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Glacial regime of the highest Tien Shan mountain, Pobeda-Khan Tengry massif

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ABSTRACT. Major processes controlling the existence of a large subcontinental glacier system were identified on the basis of glaciological, meteorological and isotopic analyses using expeditionary and long-term data. Observations occurred on the southern Inylchek glacier located in the Pobeda - Khan Tengry massif, the largest subcontinental glacier system in the northern periphery of central Asia. More than 1200 glaciers with total area about 4320 km^2 compose the massif. Melt is for the most part caused by radiation and is most intensive during periods of anticyclonic weather with foehn development. The share of solar radiation input to heat balance is more than 90%. Evaporation and condensation are of negligible effect during most times and comprise 7% of heat expenses. Accumulation was associated with cold cyclonic weather. Four ice formation zones were identified, the upper boundary of liquid runoff is at 5200 m, and the recrystallization zone is located above 5900 m. The calculated net glacier mass is negative, -318 kg m^{-2} yr^{-1}, and indicated degradation of modern Pobeda - Khan Tengry glaciers.

INTRODUCTION

Our study concerns the present conditions of continental glaciers at mid-latitudes and evaluation of snow and glacier resources. Although central Asian glaciers have received a good deal of attention (Konovalov, 1979; Krenke, 1982; Glacier Inventory of China, 1986,1987; Zhenniang, 1988; Hong et al., 1992), one of the largest, the Pobeda-Khan Tengry glacier system at the northern periphery of central Asia, has not been well explored. Studies of glacier energy and mass balance in remote alpine watersheds require detailed monitoring of the local climate. Snow accumulation and its metamorphism into the firn and ice, snow/ice melt and runoff are controlled by the magnitude of energy available to drive these processes.

The first of our investigations of remote high mountains watersheds at the mid-latitudes was completed in the northern Tien Shan, the northern periphery of central Asian mountain system, an area affected by western cyclonic and northern anticyclonic activity (Aizen et al., 1995 a,b). In 1990-1992 we carried out investigations at the southern periphery of the central Asian mountain system in the Himalayas and south-east Tibet, with monsoon climatic conditions (Aizen and Aizen, 1994a,b). This paper summarizes investigations of local temporal and spatial variations of mass-energy components in the inner subcontinental central Asian high mountains, characterized by precipitation deficit at low elevations and increasing moisture at high altitudes.

The Pobeda (Chinese name Tuomuer) - Khan Tengry massif, composed of more than 1200 glaciers with total area about 4320 km^2, is the largest subcontinental glacier system in the northern periphery of central Asia (Fig.1). The Pobeda - Khan Tengry glaciers are the major source of principal rivers in the regions of internal drainage in central Asia. These affect the great Tarim and Balkhash hydrographic systems, where 45-50% of total runoff is contributed by glaciers (Dolgushin and Osipova, 1989; Xie et al., 1982).

MEASUREMENTS AND DATA COLLECTION

In the summers of 1989, 1990 and 1992 we conducted expeditionary observations on the Inylchek glacier located at the center of Pobeda - Khan-Tengry massif (Fig.2). The Inylchek glacier covers all glacial zones from 2900 to 7450 m and has two major branches stretching 60.5 km from east to west. The area of the glacier is 794 km^2.

We carried out the field measurements and observations at four points: the active ablation zone (near the Mercbakher glacial outburst lake) at 3400 m; at 4150 m, close to the firn line, at 5200 m, the upper level of liquid runoff formation; and at 6100 m in the accumulation zone. We used standard Russian hydro-meteorological instruments and four automatic mini-met stations built by Grant Instruments (Cambridge)Ltd., England (Table 1). The data loggers of the stations recorded hourly measurements of net total radiation, total incoming radiation, reflected radiation, atmospheric pressure, snow and ice temperature, and discharge from ablation plots. Measurements were recorded at two levels (0.5 and 2.0 m) above the surface for air temperature, relative humidity, and wind speed. Wind direction was recorded at 2.0 m. The glaciological observations included measurements of ablation, accumulation and snow-firn-ice stratigraphy in the pits and ice cores. Ablation was measured on three slightly inclined 2 x 2 m ablation plots (Fig.3) at 3500, 4150 and 5200 m. Measurements occurred in the morning and evening at 121 points located in 20-cm cells. Discharge from these plots was measured with a current-meter automatically recording the passing water. Snow density measurements occurred in a snow pit located near the ablation squares. Density of melting ice was assumed as 890 kg m^{-3} (Shumskiy, 1978). Discrepancy between measured ablation and discharge averaged 5 mm.

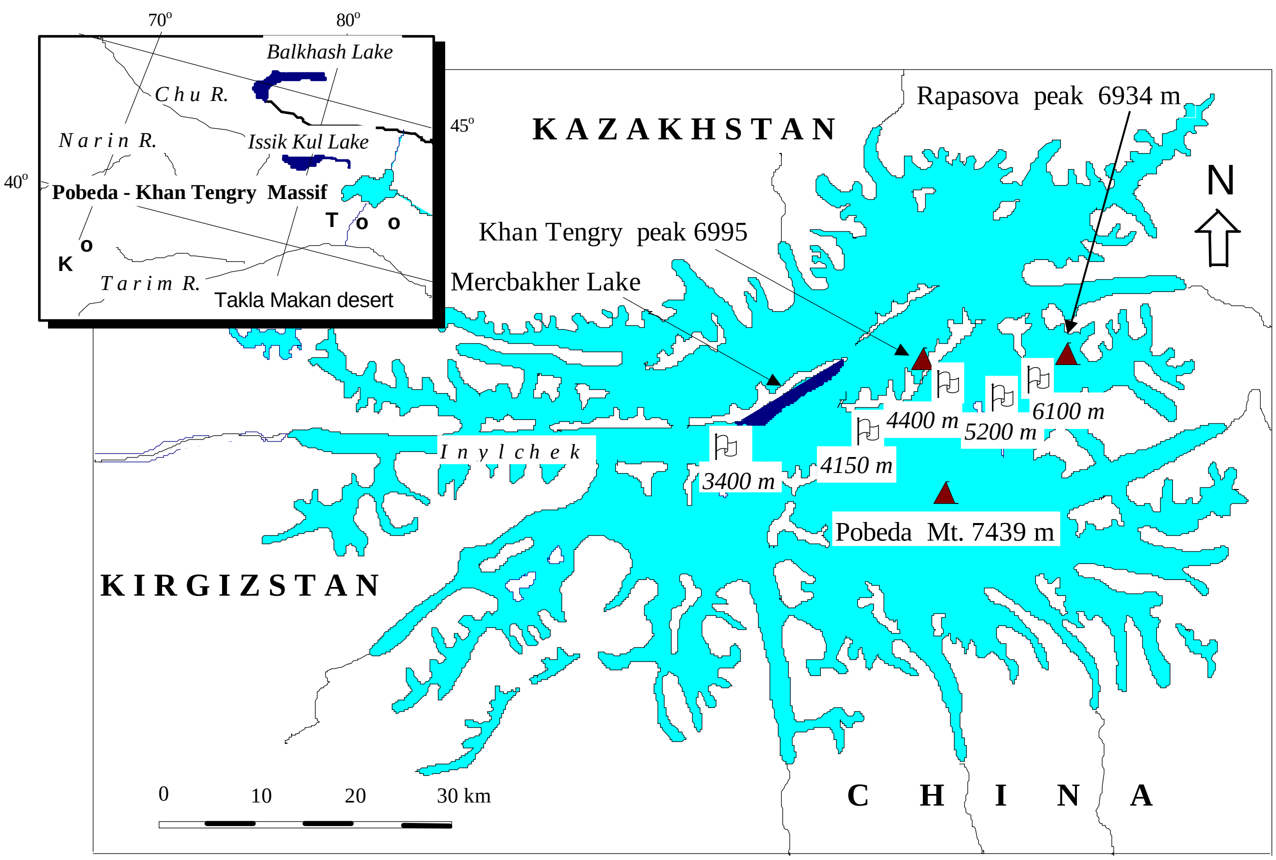

Fig.1 Pobeda-Khan Tengry glacier massif, central Tien Shan. Shading denotes glaciers; ⚐ are observation stations.

Measurements of accumulation were carried out in the accumulation zone at the beginning and end of summer because maximum precipitation occurs during summer in this region. Depth of snow cover was measured five times at more than 400 points located 50 m from one another. The measuring error was about 5% of average at a point. Snow density on snow surveys was measured by electric balance.

We analyzed the tritium concentration (^{3}H) in atmospheric moisture at 2 m above the surface, and in water from glacial channels in different glaciation zones (Aizen et al., 1995d), and in samples collected from snow and firn pits and obtained by hand drilling. The collection interval in the core varied from 5 to 30 cm depending on homogeneity of the layers. The equilibration technique for preparation of samples was applied (Epstein and Mayeda, 1953). Precision of the samples data was 1-10 TU.

The statistical analysis and simulation of present and past meteorological conditions in this region were based on long-term data from a meteorological station located 150 km west of the glacier massif. The station operated from 1930 to 1990 (Reference book, 1990). We also used precipitation data collected from 1959 to 1972 at sites located at altitudes from 2800 - 4200 m in the Inylchek glacier basin. Topographic maps of central Tien Shan region of 1:25,000 scale and synoptic maps of surface and 500 mB were used.

METHODS OF CALCULATIONS OF HEAT AND MASS BALANCE

The simplified thermal balance equation may be stated as:

$$lW = B + P_t \pm LE \qquad (1)$$

where W is the melt intensity in a point (kg m^{-2}); l (J kg^{-1}) is the latent heat of ice fusion; B is the total radiation balance (J m^{-2}), including the short-wave radiation balance (Q(1-A)) and long-wave radiation balance; Q is the income of short-wave radiation, A is the surface albedo, Pt is the turbulent heat flux from the atmosphere (J m^{-2}), LE is the latent heat flux due to evaporation or condensation (J m^{-2}). Using hourly gradient measurements, turbulent heat and humidity fluxes were calculated from functions of similarity computed by eq. 2. All calculations were carried out using the theory of surface boundary layer in homogeneous fluid developed by Monin and Obukhov (1954) and Kazanskiy (1965).

$$d > 0: \quad f_t(x) = f_q(x) = 1 + 5x \qquad (2)$$

$$d < 0: \quad f_t(x) = f_q(x) = (1 - 16x)^{1/2}; \qquad f_V(x) = (1 - 16x)^{1/2}$$

$$x = (z - d_o)/d \qquad (3)$$

where t (^{o}C) is the air temperature, q (mB) is air humidity, v (m s^{-1}) is wind, d is the distance found from non-linear equations, d_o is surface roughness, z is height of measurements above the surface. Evaporation was measured also by repeated weighing of decimeter cubes of snow and firn using electric balance with accuracy of 0.1 g.

To calculate an annual mass-balance index (I_{bi}), equation (4) was used. All components were determined at long-term mean altitude of equilibrium line position ($H_{e.l.}$= 4476 m) that was calculated by Kurowsky's method (1891). We assume this elevation is the level of average characteristics of mass exchange (Ahlmann, 1924; Krenke,1982).

$$I_{bi} = P_{e.l.} - W_{e.l.} \pm E_{e.l.} + J_{e.l.} \qquad (4)$$

where $P_{e.l.}$ is annual solid precipitation (from October to September) at altitude of equilibrium line position, $W_{e.l}$ is total glacier melt, $E_{e.l.}$ is mass of evaporation or condensation, $J_{e.l.}$ is refrozen melt water.

The total precipitation were calculated from eq.5:

$$P_{e.l.} = P_0 + \gamma(P) \cdot (H_{e.l.} - H_0) \qquad (5)$$

where P_0 (mm) is mean precipitation at the Tien Shan meteorological station at H_0 =3614 m altitude; γ(P), 0.52 mm / m, is mean altitudinal gradient of precipitation, calculated from data at the Tien Shan meteorological station (308 mm) and long-term data from precipitation sites at 4200 m (673 mm).

To estimate the total glacier melt, the air temperature at altitude of equilibrium line position ($T_{e.l.}$) was calculated by eq. 6.

$$T_{e.l.} = T_0 - \gamma(t) . (H_{e.l.} - H_0) \qquad (6)$$

where T_0 (°C) is mean air temperature at the Tien Shan meteorological station; γ(T), 0.0053°C / m, is mean altitudinal gradient of air temperature, calculated from data at the Tien Shan meteorological station and expeditionary observations at 4150 m on the glacier.

CIRCULATION and CLIMATIC PROCESSES

The high ranges surrounding the central Tien Shan prevent the entrance of moisture; hence winter precipitation is small, especially in January and February, accounting for only 8-10 % of the total in this region (Reference book, 1990). In summer, the level of condensation rises, which leads to precipitation increase at high elevations. Development of convection and strengthening of unstable atmospheric stratification result in a summer maximum of precipitation in June and July caused by cold moist air masses from west. At the same time, these high mountains are an obstacle to dry tropical air masses formed over the Takla Makan, Gobi, Alashan and Tsaidam deserts and moved to the north. These processes have a substantial effect on the mass and energy exchange of glaciers.

According to our observations on the Inylchek glacier and the analyses of synoptic maps, there are four main synoptic processes (Fig.4, Table 2):

Fig.2 Southern Inilchek glacier

Anticyclonic weather with foehn development (A_w) is the most favorable synoptic process for glacier ablation, observed with 33% frequency during two expeditionary summers. Dry foehns with low relative humidity occurred after an advection of cold air masses. Warm air masses over the Takla Makan desert flow up the southern slopes of the Kok Shaal Too range and pass down into the Inylchek and other adjoining valleys. A foehn cloudiness is formed above the ridge top while air temperature can rapidly increase 5°C on the glacier. A great amount of loess dust is brought into the valley with foehns. The atmosphere becomes less transparent and long-wave radiation increases. In two summers, the total radiation balance reached its maximum of 15 MJ $m^{-2}\cdot day^{-1}$ and albedo its minimum (34%) (Table 2). Glacier melt intensified abruptly because of heat advection. Turbulent heat exchange in heat balance was 6% (Table 2), while during the other observed types of weather the turbulent component did not play a significant role in glacier melt. This period was characterized by the contribution of condensation heat into the heat balance. Despite the foehn advection, humidity remained relatively high (76%). High humidity and aerosol dust provide the formation of intermass cloudiness and local precipitation, especially at elevations above 5000 m. According to Berg (1938) and Grudzinskiy (1959), aerosol dust is delivered from northwest of Kazakhstan and Turan to central Tien Shan. However, our observations indicated that dust is delivered by air fluxes from central Asian deserts. During this synoptic process, melt was maximum, did not stop even at night and averaged 47 mm·day^{-1}. During foehn development, it reached 82 mm·day^{-1}.

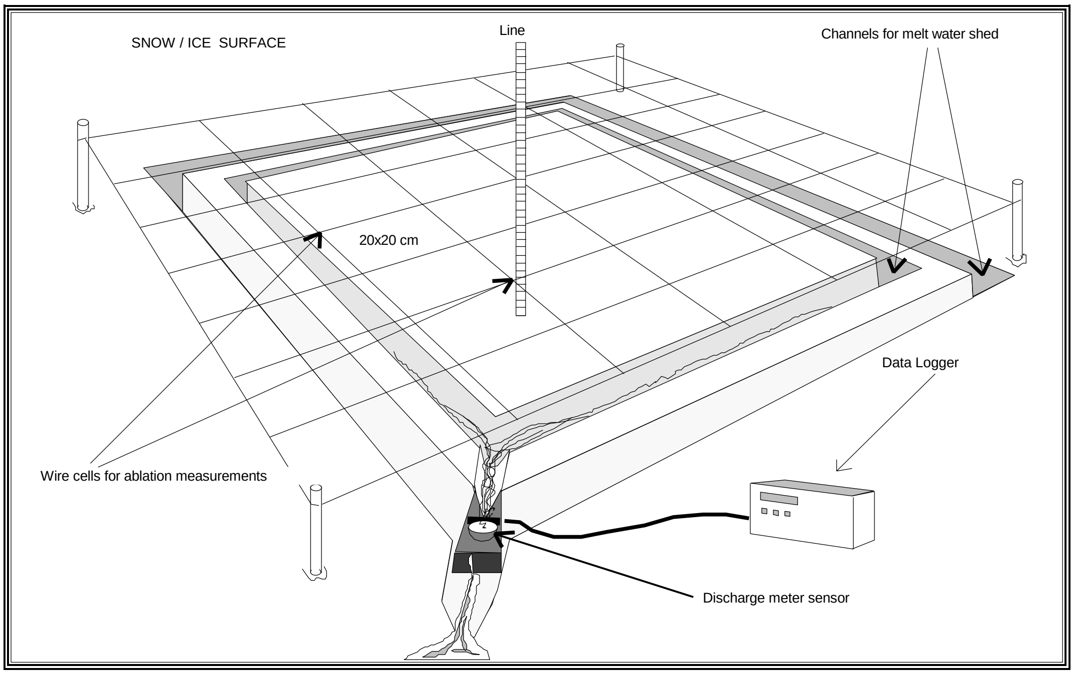

Fig.3 Ablation plot for measurements of ice and snow melt.

Anticyclonic cold weather (A_c), without precipitation occurs as cold air intrusions are followed by a slight temperature increase due to insolation and a transition to thermal depression. The frequency of this type was 19%. There was a slight decrease in net short-wave radiation and total radiation balance compared to anticyclonic warm weather (Table 2). Melt associated with radiation amounted to 23 mm day^{-1}. Due to high values of radiation balance, ice and snow melt took place at negative air temperatures with diurnal mean of -3.3ºC. During this weather, latent heat and turbulent exchange did not play any significant role in heat balance, and refreezing occurred. Relative humidity rose to 86%.

Cyclonic, warm weather (C_w) occurred with a frequency of 24%. The regime is associated with north-western intrusions, when the cold front lingering near the mountains develops wave activity (Fig.4b,c) and brings inclement weather with frequent mixed precipitation. During such periods rain was observed even at 4150 m. Net short-wave radiation falls to 19.2 MJ m^{-2} day^{-1}, albedo reaches 48%, while total radiation balance falls to 5.6 MJ m^{-2} day^{-1}. Mean diurnal temperature was 0.9ºC. Evaporation in such periods prevails over condensation reaching 13%. Melt amounted to 15 mm·day^{-1}.

Cyclonic cold weather (C_c) had 24% frequency. Cyclonic activity develops in mid-latitudes of central Asia. Cold intrusions bring precipitation (Fig.4d). During this weather in summer, snow-fall plays a key role in glacier accumulation. Net short-wave radiation (20.1 MJ m^{-2} day^{-1}) was higher than during warm cyclonic process because of multiple reflection from slopes covered by new snow. Albedo increased to 70%. In such periods we observed the lowest values of temperature (-6.9 ^{o}C) and total radiation balance (2.6 MJ m^{-2} day^{-1}). Ice and snow melt averaged 7 mm·day^{-1}, from radiation alone with little turbulent exchange (only 2%).

RESULTS OF EXPEDITIONARY MEASUREMENTS

Heat balance component. In heat balance, during summer expeditionary observations in 1989 and 1990 at 4150 m, the radiation income reached up to 96% of total, while the turbulent heat was about 4% of total. Heats of evaporation and condensation at 4150 m were negligible (Table 2) and, on whole, were compensatory taking only 7% of heat for evaporation. Evaporation prevails on average in daytime, and condensation at night, with the exception of foehn days when condensation is continuously operating (day and night). The major portion of incoming radiation is used for ice and snow melt.

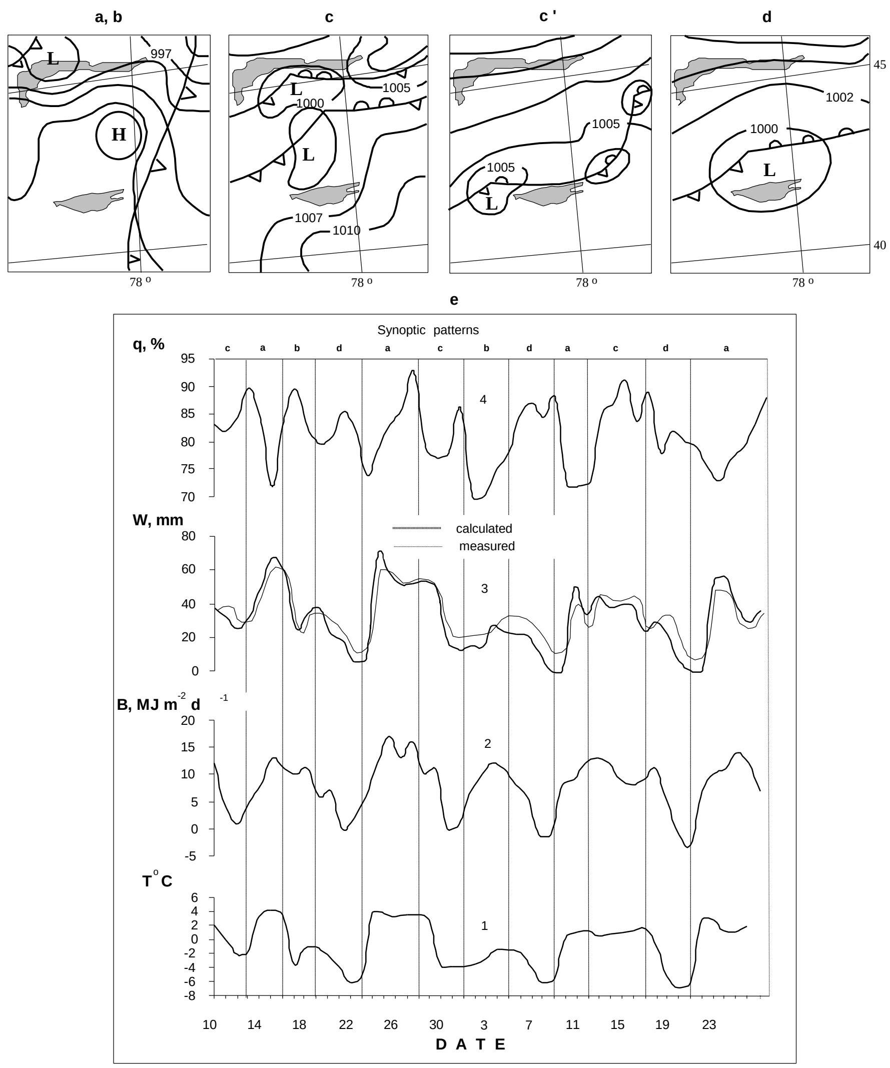

Fig.4 Synoptic (a-d) and meteorological (e) conditions at 4150 m on the southern Inylchek glacier during ablation period 1989 (July - August) of expeditionary observations. a and b are anticyclonic warm and cold weather; c and c' is cyclonic warm; d is cyclonic cold weather; e is diurnal mean air temperature (1), total radiation balance(2), glacier ablation (3), relative humidity(4).

Snow and ice melt occurs through radiation (Table 2) and can proceed both with positive and negative air temperatures. Snow and ice melt was calculated three ways: through heat balance (eq.1), solar radiation data (eq.7) and air temperature associated with different airflow patterns (eq. 8-9). The equations (7-9) were based on expeditionary measurements made on the Inylchek Glacier and were checked on the other glaciers of Pobeda - Khan Tengry massif.

$$W_d = 1.59 \cdot 10^{-3}[23.9 \cdot Q(1-A/100)]^{1.68} \quad r = 0.73 \quad (7)$$

where W_d is the daily value of snow, ice and firn melt, mm day^{-1}, Q is the daily net-short wave radiation during summer, MJ m^{-2} day^{-1}, A is the albedo, %.

$$W_d(A_w,C_w) = 12.1 + 12.5\,T \quad \text{when } T > 0.9°C \quad r = 0.71 \quad (8)$$
$$W_d(A_c,C_c) = 40.0 + 4.6\,T \quad \text{when } T<0.9°C \quad (9)$$

where $W_d(A_w,C_w)$ is melt during warm anticyclonic (A_w) and cyclonic (C_w) weather patterns, mm day^{-1}, $W_d(A_c,C_c)$ are the melt during cold patterns (A_c,C_c) of weather, mm day^{-1}.

Table 1. Technical specification of meteorological equipment.

X	System	Range	System accuracy
Air temperature	VH-G-Z1(RAD)	-30 to +70° C	0.4° C
Air humidity	VH-G-Z1(RAD)	0 to 100% rh	±2% rh
Ice temperature	CS-U	-30 to +70° C	0.4° C
Wind direction	W200	under 0.3 to 75 m/s -25 to +55° C	>10°
Wind speed	A100	-.15 to 75 m/s	±0.1 m/s
Rainfall, discharge	ARG100	under -30 to +65° C	0.2mm
Atmospheric pressure	PTB100A	800 to 1060 mbar	±0.30 mbar
Solar radiation	SES	300 to 1100 nm	
	pyrgeometer	300 to 4000 nm	
Total radiation	balansomer	> 4000 nm	

Means of daily melt calculated through these methods were close (Table 3). The relative error between calculated and measured values of melt was 2.3% - 7.6% of the average. Therefore, it is possible to calculate the melt through the solar radiation data (eq.7), or to use air temperature associated with different airflow patterns (eq. 8-9). Intensity of melt on the Inylchek glacier was high and reached 12.5 mm per 1°C.

Table 2. Average components of the heat balance and mean meteorological characteristics during different synoptic processes (SP) of ablation period (June -August, 1989, 1990) at 4150 m of Inylchek glacier. A_w and A_c are anticyclonic warm and cold weather; C_w and C_c are cyclonic warm and cold weather; Q is net short-wave radiation; B is total radiation balance; P_t is turbulent heat fluxes; LE is latent heat fluxes due to evaporation or condensation, lW is heat used for ice and snow melt; A is albedo; q is relative humidity; f is frequency of synoptic process, T is air temperature.

SP	Q	B	P_t	LE	IW	B	P_t	IW	LE	A	q	f	T
	MJ m^{-2} day^{-1}					Proportion in heat balance, %				%	%	%	°C
A_w	30.5	14.9	0.9	0	-15.8	94	6	100	0	34	76	33	3.1
A_c	26.9	8.9	0.1	-1.2	-7.8	98	2	87	13	51	86	19	-3.3
C_w	19.2	5.6	0.4	-0.8	-5.2	93	7	87	13	48	87	24	0.9
C_c	20.1	2.6	0.05	-0.2	-2.45	98	2	93	7	70	89	24	-6.9
Whole	24.6	8.5	0.4	-0.5	-8.5	96	4	93	7	49			

Meteorological regime. The average diurnal air temperature variations, its jump between glacial and non-glacial surfaces, radiation balance and relative humidity during different types of weather observed during two summer expeditions are presented on Fig.5 a-e.

Maximum diurnal variation of radiation balance was observed during anticyclonic types of weather, while the highest diurnal amplitudes of air temperature occurred during cold types of weather with substantial cooling at night and heating at daytime. The altitudinal gradient of air temperature calculated based on observational data at the altitudes of 3200, 4150, 5100 and 6100 m was found to be, on average, 0.36 ^{o}C per 100 m over glacial surface. Statistically significant correlation (r = 0.84) was revealed between mean daily air temperatures at the Tien Shan meteorological station and at the 4150 m, Inylchek glacier. Altitudinal gradient of air temperature based on records at the Tien Shan meteorological station and at 4150 m on the glacier amounted to - 0.53^{o}C per 100 m.

Anticyclonic weather was characterized by the highest frequency of northern and eastern winds (81%), especially in the first half of day. Mean wind speed in anticyclonic weather did not exceed 1.2 m s^{-1}, since calms were rather frequent that time. During cyclonic processes the frequency of western and northern winds increased to 75%, and their speed reached 2.7 m s^{-1}.

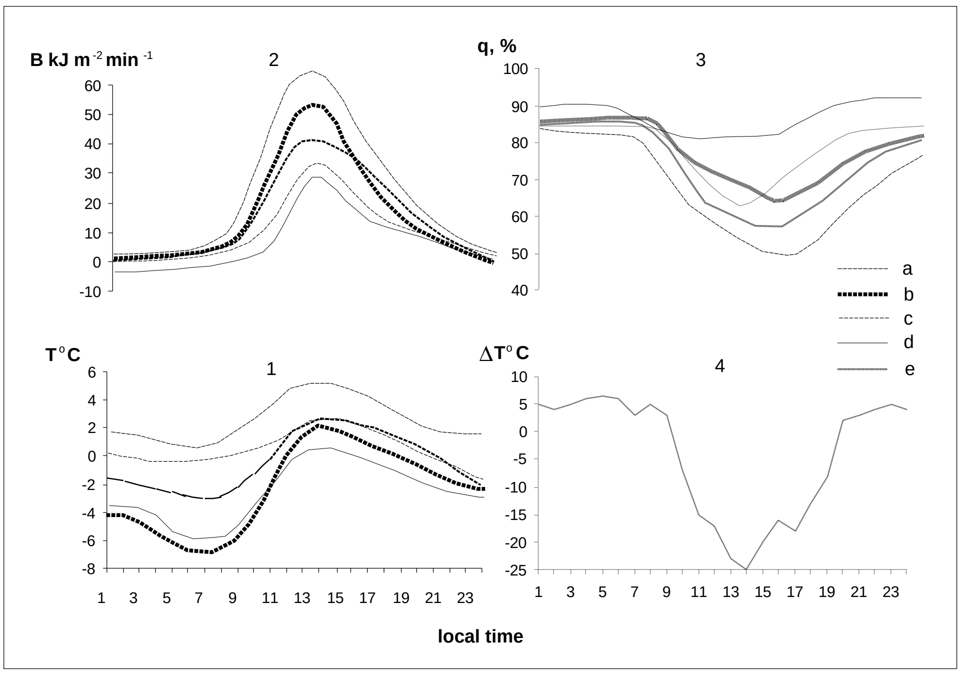

Fig.5 Diurnal variation of mean meteorological characteristics during different synoptic patterns at 4150 m on the southern Inylchek glacier during ablation period (July - August) of expeditionary observations. 1 is air temperature; 2 is total radiation balance; 3 is relative humidity; 4 is air temperature difference between glacier and moraine. a is anticyclonic warm; b is anticyclonic cold; c is cyclonic warm; d is cyclonic cold weather; e is average during whole expeditionary period.

Tritium measurements. At 4150 m the concentration of tritium in atmospheric moisture varies from 59 to 154 TU over the observation period (Table 4, Fig.6). At 5200 m the concentration of tritium in atmospheric moisture varies from 610 to 1277 TU. The high concentration of tritium there might be associated with a penetration of stratospheric moisture through a rupture of the tropopause during the passage of atmospheric jet streams, or with some other natural phenomena, including heliophysical ones. Using the tritium analysis (^{3}H) we obtained the pattern of diurnal runoff distribution in water courses in ablation zone. The abrupt increase in tritium concentration in ice melt water at night in the ablation area results from runoff from the warm firn zone. This assumption is supported by the increased tritium content at night observed only in water courses that have direct connections with the accumulation area. In smaller water courses, especially in those lying close to moraines, night-time tritium concentrations are similar to the day-time values.

STUDIES IN THE ACCUMULATION AREA

The firn fields of the southern Inylchek glacier stretch from southeast to northwest, from the slopes of Voyennikh Topografov (6873 m) and Rapasov's (6934 m) peaks to the base of Khan-Tengry peak. The area is more than 30 km^2 and the difference between lowest and highest points is 1900 m (Fig.7). A 700-m high icefall divides this area into two large parts with slightly inclined surfaces, one from 4400 to 5200 m and another from 5800 to 6300 m. The minimal wind and absence of snow avalanche redistribution inside this area are favorable for the natural accumulation of precipitation. Steady snow regime is proved by its small spatial variability ($\sigma = \pm 88$ kg m^{-2}).

According to our observations in 1989, 1990 and 1992 snow melt and runoff in the accumulation area occurred to 5200 m, while on southern slopes this boundary reached 5800 m. The annual accumulation here is saturated, and during the day air temperatures are about zero. During anticyclonic weather a thin radiation ice crust is formed on the snow surface. Under the crusts, meltwater forms vast "firn bogs" in places with slight inclinations and depressions. Night cooling is not sufficient to freeze this moist snow pack, therefore melt-water was drained from this zone during day and night.

From 5800 to 6300 m, the annual mean snow accumulation was found to be 918 g m^{-2} (in 1989). Simultaneous measurements of precipitation occurring during observation periods at 5200 and 6100 m revealed an altitudinal increase of precipitation of 2 mm per 100 m.

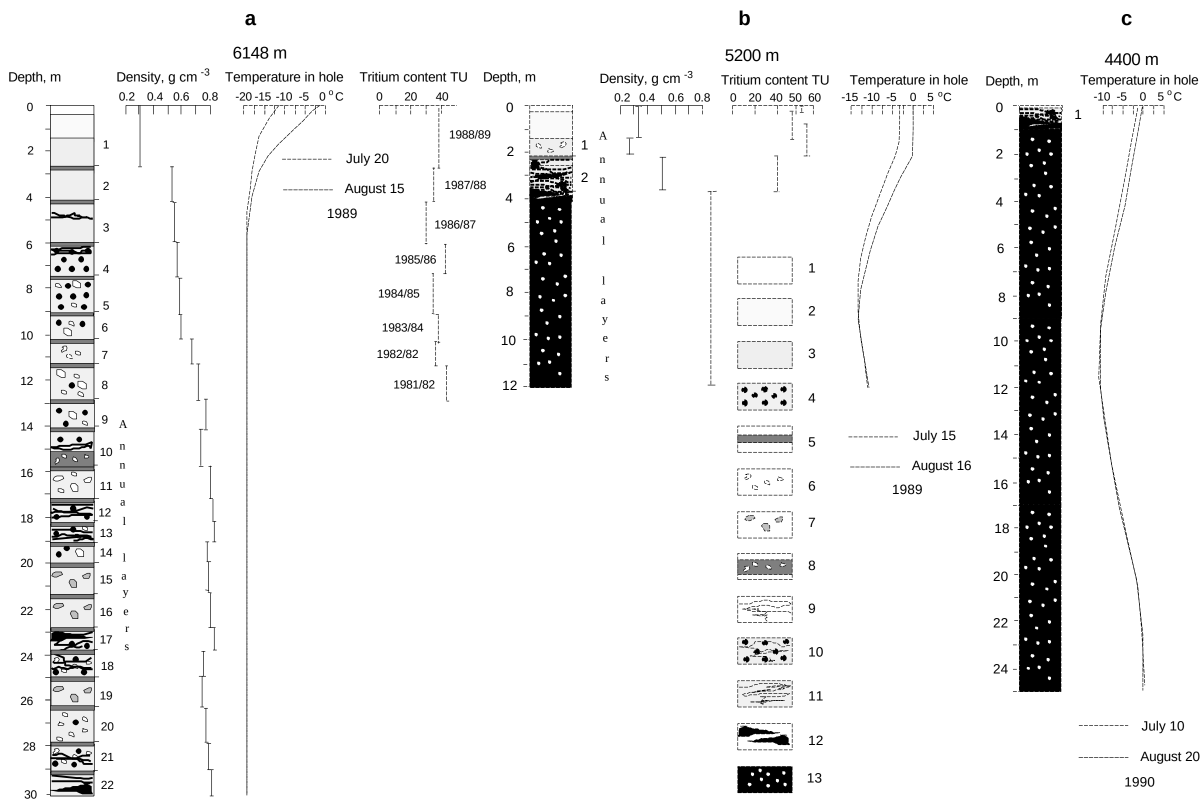

Fig.6 Stratigraphic profiles of snow, firn and ice; the temperature in drill holes and tritium content in samples from the snow, firn and ice cores at the 6148 m (a), 5200 m(b, 4400 m (c) of southern Inylchek glacier. 1 is new snow, 2 is fine grained firn, 3 is medium grained firn, 4 is coarse grained firn, 5 is crust with dust, 6 is ice lens, 7 is dense firn lens, 8 is crust dust and ice lens, 9 is trace of get wet through firn layer, 10 is get wet layer coarse grained firn, 11 is get wet layer medium grained firn, 12 is ice crust, 13 is monolith of ice, 14 marks of annual layers.

To assess the annual accumulation and temperature, two cores about 30 m long were drilled at 6148 m. Fig.6 shows the structure of two averaged snow-firn cores. Twenty one annual layers of accumulation were separated in the drilled holes by snow/firn/ice core stratigraphic analysis and 23 in the 28 m depth section along the cleared firn/ice wall of the crevasse at the same altitude. Annual layers were identified by summer horizons of more compact firn and yellowbrown aeolian dust. According to ours and previous studies (Racek, 1954), dust indicated the annual layers is delivered from deserts only in the second half of summer and beginning in autumn during steady anticyclonic weather.

Verification of annual layers was made also by tritium (^3H) sampled from the strata (Fig.6). The marks were the layers accumulated during rather high tritium content in 1981-82 and 1985-86, caused by nuclear tests conducted in China and the disaster at Chernobyl. According to identification of annual layers in the cores, the mean annual snow accumulation, was found to be 900 mm (Table 5) at 6148 m. Results of stratigraphic analyses is justified by a good correlation (eq.10) between annual accumulation measured at 6148 m and annual precipitation measured at Tien Shan station.

$$A_k = 27.7 \cdot P^{0.61}, \quad (r = 0.89) \quad (10)$$

where A_k is accumulation over the hydrological year (from September to August) in Inylchek glacier (6148 m), P is annual precipitation measured at Tien Shan station, η correlation ratio. According to Chinese results (Mount Tuomuer, 1982), the annual precipitation was about 800 mm at the same altitudes on the southern slope of Kok Shaal Too near the Pobeda peak. Increase of precipitation with altitude is not a linear function (Fig.8). The altitudinal distribution of precipitation was calculated on the basis of long term meteorological data from Tien Shan meteorological station, precipitation sites and snow surveys in Inilchek glacier area.

Table 3. Calculated means of ice and snow melt (W, mm day^{-1}) and measured ablation (Am, mm day^{-1}) during different synoptic processes (SP) of ablation period (June -August, 1989, 1990) at 4150 m of Inylchek glacier. A_w and A_c are anticyclonic warm and cold weather; C_w and C_c are cyclonic warm and cold weather; $W_{h.b.}$ is calculate melt though heat balance, W(T) is calculate melt though air temperature; W(Q) is calculate melt though short wave radiation balance.

SP	$W_{h.b.}$	W(T)	W(Q)	Am
A_w	-47	-51	-51	-44
A_c	-23	-25	-25	-22
C_w	-15	-23	-16	-19
C_c	-7	-8	-7	-1
Whole	-25	-29	-27	-23

Four ice formation zones have been revealed in the southern Inylchek accumulation area (Fig.7), none of them having any clearly delineated distribution area. The icefall dividing the accumulation area into two parts seems to lie in the cold infiltration-recrystallization zone where the meltwater becomes ice due to infiltration. Stratification analysis of snow firn layers has shown that over 6000 m ice was formed by subsidence and recrystallization at depth exceeding 30 m. Therefore, the altitudinal belt over the 6000 m, we determined as recrystallization zone where melt does not occur.

The value of ice formation in lower zones (F) was calculated by Zikin's method (Zikin, 1962).

$$F = \frac{c \cdot p}{l} \cdot \int_{Z1}^{Z} \Delta T(Z) dz, \quad (11)$$

where c = 2.09×10^3 J kg^{-1} °C^{-1}, is specific heat capacity of ice; l = 333.6×10^3 J kg^{-1}, is heat of ice melt; p, kg m^{-3}, is ice density; Z_1, m, is boundary between firn and ice; Z, m is the lower boundary of active ice layer; and ΔT, ^{o}C, is ice temperature variation. Ice temperatures in drill holes at altitudes 6148, 5200 and 4400 m were measured at the beginning and end of ablation period (Fig.6a,c). The value of ice formation in the warm infiltration-recrystallization zone (4600-5200 m) calculated by eq.11 was 140 kg m^{-2}, under p = 880 kg m^{-3} and Z = 7 m. In the infiltration zone (4200-4600 m), the value of ice formation was 90 kg m^{-2}, under p = 890 kg m^{-3} and Z = 9 m.

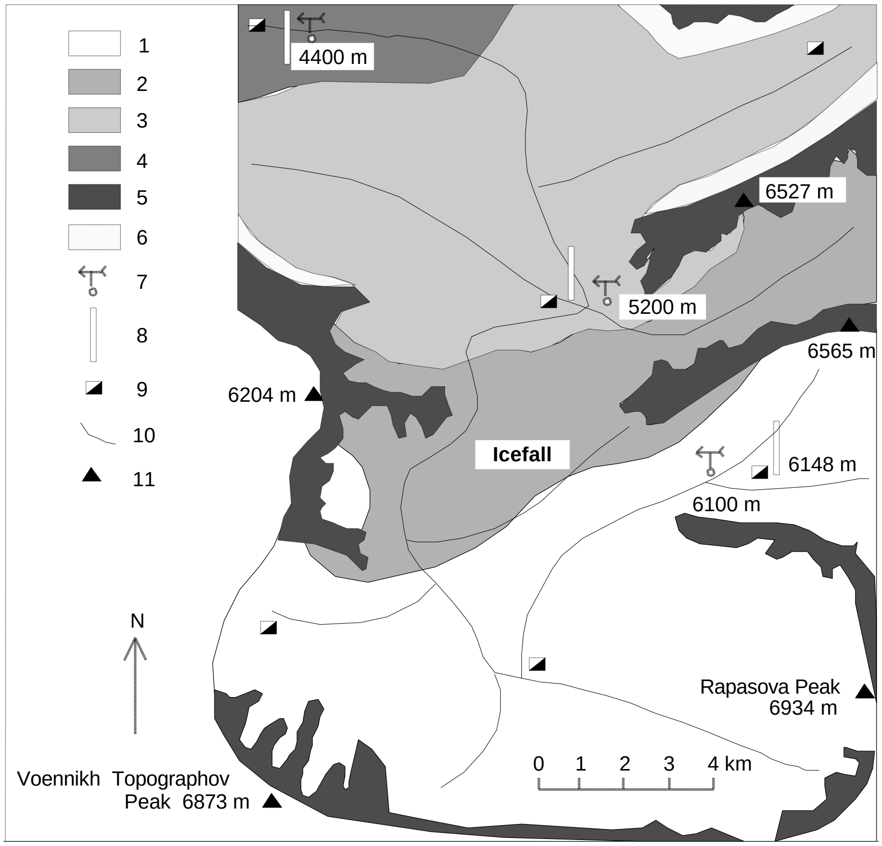

Fig.7 Ice formation zones on firn field of the southern Inylchek glacier. 1 is recrystallization, 2 is recrystallization - regelation and cold infiltration, 3 is warm infiltration, 4 is infiltration, 5 is rocks, 6 is moraine terrace, 7 is observation site, 8 is drilling holes, 9 is snow pits, 10 is snow survey transects, 11 is altimetric points.

Table 4. Range of tritium concentration (^{3}H,TU) in samples of atmospheric moisture(am), glacier runoff (gr), channel water (cw), water in glacial lakes (wl), new snow (ns), surface snow (ss), moister firn (mf) and ice (i) in the Inylchek glacier in July, August, 1989.

H, m	am	gr	cw	wl	ns	ss	mf	i
1200		48	6-20					
4100	59-154			4	50-53	52-61		3-4
5100	610-1277			38	39-45		40	54

In the 30 m hole drilled at 6148 m, diurnal temperature changes were observed only in the top layer of annual accumulation (Fig.6a). At greater depths, the temperatures were constant, and at the bottom temperature was -21^{o}C, that is about annual mean air temperature at this elevation. Calculations of mean annual air temperature at this level were made through the Tien Shan station data using temperature gradient of -0.53^{o}C per 100 m. At 6100 m, in the August, 1989, and 1990 mean diurnal air temperature was about -10^{o}C. During daytime it did not rise over -2.0^{o}C, while at nights it could be as low as - 25.0^{o}C. At these altitudes, air temperature and moisture variations mostly depend on intermass processes. Heat flux brought by foehns was not significant there. High humidity, observed especially at night (85-95%), was favorable for hoarfrost forming. The condensation overnight can be as high as 1.5 - 2.0 mm. At accumulation area of the southern Inylchek screened from the west, the average wind speed was 1.7 m s^{-1}, and never exceeded 6 m s^{-1}. At the same time, on Kok Shaal Too and Tengry Tag slopes, the wind speed reached 40-80 m s^{-1} during cyclonic and foehn weather.

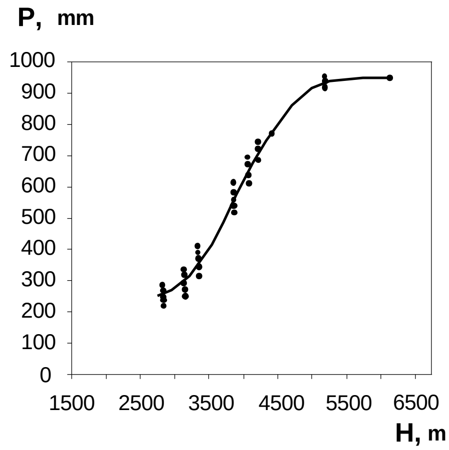

Fig.8 The vertical change of annual precipitation in the Inylchek valley.

During cloudless weather, at 55 - 60% relative humidity, the evaporation was 1.5-2.0 mm per day. It is lesser than at the same altitudes of western Kun Lun, in extra-continental climate where evaporation reached 5.5-9.7 mm day, with 30% relative humidity (Glaciological Studies in West Kunlun Mountains, 1987). During anticyclonic weather local vertical fluxes develop cloudiness, humidity increased abruptly and from 2:00 to 3:00 p.m. snow started. Precipitation from such cloudiness being typically local amounted to 5-7 mm per day. At nights the cloudiness was dispersed or disappeared.

Table 5. Thickness of annual snow-firn layers (h_i, cm), density (p_i, g cm^{-3}) and water equivalent (C_i, mm) in the recrystallization zone of Inylchek glacier, 14-15 August, 1989 at the 6148 m.

Years	h_i	ρ_i	C_i
1989	275	0.32	880
1988	152	0.53	806
1987	170	0.55	935
1986	160	0.57	912
1985	146	0.58	847
1984	114	0.6	684
1983	105	0.68	714
1982	138	0.71	980
1981	130	0.78	1014
1980	137	0.73	1000
1979	133	0.8	1064
1978	97	0.81	786
1977	88	0.83	730
1976	97	0.78	757
1975	123	0.79	972
1974	137	0.8	1096
1973	90	0.83	747
1972	124	0.76	942
1971	129	0.74	955
1970	135	0.77	1039
1969	133	0.79	1051
Ave.			900

MASS BALANCE of INYLCHEK GLACIER

To calculate annual mass balance indices of the Inylchek glacier (Fig.9), the long term data of total precipitation and mean summer air temperatures at the Tien Shan meteorological station were extrapolated up to elevation of equilibrium line position (4476 m). Annual precipitation was calculated by eq.5, annual ablation by eq.6, 8, and 9. Assessment of annual melt ($W_{e.l.}$) has been calculated by eq.12

$$W_{e.l.} = W_d \cdot m \qquad (12)$$

where m is number days when melt occurs under the certain state of 8, 9 equations. We assumed evaporation loses and condensation gains compensate, and a consistent value of refrozen meltwater equaled 90 mm per year.

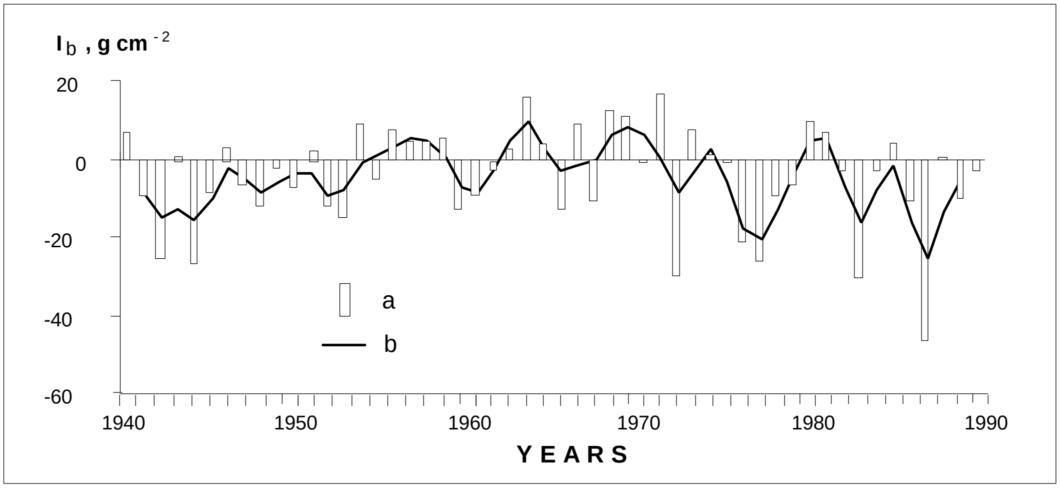

Fig.9 Indices of glacier mass balance (a) and their centrally weighted moving average values (b) of the Inylchek glacier, central Tien Shan.

There are about decade periods of positive and negative deviations in glacier mass balance indices (Fig.9). From 1940 to 1953 and from 1973 to present the glacier had a negative mass balance. For the Inylchek glaciers the average weighted mean annual accumulation is 752 mm, the snow/ice ablation average weighted mean is 1070 mm, and the index of net glacier mass change is negative, -318 kg m^{-2} yr^{-1}, indicating degradation of modern Pobeda - Khan Tengry glaciers.

CONCLUSIONS

The result of our analysis is extending understanding of the climatic, meteorological and hydro-glaciological conditions around the continental glacial Pobeda - Khan Tengry massif, one of the largest in the World.

Four major synoptic situations have been identified, with an average four-day duration, which control regimes of temperature, radiation balance and melt. In the accumulation area, weather conditions have a lesser effect, and a considerable role is determined by internal processes affecting a local water exchange. The development of internal processes is promoted by the high moisture content of air masses coming mostly from the west. At the same time our observations indicated that dust is delivered by air fluxes from central Asian desserts during foehn development.

Radiation contributes more energy for snow and glacier melt then the combination of all other forms of heat transfer and amounts more than 90% of input in heat. Melt is most intensive during periods of anticyclonic weather with foehn development. Only at these periods, turbulent exchange and condensation occurred. Foehns bring huge amounts of dust from Tarim effected radiation balance and caused the development of local cloudiness and precipitation formation. Because the melt regime is determined there mainly by solar radiation, it was better to calculate the melt and runoff through the solar radiation data, or to use air temperature associated with different weather patterns. Evaporation and condensation are either mutually compensatory or of negligible effect during other synoptic situations. Spatial distribution of ice formation zones yielded the upper boundary of liquid runoff at 5200 m.

Accumulation process was associated with cold cyclonic weather. Estimation of annual accumulation was obtained from 4150 to 6300 m widen information about precipitation distribution in accumulation areas of the Tien Shan sub-continental glaciers. Spatial distribution of ice formation zones revealed that the recrystallization zone locates above 5800 m. Four ice formation zones have been revealed in the southern Inylchek accumulation area.

The net glacier mass change is negative, -318 g m^{-2} yr^{-1}, indicating degradation of modern Pobeda Khan Tengry glaciers.

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REFERENCES

Aizen, V.B., E.M. Aizen and J.M. Melack, 1995a. Characteristics of runoff formation at Kirgizskiy Alatoo, Tien Shan, *IUGG XXI*, Boulder, Colorado, *Proc.International Meeting*, **208**, 413-430.

Aizen, V.B., E.M. Aizen and J.M. Melack. 1995b. Precipitation, melt and runoff in the northern Tien Shan. *J. Hydrology*, USA,. (in press).

Aizen, V.B., E.M. Aizen and J.M.Melack, 1995c. Climate, snow cover and runoff in the Tien Shan, *Water Resources Bulletin*, USA, **31** (6), 1-17.

Aizen, V.B., E.M. Aizen, J.M.Melack and T.Martmaa, 1995d. Isotopic measurements of precipitation on central Asian glaciers. (Southeastern Tibet, northern Himalayas, central Tien Shan). *J.Geophys. Res.* USA. (in press).

Aizen, V.B. and E.M. Aizen, 1994a. Regime and mass-energy exchange of subtropical latitude glaciers under monsoon climatic conditions: Gongga Shan, Sichuan China, *Mountain Research and Development*, USA, **14**(2), 101-118.

Aizen,V.B. and E.M.Aizen, 1994b. Features of regime and mass exchange of some glaciers on central Asia periphery. Japan, *Bull. Glacier Research* **12**, 9-24.

Ahlmann, H.W., 1924. Le niveau de glaciation comme fonction de l'accumulation d'humidite sous forme solide. *Geogr. Annal*., 223-272 (French)

Berg, L.S. 1938. The basis of climatology, Leningrad, *Teacher Publishing*, 43. (Russ.).

Dolgushin, L.D. and G.B. Osipova. 1989. Glaciers, Moscow, *Misl Publishing*, 447. (Russ.).

Glaciological Studies in West Kunlun Mountains, 1987. Water Research Institute, Nagoya University, Japan and Lanzhou Institute of Glaciology, *Academia Sinica, China*, 196.

Glacier inventory in China. Tien Shan Mountains. 1986-1987. LIGG, III, *Academia Sinica* (Chinese).

Grudzinskiy, M.A. 1959. Zvezdochka glacier. in book: Victory Peaks, Moscow, *Geographical literature Publishing*, 167-214. (Russ.).

Hong,M., L. Zongchao and L. Yifeng. 1992. Energy balance of snow cover and simulation of snowmelt in the western Tien Shan mountains, China. *Ann.Glaciology*, **16**, 73-78.

Kazanskiy, A.B. 1965. About Richardson's critical number. The physics of atmosphere and ocean, Moscow, *AS USSR*, Part **I**, 875-879. (Russ.).

Konovalov, B.G., 1979. Calculation and forecast of Middle Asia glacier melt, Leningrad, *Hydrometeo Publishing*, 1-232. (Russ.).

Krenke, A.N. 1982. Mass-exchange of glacier systems on USSR territory, Leningrad *Hydrometeo Publishing*, 1-288. (Russ.).

Kurowski, L.,1891. Die Hohe der Schneegrenze mit besonderer Berucksichtingung der Finsteraargorn-gruppe. - *Pencks geogr. Abhandlungen*, Bd **5**.

Monin, A.S. and A.M.Obukhov. 1954. Main characteristics of turbulent mixing in atmosphericsurface boundary. *Works Geophysical Institute, AS USSR*, **24** (151), 3-17. (Russ.).

Mount Tuomuer. 1982. Scientific expedition, Academia Sinica, *Xinijang People Press*, 1-154.

Racek V.I. 1954. Glaciation of Peak Pobeda massif. Moscow, Leningrad, In book: *Geographical collection*, **IV**, 59-81. (Russ.).

Reference book of climate USSR, 1990. Kirgizskaya SSR, Leningrad, *Hydrometeo Publishing* Vol. **18**, **19**, **31**, **32**, parts 1, 2, 4. (Russ.)

Shumskiy, P.A. 1978. Dynamic glaciology. Translated from the Russian by U. Radok and V.J.Vinocuroff. Amerid Publishing Co., New Delhi, India. (Original publication 1969).

Zhenniang, Y. 1988. General situation of research hydrology of glaciers in China in the last years. *J Glaciol. Geocryol.*, **10** (3), 256-261. (Chinese)

Xie, Z., B. Zheng, J. Li and Y. Shi. 1982. Distribution, features and variations of glaciers in China. Proc. Conference on Glaciology and Geocryology of Chinese Geographical Society, *Science Press*. (Chinese.)

Zikin, E.M. 1962. Mass accumulation in firn glacial zones (method of investigation based on temperature profile), Moscow, USSR, *AS USSR Publishing*, 95. (Russ.).