from the measurement point. Parameterization of the roughness length depending on the properties of the micro relief of glacier surface is discussed in some works [e.g. *MacDougall and Flowers*, 2011]. In our calculations the roughness length is constant (because of the relative homogeneity of the ice surface in meteorological site area).

According to the Monin-Obukhov similarity theory [*Zilitinkevich*, 1972], turbulent fluxes are written in terms of parameters determined by the vertical profiles of the corresponding variables:

$$LE = \rho L u_* q_*, \qquad H = \rho C_p u_* T_* \qquad (3)$$

where u_* – friction velocity (velocity scale), T_* and q_* – temperature and humidity scales respectively. Thus, the problem is reduced to finding the scales of speed, temperature and humidity. A calculation scheme for u_*, T_*, q_* for an arbitrary number of measurement levels is presented in [*Zilitinkevich*, 1972]:

$$a_* = \frac{N_a \sum\limits_{n=1}^{N_a} a_n f_a\left(\frac{z_n}{L}\right) - \sum\limits_{n=1}^{N_a} a_n \sum\limits_{n=1}^{N_a} f_a\left(\frac{z_n}{L}\right)}{N_a \sum\limits_{n=1}^{N_a} f_a^2\left(\frac{z_n}{L}\right) - \left[\sum\limits_{n=1}^{N_a} f_a\left(\frac{z_n}{L}\right)\right]^2}$$

Here a_*, a and f_a depends on required variable: $a_* = T_*$, $a = T$ and $f_a = f_T$ for sensible heat flux; $a_* = q_*$, $a = q$ and $f_a = f_q$ for latent heat flux; N_a – number of vertical levels; f_a – universal function, defined as:

$$f_a = f_T = f_q = \begin{cases} \ln\left(\frac{z}{L}\right) + \frac{10z}{L}, & \text{if } \frac{z}{L} > 0 \\[2mm] \ln\left(\left|\frac{z}{L}\right|\right), & \text{if } -0.07 \leq \frac{z}{L} \leq 0 \\[2mm] 0.25 + 1.2\left(\frac{z}{L}\right)^{-1/3}, & \text{if } \frac{z}{L} < -0.07 \end{cases} \tag{4}$$

where L – Monin-Obukhov length:

$$L = \frac{u_*^2}{\kappa \beta T_*}$$

where κ is Karman constant and β – buoyancy param-

eter equal to g/T. If we take the equations for u_* and T_* and the equation for the universal function, we obtain a system of three equations with three unknowns – u_*, T_* and L. Solving the transcendental equations for u_* and T_* by the root selection method, we find all the unknowns and for the resulting L we calculate q_*. Then it is not difficult to calculate turbulent fluxes according to formulas (3).

Aerodynamic (bulk) method.

It is the most often used method in studies dedicated to glacier heat balance. In general, the formulas for the fluxes of sensible and latent heat have the form

$$H = C_p K \rho (T_2 - T_0), \quad LE = LK\rho(q_2 - q_0)$$

The only unknown term is the turbulent exchange coefficient K, because air temperature T and specific humidity q at two vertical levels are measured. It is usually defined as follows:

$$K = \frac{\kappa^2 u}{\left(\ln \frac{z_2}{z_0}\right)^2} f(Ri_b)$$

where z_0 – roughness length, for different glaciers it ranges from 0.5 to 3 mm, in our case $z_0 = 1$ mm; $f(Ri_b)$ – function of bulk Richardson number, which takes into account stratification in the atmospheric surface layer:

$$f(Ri_b) = \begin{cases} (1 - 5Ri_b)^2, & Ri_b > 0 \\ (1 - 16Ri_b)^{0.75}, & Ri_b < 0 \end{cases}$$

where

$$Ri_b = \frac{g}{T}\frac{dT/dz}{(du/dz)^2}$$

Method of turbulent pulsations (or direct method).

It involves measuring the pulsations of three velocity components (vertical and two horizontal) u', v', w' and acoustic temperature in a layer of constant fluxes (surface layer) with sonic anemometer based on the Doppler effect. Heat fluxes are calculated as follows [$Kaimal\ and\ Gaynor$, 1991]:

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

Turbulent pulsations of specific humidity q' and air temperature T' are not measured directly but can be

derived from measured acoustic temperature and wind pulsation [*Kaimal and Gaynor*, 1991]. The required measurement frequency is 10–50 Hz, the averaging interval should be such that the results are statistically stable [*MacDougall and Flowers*, 2011]. Special studies performed in the classical work [*Volkov et al.*, 1968] showed that the optimal average interval is 30 minutes.

In this paper, turbulent heat fluxes are calculated using all the above mentioned methods.

3. Results and Discussions

3.1. Accuracy of Methods in Ablation Layer Estimation

The use of different methods for the calculation of turbulent heat fluxes made it possible to evaluate their applicability for the problem of estimating the ablation layer. Direct measurements of the ablation layer combined with sufficiently accurate measurements of the components of the radiation balance allow to select the most optimal method for calculating turbulent fluxes on the basis of equation (2). Components of radiation balance are estimated from the observation

data and remained unchanged, while the values of H and LE vary depending on the calculation technique described in Section 2. Calculated value of the ablation layer is compared with the measured one.

Scatter diagrams (Figure 2) clearly show that the accuracy of simulation of the ablation layer essentially depends on the choice of the method for calculating turbulent heat fluxes. The coefficient of determination R^2 shows the accuracy of the approximation of the linear regression. However, the accuracy of the methods themselves can be evaluated from the regression equations, which for all four methods have the form $Y = kX + b$. It is noteworthy that for all methods the value of b, which characterizes the systematic overestimation of the ablation layer, is 0.12 m per 5 days. Statistical analysis of the error showed that its distribution is close to the Gaussian distribution, while the RMS is 0.04 m. This means that this error can be considered as systematic, therefore, it can be easily removed. The coefficient k varies from 0.7 to 1.6. It is remarkable that for the method of turbulent pulsations the value of the coefficient is 1 (Figure 2d). This means that the direct method based on the data from sonic anemometer GILL can be considered as the reference. The error of this method is related only to the overall overestima-

tion of the ablation layer. The Monin-Obukhov method is the least accurate (Figure 2c): its application for estimating the turbulent heat flux leads to an overestimation of the calculated five-day melt layer by 2–2.5 times compared to the observed. Kuzmin's method seems to be not very proper as well, although this scheme was developed specifically for turbulent heat and moisture transfer over the snow and ice surfaces [$Kuzmin$, 1961]. It has the greatest variety of errors in comparison with other methods; coefficient of determination is the lowest (0.44). On average, the value of turbulent heat flux is overestimated by 30%. The most correct (besides the method of turbulent pulsations) is the method of aerodynamic formulas: the average error (without systematic error) is -10%.

Figure 3 presents an example of comparing the average daily values of turbulent heat fluxes, calculated by all methods, in 2014. All schemes, except for Monin-Obukhov, successfully reproduce the day-to-day variability of turbulent heat exchange. Large errors of Monin-Obukhov method are apparently associated with variations in the roughness of the glacier surface, as well as with the need to select the parameters of the universal function (4) for a specific glacier. The maximum errors are observed on light-cloud days, as well as on
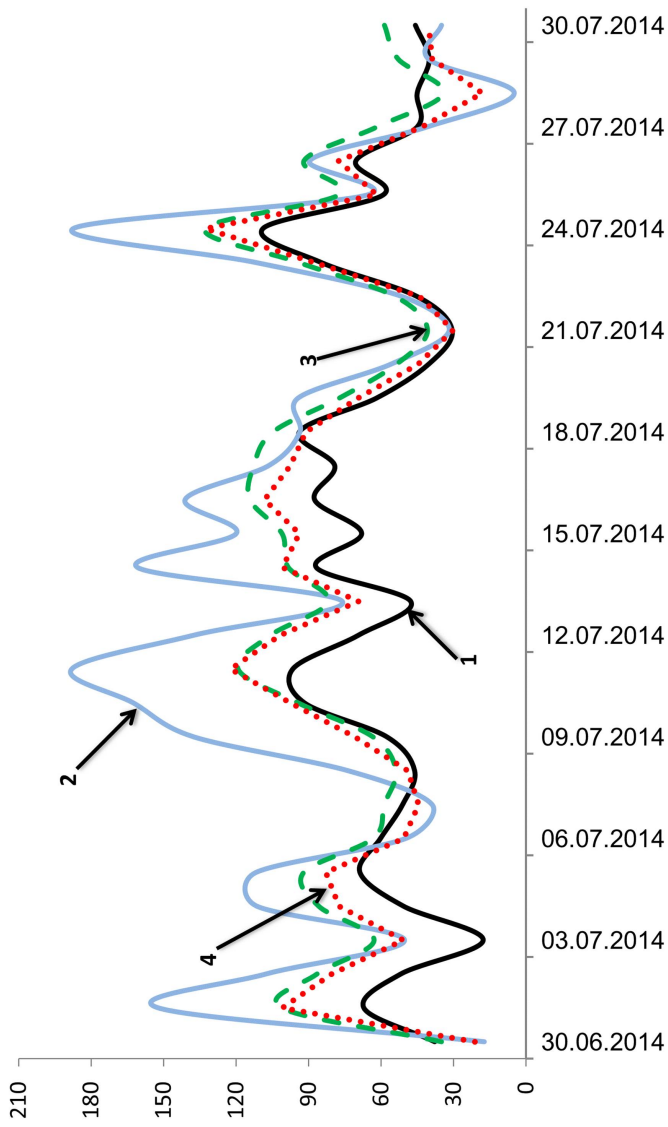
Figure 3. Daily averaged values of sensible heat flux H in ablation season 2014 calculated using different methods: 1 – direct method, 2 – Monin-Obukhov method, 3 – Kuzmin's method, 4 – aerodynamic formulas method.

days with foehns. Apparently, the stationary conditions are most violated in these days.

3.2. Physical Interpretation of Systematic Error

The simplifications of equation (2), discussed in Section 2.2, are used by many researchers [*Hock and Holmgren*, 2005; *MacDougall and Flowers*, 2011; *Mölg and Hardy*, 2004; *Voloshina*, 2001; *Wheler and Flowers*, 2011]. However, the comparison of the calculations of the ablation layer with these simplifications and observational data, presented in this paper, shows that the above simplifications can entail the inevitable accumulation of errors, related to the underestimation of physical processes, as well as the spatial distribution of glacier moraine material.

Firstly, the detected systematic error can be associated with the possible systematic underestimation of reflected radiation flux at a specific measurement point, while the albedo of the glacier's elementary area of 100×100 m, chosen in the ablation zone, is highly variable, and as shown by field measurements, can vary from 0.2 to 0.4 (depending on the contamination of ice, the presence of water, snow, etc.). Another reason for overestimation of the ablation layer can be the

assumption that the temperature on the surface of the glacier is 0°C, whereas the glacier surface is a mixture of melting ice with fine moraine material and water. In the latter case, the temperature gradient in the lowest layer near the surface is smaller, so the actual value of the turbulent heat flux will be somewhat less than the calculated one. Another reason for the error may be the underestimation of the heating of liquid water on the surface of glacier. All of the factors listed above affect the heat balance permanently, and therefore the resulting errors are systematic.

We've evaluated the energy equivalent of the systematic overestimation of ablation, and also the contributions of the mentioned above factors. The value of the daily ablation error is 0.025 ± 0.008 m. It equals to a daily energy amount of 8.2 MJ, or an instantaneous energy flux of 95 ± 25 W/m^2. This value is significant and commensurable with the average value of the turbulent heat flux obtained from sonic anemometer measurements. The fact that the average magnitude of the error is the same for all considered methods (see Figure 2) indicates that this error is associated with a physical effect not related to turbulent heat exchange.

We can also assume that the values of the albedo measured by radiometers at the point of the AWS on

the glacier are underestimated. The data of albedo measurements shows that the spatial variability of the albedo in the ablation zone is characterized by RMS of about 10%. Assuming that measurements at the site characterize the underestimated albedo (23%), and taking the value equal to 33%, we find that the average incoming short-wave radiation is 267 W/m^2 (Table 2), the new value of reflected radiation will be 88 W/m^2, i.e. 27 W/m^2 less than actually observed. Thus, this correction is approximately 3.5 times less than the systematic error. Moreover, A. P. Voloshina in the review [*Voloshina*, 2001] showed that the average albedo of the ice surface in the ablation zone with moderate amount of moraine material is 23%, which correlates perfectly with our data (Table 2).

Another probable cause of the systematic error in calculating ablation is the underestimation of evaporation. The latter may be due to the effect of small moraine material and liquid water on the surface of glacier on the surface temperature, and hence the moisture content at the level of roughness. The presence of "pollutants" on the surface of the glacier leads to the fact that, from the point of view of physical properties, it is no longer ice, and consequently its temperature in melting conditions can be, on average, above zero and

theoretically reach $\sim 2 - 3°$C. Unfortunately, it is not yet possible to confirm this physically reasonable assumption instrumentally, since it is difficult to correctly measure the glacier surface temperature under direct solar radiation. The presence of liquid water on the ice surface can substantially increase the evaporation layer. On the contact surface of the water layer with ice, the water temperature is close to $0°$C, while on its surface it can be substantially higher than $0°$C, especially under "good" weather conditions. From simple considerations based on the theory of molecular diffusion, the amount of evaporation of liquid water increases with increasing temperature of the water layer. Underestimation of this effect can cause a general overestimation of the ablation layer.

4. Conclusions

The main result of this work is the quantitative evaluation of the accuracy of various algorithms for calculating turbulent heat transfer over the mountain glacier. The problem of choosing the optimal scheme for calculating the turbulent heat transfer over snow and ice surface has long been considered uncertain [*Voloshina*, 2001]. New methods of measurement can partly solve

this problem. Direct measurements of the radiation balance components with an accuracy up to 20 W/m^2 combined with measurements of ablation layer with an accuracy of 0.005 m per day and with measurements of wind speed and temperature pulsations at a frequency of 10 Hz allow to estimate the heat consumption for melting, radiation balance and turbulent heat transfer with a high degree of accuracy.

It is shown that the use of turbulent heat transfer calculations based on sonic anemometer data (using the turbulent pulsation method) for ablation estimation gives a good agreement with the measured ablation layer (Figure 2d). Thus, this method can be considered as a reference one. Evaluation of the main methods of calculation of heat fluxes showed that the method of aerodynamic formulas is the most correct in comparison with the "reference" method. The Monin-Obukhov method proved to be the worst, which agrees well with the results given in [*Voloshina*, 2001].

The systematic overestimation of the ablation layer (by 0.025 m per day in comparison with the measurements) by all methods for calculating turbulent heat fluxes, including the "reference"one, is most likely due to the underestimation of the heat consumption for evaporation of liquid water from the glacier surface.

Underestimation of the magnitude of the reflected solar radiation due to the large spatial variability of the albedo is another potential reason of ablation overestimation.

The generalization of meteorological and actinometric measurements at the Djankuat glacier during intensive ablation periods of 2007–2016 is a secondary but practically important result of current study.

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