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Assessment of modern glaciological and climatic indicators in the Mountainous Altai area

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According to some meteorological and glaciological observations using statistical methods of cluster, harmony, and correlation analyses the assessment trends of the Altai mountainous region glacilogical indicators and temperature regime have been obtained. The glacilogical effect of the atmospheric circulation of the area under review by means of B.L. Dzerdzeevsky's typing is studied.

Keywords: the Altai Mountainous; regime characteristics; elementary circulatory mechanisms.

Introduction

It is widely known that glaciers are the most sensitive indicators of the Earth's climate. Their balance and sizes quickly affect such meteorological characteristics as atmospheric precipitation and the temperature of the air. Monitoring of the Altai glaciers initiated by V.V. Sapozhnikov, B.V. and M.V. Tronov has made it possible to store up extensive data concerning their state and dynamics. Special attention was given to the research of the Aktru mountain and glacier basin where a meteorological station with the standard amount of observations was opened in 1971. Interest in the glacier basin is due to its geographical position in the centre of the Eurasian continent as well as the availability of a long series of direct observations made on the major glaciohydroclimatology parameters which are indicative of the current trends of glaciers dynamics in the acutely continental climatic conditions. From this point of view the Aktru glaciers are regarded as the Siberian basic objects and they are included in the World Glacier Monitoring Network [1–3].

The aim of the current research is to evaluate the meteorological conditions of the mountainous Altai taking into account the present-day climatic trends.

Results

The article provides a profound analysis of the atmospheric circulation processes, accumulation value, ablation and balance of the Malyi Aktru glacier as well as climatic indicators of temperature regime near the earth's surface above the Altai mountains area. This territory is the so-called fourth-class area determined by means of cluster analysis (spacial classification method) of the average monthly air temperature field (Fig. 1).

Fig. 1. Distribution of the air temperature of the classes in the area of the Altai region [4]

The quality of the classification favours the view that intra-class distances are 2–5 times less than inter-class ones. The fourth-class territory includes the most mountainous part of Altai. The Ak-Kem, Aktru, Bertek, Kara-Tureck, Kosh-Agach are located in this area while Ulandryk meteorological station is situated not far from here. This area is characterized by the lowest annual temperatures and the highest intra-class differences (Table 1). These stations are isolated from the impact of warm and humid air masses coming from the Atlantic Ocean. They are located closer to the centre of the Asian anticyclone, which contributes to the forming of severe climate in this area.

Table 1. Characteristics of classification of the temperature field in the region

class	The number of stations	Average tempera-ture, °C	Variace, °C^2	Average correlation coefficient	The intraclass distance, °C	The interclass distances, °C		
						2	3	4
1	21	2.5	172	0.99	0.17	0.32	0.25	0.77
2	3	4.0	106	0.99	0.20		0.43	0.88
3	4	0.0	164	0.99	0.20			0.52
4	5	-4.1	153	0.97	0.36			

Circulatory processes

The meteorological conditions on which the glacier regime is dependent are determined by great circulatory atmospheric processes. In this connection, it is important to reveal the glaciological and climatic effect of the atmospheric circulation relating to the mountainous part of Altai. The atmospheric circulation state is estimated as in the instance of [5] by means of the B.L. Dzerdzeevsky's typing [6]. The elementary circulatory mechanisms (ECM) regularity was estimated according to the ablation and the accumulation periods of the Malyi Aktru glacier.

The date of the stable transition at 0 °C average daily temperature of the air in the low glacier boundary was regarded as the conditional limit of accumulation and ablation periods. The end of the ablation period (or the beginning of a new balance year) corresponds to the time of complete covering of a glacier by stable snow cover and a change-over of annual daily temperature of the air to 0 °C in the direction of negative meanings. Warm weather, however, occurs during this period and the following several days, which on the whole, can increase humidity of snow cover in the absence of glacier snowmelt runoff. This snow is the initial stage of winter balance mass glacier formation for the following balance year [1].

As a rule, the beginning of accumulation period (the end of August – the beginning of September) is connected with a series of powerful and intensive snowfalls which result from cyclones coming from the Barents Sea and the Kara Sea as well as the north-west cyclone shifts and formation of high cyclone over the Mountainous Altai [7].

The complete period of the onset of stable negative temperatures of the air is associated with the formation of high pressure area in the form of Asian (Mongol) anticyclone spurs and the penetration of cold Arctic air into the Altai highlands [1, 7].

Overall annual accumulation (c_t) and ablation (a_t) values as well as internal power supply (*f*) lead to annual mass balance (*b*):

$$b = c_t - a_t + f.$$

Duration of accumulation periods (c_t) and the Aktru glaciers snowmelt sufficiently change over the years and depend upon the nature and characteristics of the atmospheric circulation processes. The correlation analysis of the regularity (days) the ECM and constituents of the glacier mass balance (in specific units of g/cm^2) showed the most significant relationships. On the basis of the correlation analysis glaciological effective ECM are revealed. They are especially favourable at 5% level: type processes ***3***, ***13w*** (inverse) and ***11a*** (direct link) refer to c_t, a_t and *b* with ***7as*** processes (direct and invesre links respectively), ***5d*** (invesre and direct links) shown in Fig. 2.

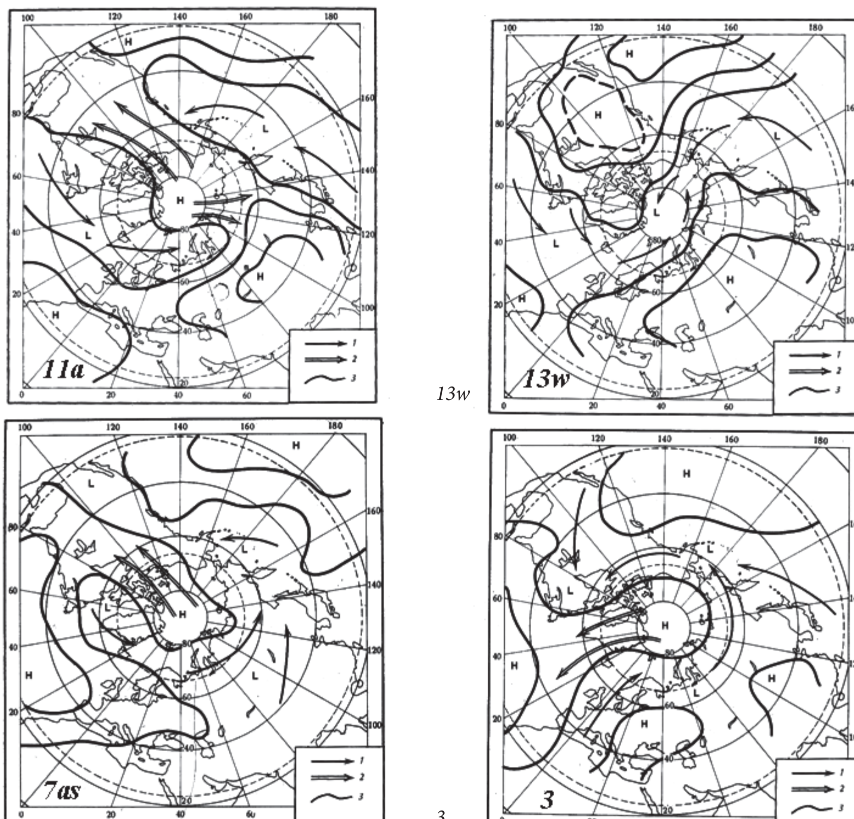
Thus, the high values of c_t favour ***11a*** subtype processes relating to the northern meridional group and, on the whole, they are prevalent during an accumulation period.

Processes of this subtype allow the Siberian anticyclone to occupy almost the entire continent. Gradual circulation of Arctic air south-wards enhances the anticyclone and leads to its stationary state. Cyclonic activity over the oceans is associated with the Arctic front and regeneration of its polar-front cyclones. Cyclonic bursts coming from the South take place along the eastern coast of North America (the Atlantic Ocean) and Asia (the Pacific Ocean). Some cyclones reach the Arctic Ocean (Novaya Zemlya Island and the Kara Sea).

ECM ***3*** and ***13w*** make it possible to reduce accumulation values. During subtype ***3*** which is characteristic of a warm half a year period, the Mountainous Altai is in the field of high pressure formed by the local conditions. The negative relationship can be accounted for by the fact that this subtype is typical of the warmer periods which are the most common ones in summer, thus, determining the ablation.

When ECM ***13w*** occurs, a powerful stationary anticyclone occupying almost the entire Eurasian continent creates a strong blocking to the western flow in the temperate latitudes, thus, preventing precipitation. Processes of ***7as*** subtype are favourable for the intensive glacier ablation. During ***7as*** an active cyclonic activity at the polar front takes place. This ECM also has a high repetition during the ablation period. On the contrary,

5d ECM prevents the thawing processes in summer because it mainly occurs during the colder period with the availability of the stable and extensive winter Siberian anticyclone exhanced by the Arctic influence in the eastern Asian direction [6]. At the same time, ***5d*** process has a positive link while ***7as*** process has a negative connection with the annual balance.



11a *13w* *7as* *3*

Fig. 2. Dynamic ECM schemes: 1 – generalized cyclone trajectories; 2 – the same for anticyclones; 3 – demarcation lines [6]

Instrumental (1962–2010) and reconstructed (1900–1961) data on performance characteristics of glaciers Aktru have been used [1–3] for the following circulatory conditions of the dynamics of glacier balance mass constituents are revealed.

The period of c_t rise from the early of the XXth century up to the maximum value 138 g/cm^2 in 1921 was characterized by a high regularity of the northern meridional circulation (***11a*** ECM in particular) during the colder periods of the year, having their major maxima in 1917, 1919, 1921. Between 1922 and 1935 the decrease of both characteristics of c_t and ECM in a pre-spring period and winter was observed. From 1985 to 1995 the number of days relating to ***11a*** sub-type also increased as well as the glacier balance mass constituents.

Annual mass balance of the glacier which is closely associated with amount of the accumulation decreases with the increase of zonal circulation.

On the contrary, glacier ablation during summer depends on the activity of zonal flows (ECM ***7as***). One can observe their overall increase in the first half of the XX[th] century. During the second half of the period the observed zonal processes weakened. This tendency relating to a_t values had been observed until 1985. a_t increase over the last decades is evidently due to the global warming which is accompanied by the southern meridional circulation increase.

Warming which began in the mid 1970s has resulted in precipitation increase during the colder period and accumulation values intensity.

The links revealed between the changes in the characteristics of the Malyi Aktru glacier mass balance and overall atmospheric circulation make it possible to regard the ECM as good indicators and objective signs of climatic variability of the region concerned.

Glaciological and Climatic Indicators

The link between glaciation and the climate expressed by the dependence **Glaciers = f (climate, topography)** can be specified by glaciological and climatic indicators which are better designed for the Aktru basin mountain glacier [8] . Some of the basic glaciological and climatic characteristics are the following: the amount of overage daily above zero air temperatures $\Sigma(+t)$, indicators in the 1° temperature value ablation, duration of ablation period (P_{At}), the annual number of days with snow cover, vertical gradients of meteorological elements, indicator-equivalents (e.g. summer air temperatures decrease by 1°, the increase of solid precipitation) etc.

These indicators as climatic ones are widely used in glaciology for balance estimations and they refer to the first type of glaciological and climatic indices. Based on these indicators M.V. Tronov and A.N. Krenke [9] compared them with agroclimatic indices bearing in mind that the conditions of heat and humidity which plants need are also important for glaciers. The difference lies only in the nature of impact (favourable or unfavourable) and the time required for such a manifestation.

These indicators relate to the dates of daily average air temperature transition at fixed values (0°C, 10°C), duration periods with positive temperatures, the accumulated amount of positive temperature, hydrothermal coefficient, etc.

Our research deals with the thermal regime characteristics (glaciological and climatic parameters) according to the meteorological observations (of daily and monthly resolution) made from 1939 to 2009. The dates of the stable daily transition temperature 0°C (D_0), the P_{At} positive temperature duration period, the sum of positive temperatures during the stable transition period at 0 °C ($\Sigma(+t)_y$). The sum of positive temperatures from March to November ($\Sigma(+t)$) was also taken into account.

Fig. 3. illustrates the dynamics of the regime characteristics of the Malyi Aktru glacier.

The climatic parameters are shown in Table 2. On the basis of these results one can state that the P_{At} longest period is observed at the Kosh-Agach station, while the shortest period is seen at the Kara-Tureck station.

The calculation is not statistically provided by the available daily observation amount of data.

P_{At} amplitude over the area of the district is 48 days which further points to the significant impact of local conditions. Assessment of the trends points to an earlier transition through 0 °C in spring and later to the autumn transition which is reflected in the P_{At} positive trend. These trends may present part of the cyclical processes which are characteristic of the climatic system.

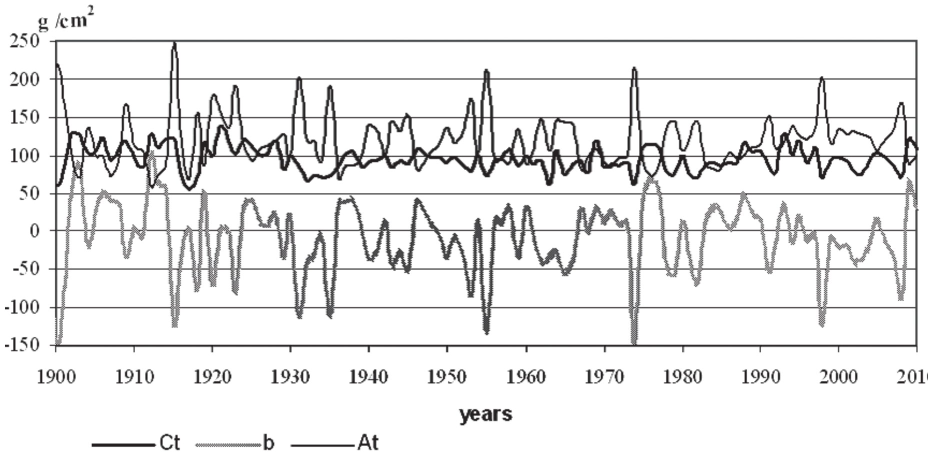


Fig. 3. Time course of the a_t, c_t, b in Malyi Aktru glacier

Table 2. Glacioclimatological indicators

Station(s) (observation period)	Long-term average						Rate of change			
	D_0		STD D_0		$\Sigma(+t)_y$	P_{At}	D_0, days/ 10 years		$\Sigma(+t)_y$, °C/10 years	P_{At}, days/ 10 years
	spring	autumn	spring	autumn			spring	autumn		
Ak-Kem (1961–2003)	May 01	Oct. 01	9	10	896	153	0	2	44	2
Kara-Tureck (1940–2010)	May 16	Sept. 21	13	11	612	128	–1	1	17	2
Kosh-Agach (1940–2010)	Apr. 15	Oct. 08	9	8	1573	176	–1	1	39	2
Aktru (1971–1984)	Apr. 28	Oct. 01	11	10	–	157	*	*	–	–
Bertek (1959–1983)	May 04	Sept. 25	9	7	–	145	–2	2	–	–
Ulandryk (1961–1984)	Apr. 26	Oct. 01	10	8	–	159	–3	2	–	–

* The trend is not statistically significant

Harmonic analysis was used with the aim of identifying the cyclic constituents in the dynamics of the characteristics under study (Fig. 3) and its results are shown in Table 3. The periods of primary importance 12 harmonics (determined by the oscillation amplitude) are presented.

Table 3. The cyclic periods of ECM indicators (years)

Aktru			Kosh-Agach			Kara-Tureck		
Ct	At	b	P_{At}	$\Sigma(+t)_y$	$\Sigma(+t)$	P_{At}	$\Sigma(+t)_y$	$\Sigma(+t)$
6	9	9	5	26	29	55	12	9
16	55	21	17	12	12	8	57	12

9	20	13	3	17	9	25	9	58
21	13	6	7	7	8	16	3	3
4	5	4	2	8	4	4	17	8
11	4	58	38	4	18	11	8	17
7	11	11	6	9	55	7	23	23
5	3	3	12	3	7	5	4	36
3	6	7	8	6	3	6	34	4
13	7	16	9	2	6	13	7	6
56	8	5	24	26	5	9	6	7
30	28	28	4	7	10	23	10	10

Low-frequency harmonic with the period of 55–58 years (Quasi-half a century cycle) determined by the position of the planets of the Solar system and the influence of the asymmetry of the centre of mass of the Solar system is revealed practically in all the ranks of indicators [10–13]. This harmonic is vividly manifested by Kara-Tureck change of indicators, but it is exhibited to a lesser extent in Kosh-Agach which points to the dominant contribution of large circulatory rearrangements in long-term glaciological and climatic indicators variability in Kara-Tureck. At the same time, their influence at the Kosh-Agach station is evidently disguised by synoptic scale processes as well as the local circulation. As a result high-frequency cycles from 5 to 29 years prevail at the Kosh-Agach station due to the variability of solar-physical and geophysical factors.

Fig. 4 Time ablation course and its harmonics with the period of 55 and 11 years (Malyi Aktru glacier)

A_t harmonic analysis (Fig. 4) confirms a 55-year harmonic reflecting the major trends and the other characteristics concerned. In addition, 3, 4, 6, 9, 11 years of periodicity (regularity) are revealed in a_t as well as in C_t and *b*. This cycling is obviously manifested in the rate of change of glaciological and climatic indices during different time intervals (Table 4).

Table 4. Rate of change of glacioclimatological indices during the various periods of time (10 years)

				Kosh-Agach			Kara-Tureck		
				P_{At}	$\Sigma(+t)_v$	$\Sigma(+t)$	P_{At}	$\Sigma(+t)_v$	$\Sigma(+t)$
1940–2010	0.6	1.2	0.3	2.0	39.4	34.9	2.5	17.1	18.5
1981–2010	2.5	–6.4	7.9	1.2	76.7	85.9	0.4	52.0	63.0
1995–2010	0.1	17.6	–17.1	–1.6	–6.0	62.1	–0.6	–33.6	–36.9

Furthermore, the relationship between the presented climatic characteristics and glaciological indicators of the Malyi Aktru glacier was studied. Due to the limited data of the meteorological observations at the Aktru station (1971–1995) in comparison with the other stations (Kosh-Agach, Kara-Tureck) of the area concerned was also made. The observations made at the Aktru station were not quite sufficient to provide an adequate climatic analysis.

The results of the correlation analysis are shown in Table 5, which implies that the Kara-Tureck climatic indices have closer links with the regime characteristics of the Malyi Aktru glacier.

Table 5. The linear correlation coefficients between the glacioclimatological indicators

	Climatic indicators			
	Kosh-Agach		Kara-Tureck	
	$\Sigma (+t)_y$	$\Sigma (+t)$	$\Sigma (+t)_y$	$\Sigma (+t)$
C_t	–0.07	–0.17	–0.32	–0.31
b	–0.33	–0.43	–0.65	–0.65
A_t	0.44	0.51	0.72	0.72

Similarity of the trend of long-term ablation values dynamics at the Malyi Aktru glacier and sums of positive temperatures during the stable transition at 0°C at the Kara-Tureck station are also confirmed (Fig. 5).

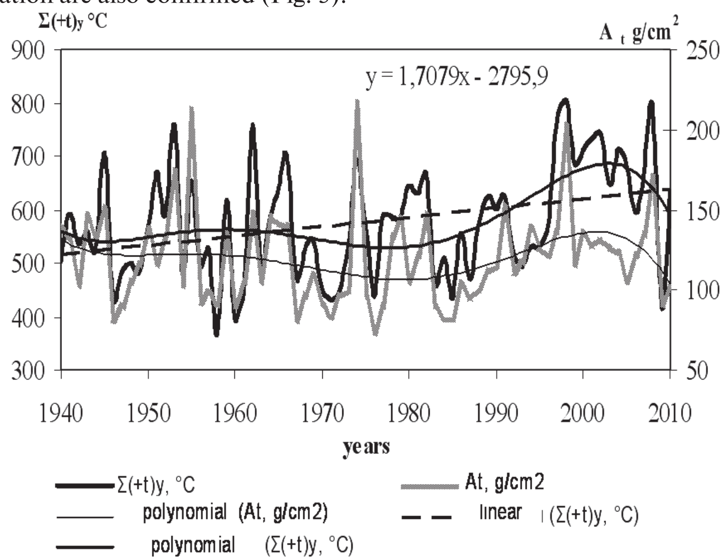


Fig. 5. Aktru glacier At dynamics and $\Sigma (+t)_y$ at the Kara-Tureck station

Estimation changes of the glaciological and climatic indices in the future.

The Mounatainous Altai glaciation reaction to possible climatic changes in the global surface air warming based on paleoclimatic reconstructions for the Holocene optimum epochs and Mikulino inter-glacier period can be found in [14]. The climatic scenario based on these reconstructions leads to a rise of 2.8 °C of the average winter temperatures, and 0.2–0.3 °C average summer temperatures in the Altai Mountainous. The amount of atmospheric precipitation will increase by 15% in comparison with the current one [15]. At these values the height of supply line will remain below the upper limit of modern glacier distribution and the Altai glaciation itself will be kept in accordance with the variant of climatic conditions development in the Holocene optimum.

The present-day characteristics of the thermal regime in the area concerned and their trends are illustrated in Table 6. These data can be used to calculate the climatic scenarious [15] of the future glaciological and climatic characteristics of the area under study.

Table 6. Statistical characteristics of the average monthly temperature of the air (1961–2005)

Station(s)	Average temperature	Dispersion	Average min.	Average max.	Rate of change
Ak-Kem	−3.8	94.9	−25.1	11.4	0.4
Kara-Tureck	−5	79.9	−25.2	11	0.4
Kosh-Agach	−4.7	231.6	−37.6	20.2	0.6
Aktru	−4.5	162.4	−33.4	15.5	0.9
Bertek	−6	166.5	−35.2	14.6	1.8
Ulandryk	−2.3	164.9	−28.4	21	1.2

Probable variant of the development of the climatic changes is illustrated in Table 7 by the forecast of climatic indices values for the Central Altai area.

Table 7. Glacioclimatologic indices in the modern epoch (nominator) and their changes (denominator) for predicted warming [14]

Area	H_{bs}, m	At the height of 2500 m above the sea level		On the glacier border of supply			
		T_s, °C	Q_s, mm	T_s, °C	Q_s, mm	P_s, mm	$A_t = C_t$, m
Central Altai	3060	$\frac{5.5}{+0.3}$	$\frac{450}{+50}$	$\frac{0.6}{+0.4}$	$\frac{640}{+60}$	72	$\frac{1030}{+90}$

H_{bs} – height of border of supply; T_s – average summer temperature; Q_s – annual amount of solid precipitation; P_s – fraction of solid precipitation in annual sum; $A_t = C_t$ – characteristic of movement of glacier border supply.

Summary

According to some meteorological and glaciological observations using statistical methods of cluster, harmony, and correlation analyses the assessment trends of the Altai mountainous region glacilogical indicators and temperature regime have been obtained. The glacilogical effect of the atmospheric circulation of the area under review by means of B.L. Dzerdzeevsky's typing is studied.

The temperature field is a good attribute spaces for classification of mountainous areas and identification of representative areas (classes) in the description of the dynamics of glaciers. Warming which began in the mid 1970s has resulted in precipitation increase during the colder period and accumulation values intensity. Low-frequency harmonic with the period of 55–58 years (Quasi-half a century cycle) determined by the position of the planets of the Solar system and 3, 4, 6, 9, 11 years of periodicity (regularity) are revealed practically in all the ranks of indicators.

Statistical characteristics of glaciological and climatic indicators of the research can be used to predict seasonal, annual and current states of a climatic regime evaluation of the Altai glaciers and water resources in Western Siberia.

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