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LONG-TERM AVERAGE ANNUAL PRECIPITATION AT THE BELUKHA MOUNTAIN KNOT (CENTRAL ALTAI)

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The paper presents results of the calculation of long-term average annual precipitation in the Belukha mountain knot. The evaluation was carried out using the developed methodology which included collection and processing of available hydro-meteorological data, as well as calculation of precipitation at the equilibrium line altitude of glaciers. The calculation results allowed to construct a map of long-term average annual precipitation distribution in the Belukha knot. The revealed spatial features of precipitation distribution demonstrated, in particular, that precipitation amount increases in proportion to the absolute height on the windward slope, while on the leeward slope it is governed by the distance to the orographic barrier. The atmosphere's moisture content (humidification) is found to be reducing with the increasing distance from the axial parts of the mountain ranges. The results validation by the hydrological monitoring showed their reliability and possibility of the method application to other mountain glacier regions.

Altai, Belukha, glaciers, precipitation, humidification, surface runoff

INTRODUCTION

Evaluation of humidification and glacier runoff in the regions of mountain glaciers of Siberia presents quite a challenge, mainly because of the mountainous areas still being largely underexplored and insufficient observations of precipitation, confined primarily to the intermontane valleys. Besides, there is a stark paucity of research studies on hydrometeorological aspects of the slopes of mountain ridges.

The convential methods for calculating the long-term average annual precipitation and surface runoff values suggest their dependence on absolute altitude with account of their regionalization [*Semenov, 1969, 2007*]. In addition to these, the correction methods for archival meteorological data have been developed, embracing a wide range of topographic, reflective and some other essential properties of the underlying surface (e.g., [*Kislov et al., 2007; Kislov and Surkova, 2009*]). However, for such adjustment, firstly, the 12.5 × 12.5 km grid spacing appears fairly large [*Kislov et al., 2007*]. Secondly, as the authors put it: "Immediate verification of the obtained results, which could prove that the proposed approach is capable of improving the modeling resuls, is all but impossible in the absence of adequate observational network" [*Kislov and Surkova, 2009, p. 51*].

Some time ago, *M.V. Tronov* [*1956*] suggested using glaciers as a "natural precipitation gauge" to assess the average long-term humidification at the at the equilibrium line altitude (firn limit). This idea came to be ralized by *A.N. Krenke* [*1982*].

With this in mind, we developed a regional methodology for calculating long-term average annual precipitation of glaciated areas of mountainous regions using glaciers as the source of information [*Galakhov et al., 2013a*]. The procedure was tested by the hydrological control method, also proposed by MV. Tronov, and exemplified by the Eastern Altai and Western Mongolia [*Galakhov et al., 2013a*]. The calculations of the long-term average humidification in the Argut river basin are provided in [*Galakhov et al., 2014*], which were based on the above described technique and supplemented with the Goskomgidromet observations (State Committee for Hydrometeorology) and the glaciation data. In this paper, we have attempted to estimate long-term average annual humidification of the Belukha mountain knot (Central Altai).

OBJECT OF STUDY

Altai is a large mountainous country situated in Central Asia whose deep inland position forms an orographic barrier across the path of western and southwestern air masses, determining thereby its specific climatic characteristics featured by the predominance of anticyclone during most of the year and by the air humidification reducing southeastward.

The Belukha mountain knot is subsumed into the highest portion the Central Altai mountainous country, in the median part of the Katunsky Range. The central ridge of the Mt Belukha massif extends sublatitudinally, forming the most elevated part with its altitude averaging 4000 m, which makes this region one of the most humid in the Altai mountains. Most of the precipitation falls on the western and southwestern slopes of Mt Belukha. The region's climate is described as severe, with a long cold winter and a short summer with rain and snow events.

The Belukha massif is one of the largest glaciated regions in the Altai Mountains comprising over 160 glaciers with a total area of about 150 km^2, which accounts for almost 50 % of the Katunsky Range glaciers and for over 60 % of the area of its glaciation [*Arefiev and Mukhametov, 1996*]. Each of largest glaciers, such as Tronov Brothers glacier, Sapozhnikov glacier, Rodzevich glacier, Bolshoy and Maly Berelsky glaciers, Gebler glacier have an area of 10 km^2 or more.

EXPERIMENTAL MATERIAL AND RESEACH METHODS

The long-term average annual precipitation on the slopes of ridges was estimated using the available data from the weather stations and stream gauging stations (Fig. 1). Within this area, instrumental observations are conducted at two weather stations – Akkem (2050 m a.s.l.) and Karatyurek (2600 m a.s.l.) – located on the northern slope of the massif. Besides, on the southern slope, the Katun state meteorological (weather) station (WS) operated in the vicinity of Gebler glacier in the period from 1932 to 1935.

The observations of this region were conducted in different years at the four stream gauging stations – Belaya Berel–Berel (1120 m a.s.l.), Katun–Belukha, Kucherla–Kucherla (900 m a.s.l.) and Akkem–Akkem (2050 m a.s.l.). Additionally, the data from the Katon–Karagai WS (1081 m a.s.l.) and the Tungur water-measuring post (860 m a.s.l.) were involved in the calculations, as well as the snow measurements data collected during the Altai Glaciological Expedition within International Hydrological Decade (the 1965–1974 IHD) [*Galakhov and Danilkin, 1974; Galakhov, 2003*].

The observational network across the study area is shown in Fig. 1. Some previous studies [*Galakhov et al., 2013a, 2014*] showed that the trends in the precipitation distribution over the leeward and windward slopes of the mountain ranges differ greatly. Specifically, the amount of precipitation tends to increase on the windward slopes of the mountain ranges in the Chuya river basin, as terrain elevation increases. However, this tendency is lost on the leeward slopes, and the amount of precipitation decreases with the increasing distance to the orographic barrier. In this study, the amount of precipitation was therefore estimated separately for the leeward and windward slopes.

Humidification of the *windward slopes* of the mountain range was determined from the long-term precipitation data provided by the weather/gauging stations. The Berel gauging station data on precipitation were available from the monograph entitled "Physical Geography of Eastern Kazakhstan" [*Egorina et al., 2012*], while the Katon–Karagai WS data – in the "Scientific and Applied Handbook on the Climate of the USSR" [*1989*]. The data on precipitation during a cold season lasting from October through March was collected at the Katun WS by performing snow measurements in the Belaya Berel river basin and the routine observations using snow stakes in the upper reaches of the Katun river [*Galakhov and Danilkin, 1974; Galakhov, 2003*]. The precipitation data reported for a warm season (April–September) were determined from the cross-plot for the period of joint observations at the Akkem and Belukha weather stations (1933–1935, the number of correlated terms of series is 12, the correlation coefficient is 0.89).

The long-term average annual precipitation at the Akkem weather station is available from the "Reference Book on the USSR Climate" [*1969*]. With regard to the *leeward slopes* of the mountain knot, the average long-term precipitation data were received from the weather and gauging stations. The average long-term precipitation data from the Tungur stream

Fig 1. Observational network in the Belukha mountain knot.

I – weather stations: 1 – Karatyurek, 2 – Akkem, 3 – Katun; II – stream gauging stations: 1 – Katun–Tyungur, 2 – Kucherla–Kucherla, 3 – Belaya Berel–Berel; III – international border between the Russian Federation and Republic of Kazakhstan.

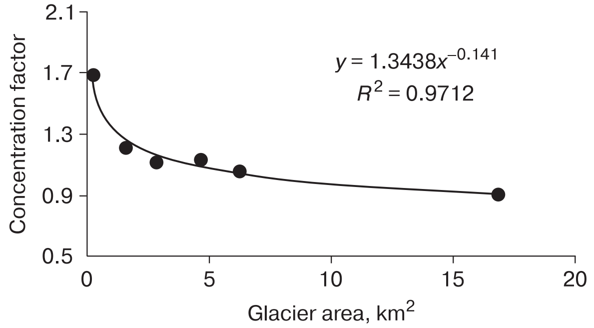

Fig. 2. Dependence between the concentration factor and the glaciers area for the Altai mountains [*Galakhov, 2008*].

gauging station, and from the Akkem and Karatyurek weather stations are given in [*Reference..., 1969*]. The average long-term precipitation based on the stream gauging station data was determined from the cross-plot for the period of joint observations at the Tungur and Kucherla gauging stations (correlation coefficient: 0.95). Estimation of the long-term average annual precipitation on glaciers was carried out using the A.N. Krenke technique [*1982*], which allows calculating ablation and accumulation at the equilibrium line (firn limit) altitude of glaciers:

$$A = 1.33\,(t_{\text{sum}} + 9.66)^{2.85}, \quad (1)$$

where A is a thawed layer at the equilibrium line altitude; t_{sum} is the long-time average annual air temperature for the summer period (June–August) at the equilibrium line altitude.

The value of A determined for a groups consisting of 5–12 glaciers of different morphological types, characterizes the accumulation, which includes avalanche and snow transport input in addition to the background precipitation.

Previous studies have shown that formula (1) applicable to the Altai area should include a regional coefficient, for the glaciers exposure to be taken into account, when the generalized Krenke formula is used for the region-specific calculations [*Galakhov and Mukhametov, 1999*]:

Exposure	N	NE, NW	E, W	SE, SW	S
Coefficient	0.82	0.94	1.07	1.19	1.31

The concentration factor derived from the ratio between accumulated snow on the glacier and the background snowpack not disturbed by avalanches and snowstorms was used to translate the obtained ablation-accumulation value into the long-term average annual precipitation. The calculation was based on the dependence obtained previously from direct observations of snow accumulation on glaciers [*Galakhov, 2008*]. Given that this dependence (Fig. 2) is applicable only to the corrie and valley glaciers, the calculations were performed specifically for glaciers of these morphological types with an area of more than 0.5 km^2.

It should be noted that the methodology for calculating the ablation-accumulation value at the equilibrium line altitude was developed under glaciers' relatively stationarity conditions, suggesting, accordingly, that during the assessment period, the equilibrium line altitude of glaciers should not vary greatly for more accurate calculation results. The experimental observations in the Aktru basin (Maly Aktru glacier) showed that the stationarity conditions were fulfilled approximately until the mid-1990s. Driven by the dramatically increased summer temperatures, the Altai glaciers are retreating extensively (specifically, over the past 15 years), having lost almost as much as half of their mass balance since the beginning of the instrumental observations [*Galakhov et al., 2013b; Samoilova et al., 2014*], imparing thereby the results of modern observations of the equilibrium line altitude. Therefore, in the previous research [*Galakhov et al., 2013a, 2014*], as well as in this work, when determining the equilibrium line, the authors opted for the World Glacier Inventory (WGI) data published in the 1980s [*Surface Water Resources..., 1969, 1978*].

The air moisture index value glaciers was also estimated separately for the windward and leeward slopes.

Table 1. **Calculation of long-term average precipitation at the firn line altitude in the upper reaches of the Katun river**

Glacier No. [*Surface..., 1969, 1978*]	Exposure	S, km^2	$H_{\text{f.line}}$, m	$T_{\text{f.line}}$, °C	Ablation–accumulation, mm	Long-term average precipitation, mm
11	NW	1.1	2750	3.0	1744	1315
12	W	0.5	2750	3.1	2023	1365
13	SW	9.0	2800	1.6	1558	1580
14	SE	3.0	2800	2.4	1915	1664
15	SE	1.5	2850	2.3	1853	1460
16	S	5.6	2850	1.7	1791	1695
Average						1513

Notes to Tables 1, 2. S is glacier area; $H_{\text{f.line}}$ is firn line altitude; $T_{\text{f.line}}$ – long-term mean annual air temperature for the summer period (June–August) at the firn line altitude.

Table 2. **Calculation of long-term average precipitation at the firn line altitude in the Akkem basin**

Glacier No. [*Surface..., 1969, 1978*]	Exposure	S, km^2	$H_{\text{f.line}}$, m	$T_{\text{f.line}}$, °C	Ablation–accumulation, mm	Long-term average precipitation, mm
203	E	1.8	1950	1.5	1390	1124
204	E	0.8	2900	2.0	1204	868
205	N	10.4	3000	0.0	694	719
206	NW	1.5	3000	1.2	1128	888
207	W	1.8	3100	0.5	1050	848
208	NW	1.5	3120	0.4	897	707
209	NW	0.9	3100	0.6	955	700
211	NE	2.0	3050	0.8	1008	827
212	N	1.1	3060	0.9	893	673
213	N	0.3	3000	1.4	1028	645
214	N	1.2	3000	1.3	995	759

In the Krenke method-based [*Krenke, 1982*] evaluation of the ablation-accumulation at the equilibrium line altitude on the windward slopes of the mountain knot we used glaciation in the Belaya Berel, the upper Katun and Kapchala river basins (the calculus example is given for the upper Katun river, Table 1). The ablation-accumulation were translated into average long-term precipitation using the previously obtained concentration coefficients [*Galakhov, 2008*].

Whilst on the *leeward slopes*, the estimation of ablation-accumulation and humidification was carried out using glaciers of the Kucherla, Akkem and Iedigem river basins (the calculus example is given for the upper Akkem river, Table 2).

RESEARCH RESULTS

The available materials from the weather/stream-gaging stations and the calculation results obtained by the authors for long-term average annual precipitation at the equilibrium line of the glaciers allowed to generate a long-term average annual precipitation distribution map for the Mt Belukha mountain knot (Fig. 3).

Likewise for the Chuya river basin [*Galakhov, 2013a*], the spatial distribution of precipitation on the leeward and windward slopes of the Belukha Mountain Complex are differentiated. On the windward slope, the long-term average precipitation is largely controlled by the absolute altitude (Fig. 4).

The research results obtained by V.I. Yakubovskii and Yu.K. Narozhny on evaluation of snow accumulation on the firn plateau of Mt Belukha (Gebler glacier) and in the firn basin of Tronov Brothers glacier at an altitude of about 4000 m indicated that the dependence calculated by the authors shows fairly good agreement therewith.

According to *Yu.K. Narozhny* [*1997*], the long-term average precipitation measures up to 2000 mm. While extrapolation of the dependence obtained by the authors gave a resulting value of 2130 mm. As such, this coincidence seems to the authors to be quite revealing. On the leeward slope, the long-term average annual precipitation is associated with the distance from the orographic barrier (axial lines of the main ridge and its co-altitude branches, Fig. 5).

Materials on the IHD snow measurements in the Akkem river basin evidenced that at Rodzevich glacier, the layer of snow fallen at the equilibrum line altitude mesures up to 750 mm. When calculating the long-term average annual precipitation by the Krenke method accounting for the concentration coefficient, the obtained value was 719 mm (No. 205 in Table 2). The non-recurring snow sirveys on other glaciers within the basin showed that in a year whose snow accumulation proved to be close to the long-term average annual (as, for example, in 1973), the difference between calculations and direct observations is not more than 10 %. In years showing a gaping difference in snow accumulation rate from the long-term average, the errors increase to 20–25 % (for example, 1974, 1975). It is obvious that glacial snow surveys in low-snow years, ranking below the long-term average, can not therefore be characteristic of the long-term average annual precipitation amount at the firn line regardless of the source data reliability, i.e. for example, the snow mass is factored in as provided by the nearby weather station oservational data.

Likewise for the Argut river basin, the authors attempted to verify the obtained data using the hydrological control method (after *M.V. Tronov* [*1956*]). The glacier discharge in the Belaya Berel river basin (the Berel stream gauging station) has been monitored since 1958. In the Akkem river basin (Akkem stream gauging station), observations were conducted in 1933–1935, 1952–1963, 1965–1976, 1978, 1980, 1983, and in 1987–1994. In the Kucherla river basin (Kucherla stream gauging station) observations were consucted in 1932–1933, and then updated in 1963. Materials of hydrometric observations of the Katun river (a stream gauging station at the foot of

Fig. 3. Long-term average annual amount of precipitation (isolines, mm) for the Mt Belukha mountain knot.

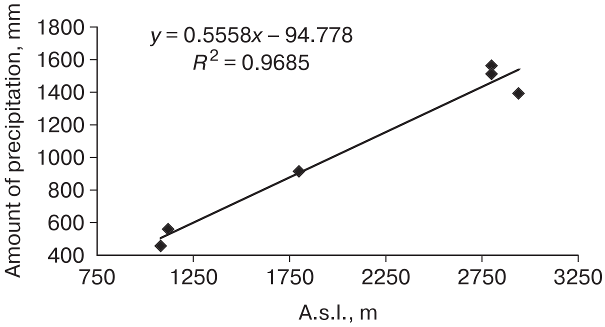

Fig. 4. Dependence between the amount of long-term average annual precipitation for windward slopes of the Belukha mountain knot and the absolute altitude.

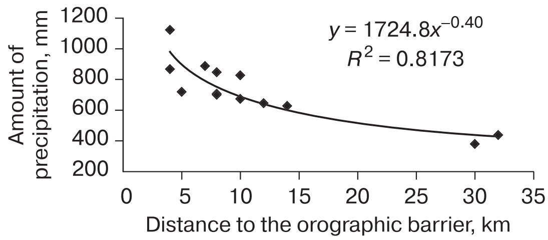

Fig. 5. Dependence between long-term average annual precipitation in the Akkem river catchment and the distance to the orographic barrier.

Table 3. **Morphometric data, long-term average humidification and average run-off of the Belukha mountain node basins**

River	Gauging station	F, km^2	H_{av}, m	X_{av}, mm	h_{av}, mm
Belaya Berel	Berel	1040	–	1068	779
Akkem	Akkem	78.9	2900	1033	903
Kucherla	Kucherla	627	2300	932	679

N o t e. F – catchment basin area; H_{av} – average height of catchment basin; X_{av} – long-term average precipitation; h_{av} – long-term average run-off depth.

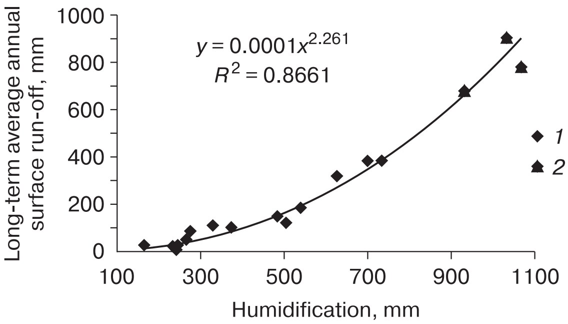

Fig. 6. Dependence between long-term average annual surface run-off (points *1*) and humidification (long-term average annual precipitation) in the glaciated basins of South-Eastern and Central Altai.

Points *2* – newly obtained values.

Mt Belukha) are available only for a fairly short period of 1933–1935, and therefore were of no avail in the calculations. The values obtained for the long-term average annual precipitation and the average multi-year runoff depth are given in Table 3.

For the purposes of hydrological control, three newly determined points are plotted on a combined cross-plot of a ralationship between the runoff depth and air moisture content, obtained earlier from the data for the Chuya depression, the upper reaches of the Khovd river, and the Argut river catchments (Fig. 6).

As can be seen in Fig. 6, the points characterizing the Belukha mountain knot basins fairly perfectly fitted into the master cross-plot. The high correlation coefficient suggests reliability of the resulting values.

CONCLUSIONS

The A.N. Krenke method for calculating the long-term average annual humidification at the firn line altitude of glaciers and concentration coefficients, along with the measurements provided by the observational network of the weather/stream gauging stations enabled evaluation of the Belukha massif humidification and to generate a map of long-term average annual precipitation.

The precipitation spatial distribution pattern for the mountain knot has been established indicating that on the windward slope, the humidification is governed by absolute altitude, and by the distance to the orographic barrier, on the leeward slope. These patterns are also characteristic of other regions of the Altai moutaineous country.

The verification of the obtained materials by the hydrological control method, proposed by M.V. Tronov, as well as data from snow surveys and glacier mass balance observations conducted on glaciers, confirmed reliability of the calculations performed. In keeping with the the authors' inferences in the previous works [*Galakhov et al., 2013a, 2014*], M.V. Tronov's idea about using glaciers as a "precipitation gauge" has been found practical. The developed technique allowed to determine the long-term average annual humidification and runoff depth in the largely underexplored mountainous-glaciated basins of Altai.

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