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Association between atmospheric circulation patterns and ice core records from a snow-firn field on the Inylchek Glacier, Central Tien Shan Mountains, Asia

1998/1999 Tien Shan field reconnaissance and preliminary research in advance of DOE/NSF 2000-2002 deep ice coring paleo-climatic reconstruction program

Technical report

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Contents

INTRODUCTION

The climate of mountainous regions exhibits complex meteorological and synoptical processes that make these environments particularly sensitive to fluctuations of these parameters. An array of high resolution, multi-parameter ice core records developed from mountain glaciers in temperate and tropical regions of the globe can be used to document regional climatic and environmental changes in the latitudes which are home to the vast majority of the Earth's human population. In the summer of 2000, we propose to recover two surface to bottom ice cores from a site in the Central Tien Shan on the Inylchek glacier (Khan Tengry massif) at 5200 m a.s.l. The objectives of this expedition are twofold: (**a**) Develop high resolution, multi-parameter paleoclimatic records for at least the past 2000-3000 years through the chemical and physical analysis of ice cores; and (**b**) investigate the synoptic climatology and quantify the sources of moisture, which nourish glaciers in the Tien Shan Mountains. For the last ten years one of the largest sub-continental glacier systems in the World, the Khan Tengry massif has experienced surface degradation equal to approximately 1.5 m in the ablation zone. What is the main factor determining the change in mountain glaciers? Is it a regional or global forcing impact; is it a periodic or continuous degradation and what will happen with this large continental glacier system in nearest future?

In order to improve our understanding of long-term glacio-climatic records we plan to recover from the region, analyze on the interaction between synoptic-scale atmospheric patterns and modifications of precipitation and temperature regimes during the 1990s was occurred. We used hydro-meteorological, synoptic, and firn/ice core records obtained from the samples collected during the 1998 and 1999 field seasons. The preliminary data sets were developed in order to improve the method of ice core interpretation and to understand the sources and timing of moisture inputs from modern observations. This information should facilitate the reconstruction of past climatic events and patterns.

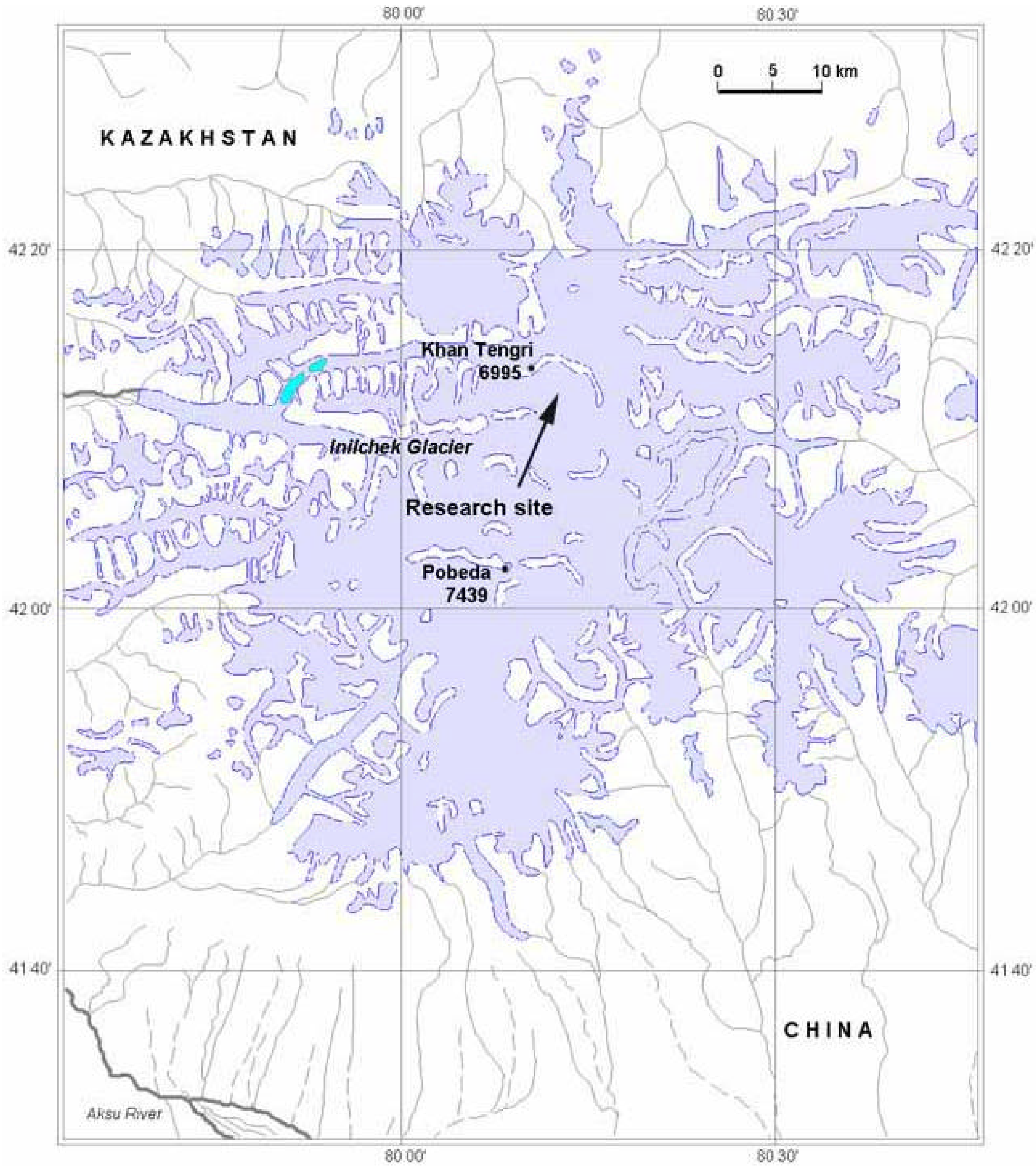


Fig. 1. Region of the research

The Inylchek Glacier in the Central Tien Shan Mountains is located (**Fig. 1, 2**) on the northwestern periphery of the central Asian highlands. This site was identified as a suitable location for the recovery of ice cores and subsequent development of paleoclimatic records for the following reasons. **First,** the Inylchek is the largest glacier in the Tien Shan Mountains extending over 60 km in length and covering an area of 794 km^2. The upper accumulation zone is characterized by a gently sloping surface ranging in elevation from 5100 to 5200 m a.s.l. and covers an area of approximately 220 km^2. Glaciological investigations over three field seasons in 1989, 1990, 1992 (*Aizen et al., 1993, 1997, 1998*) and field reconnaissance in 1998 and 1999 (*Kreutz et al., in review*) have determined that little or no melt occurs in the accumulation zone at elevations greater than 5000 m, and that annual layers can be clearly identified in the visible (dust layers) and chemical (major ions, $\delta^{18}O$)

stratigraphy (*Aizen et al., 1997; Kreutz et al., in review*). The relatively low wind speeds and the absence of snow redistribution by avalanches in the accumulation zone provide favorable environmental conditions (**Fig. 2**) for the accumulation of undisturbed, horizontal layers of snow. **Second**, the location of the Tien Shan on the northwestern margin of the Central Asia Mountains provides a unique opportunity to develop records relating to major circulation systems such as the westerly jet stream and the Siberian High. **Third**, there exists a hydro-meteorological data set and extensive synoptic information for the past 60-100 years (*Almanac, 1968; 1980; 1993*; *Reference book of climate USSR, 1990*). These hydro-meteorological and synoptic observations provide sufficient data for detailed climatological analyses and the results can be used for comparison with and calibration of ice core records.

Fig. 2. Inylchek Glacier firn fields

Data and Methods

The statistical analysis and simulation of present meteorological conditions in this region were based on long-term data from the Tien Shan meteorological station located 150 km west of the Inylchek glacier massif at 3614 m. This station has the most representative and comparable to the observations from the Inylchek Glacier data among the other alpine stations for the study region (*Aizen et al., 1997*). We used monthly frequency data for the period 1968 – 1998 on fourteen types of synoptic processes observed (*Almanac, 1968; 1980; 1993; CADB*) in Central Tien Shan Mountains identified by Baidal *(1962)* and Subbotina, *(1995)*. A description of synoptic processes (**Table 1)** and synoptic maps at 500 mB and over the Earth surface *(Manual on short- term weather forecast, 1986*) (**Fig. 3**) were used to identify patterns associated with precipitation and origination of moisture nourishing the glacier.

During the summer of 1998, snow and firn samples were collected every 3-5 cm from five 2-m snow pits and a 12.36-m firn core in the accumulation zone at 5100 m of the Inylchek Glacier. These samples were analyzed for $\delta^{18}O$ and major ions. A full description of sample collection and analytical methods used is presented in *Kreutz et al.* (*in review).* There was no sign of melt or water percolation, which is known to complicate glaciochemical records.

Table 1. Brief description of synoptic processes observed over Central Tien Shan (*Manual on short-term weather forecast. 1986.)*

	Name	Origination and trace	Description
1	South-Caspian cyclone	Eastern and central part of Mediterranean S, south of Caspian Sea, Turkmenia, Aral Sea; Uzbekistan, Pamiro-Alay; Tien Shan, western Siberia.	Dust storms over valleys; some precipitation, observed during spring, autumn and winter.
2	Murgab cyclone	Mesopotamia, Iran, south Caspian Sea, south-east Turkmenia, Tadjikistran, Fergana valley,	Significant precipitation, thaws in winter. Observed from October to May
3	Upper Amy-Darya' cyclone	Tadjikistan, Uzbekistan, Issik-Kul lake; south-east Kazakhstan	Significant precipitation. Observed spring, autumn, winter
5	N-NW cold advection	Southeastern part of Europian territory of Russia, western Kazakhstan, Ustuyrt plateau	Intensive precipitation with decreasing air temperature.
6	Northern cold advection	Urals, western Siberia and Kazakhstan	Decreasing air temperature, strong wind, possible precipitation
7	Large-amplitude stationary waves	Turkmenia, eastern Middle Asia, north-east direction.	The strong western air streams are observed at upper elevation, possible precipitation
8	Weak-mobile cyclones	Over Middle Asia	Short-time precipitation
9, 9a, 9b	S, S-E,S-W periphery of Siberian High		Possible insignificant precipitation, mainly observed during winter, spring and autumn
10	Influxes of air masses from west	Air of middle (sometimes arctic) latitudes from Atlantic, Mediterranean, Black, Caucasus M, Caspian seas	Maximum moisture content in air masses; moisture transferring at high elevation; intensive precipitation.
11	Summer thermal depression	Deserts of Central Asia	Dust storms, only in summer, strong increasing temperatures
12	High-pressure system with small barometric gradients		Clear weather without precipitation and special phenomena
13	Warm sector of a southern cyclone (types 1-3)	See types 1-3	
14	Western cyclones	Eastern Mediterranean sea, Black and Caspian seas, southern Middle Asia.	Precipitation, moisture transferring at low elevation and over southern latitudes

Samples were melted immediately prior to ion chromatographic analysis at the UNH for major ion composition. Anions (Cl^-, NO_3^-, and SO_4^{2-}) and cations (Na^+, Ca^{2+}, K^+, Mg^{2+}, NH_4^+) analyses were performed via suppressed ion chromatography (Dionex 4000 series instruments). Upon melting, an aliquot (10ml) of sample was removed, refrozen, and shipped frozen to the University of Maine for oxygen isotope ($\delta^{18}O$) analysis. A VG-Fisons Sira Series II mass spectrometer fitted with dual inlets, triple collectors, and mated to an automated CO_2 equilibration device was used for analysis (precision ±0.05%o). Sample ratios were reported relative to standard mean ocean water (SMOW).

Sensitivity of Regional Climates to Synoptic Scale Patterns

Air Temperature and Precipitation. For the summer period from 1985 to 1998, mean air temperature increased up to 1.7°C over the long-term average for the 1936 to 1984 and decreased during cold seasons by as much as 3.1°C (Table 2, Fig. 4a). During the period 1985-1998, annual precipitation has decreased on average 80 mm over the long-term average for the 1936 to 1984, i.e., by 26% (Table 2, Fig. 4b). For the past decade, a negative trend in precipitation was revealed and attributed mainly to decreases in summer precipitation (Table 2, Fig. 5a). The months of maximum precipitation shift to an earlier date because of decreasing summer precipitation (Fig. 4b).

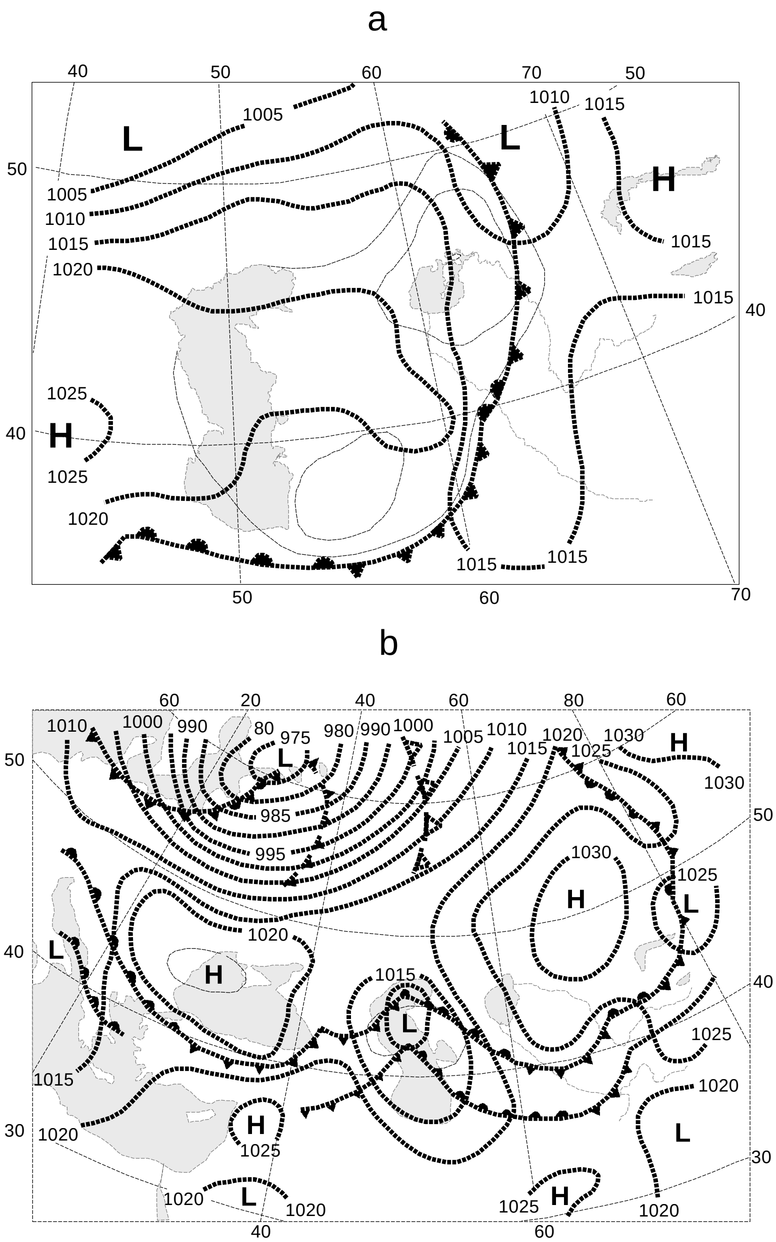


Fig. 3. Synoptic processes over the surface: (a) Influxes of air masses entering from west (10 type). January 10, 1982; (b)Western cyclone (14 type). January 21, 1982.

Association between Synoptic Processes and Regional Precipitation. In order to detect the circulation conditions that are resulted in a decrease of precipitation for the last decade in the Central Tien Shan Mountains, we computed the correlation coefficients (Table 3) between synoptic processes (fourteen types, see Table 1) and monthly precipitation. In addition we computed a monthly linear trend for fourteen types of synoptic processes for the period 1985 – 1998. Only statistically significant linear trends in frequency of the synoptic processes, which have statistically significant correlation with precipitation, are presented in Table 3. The signs of correlation coefficients and linear trends are opposite, i.e., the frequency of synoptic processes favorable for the development of precipitation (e.g., 10 type Table 3) decreased during 1985-1998, and conversely… During the thirteen years of 1985 -1998, the annual amount of influxes of air masses entering from the west (10 type) has decreased on average by thirty-five influxes (Table 3) and partially during warm

Table 2. Changes over the last decade in annual monthly precipitation (P, mm) and air temperatures (T,°C) at the Tien Shan station P_{36-85}, P_{86-97} and T_{36-85}, T_{86-97} are average precipitation and air temperatures for the periods from 1936 to 1985 and from 1986 to 1998. β is linear trend for the period from 1985 to 1998, F' = 3.29 is critical value under the degrees of freedom: $df_1 = 1$; $df_2 = n-2 = 11$ (number of observations) at the 90%; S is share of monthly trend in annual.

	Jan	Feb	March	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
P_{36-84}	6	6	14	21	43	56	58	50	28	11	8	7
P_{86-97}	3	6	13	15	32	38	34	37	15	17	8	9
β mm/yr	-0.1	-0.35	-1.34	-0.37	-1.75	-4.93	-3.62	-3.97	-1.17	-0.73	-0.08	-1.05
F	0.28	2.86	6.16*	0.28	1.27	20.41*	6.42*	6.83*	3.78*	0.53	0,02	5.11
S, %	0.5	1.8	6.9	1.9	9	25.3	18.6	20.4	6	3.8	0.4	5.4
T_{36-84}	-21.6	-16.4	-13.8	-6.7	-1	2	4.3	3.9	-0.7	-6.2	-14.2	-19.7
T_{86-97}	-21.8	-19.5	-13.9	-7.4	-1.5	2.2	5	4.1	0.9	-6.7	-14	-18.6
β grad/yr	-0.31	-0.14	0.01	-0.19	0.05	0.13	-0.01	0.05	0.13	-0.04	0.03	-0.26
F	3.7*	1.57	0.01	1.39	0.22	2.72	0.01	1.02	2.62	0.11	0.05	5.97*

Table 3. Statistically significant linear trend (β) in number of events of synoptic processes for the period 1985 - 1998 in the central Tien Shan under the significant correlation coefficient (at 10%) between precipitation and synoptic processes, r is coefficient of determination; F' = 3.29 is critical value under the degrees of freedom: $df_1 = 1$; $df_2 = n-2 = 11$(number of observations) at the 90%.

Type of synoptic process		3	6	7	8	9, 9a, 9b	10	12	13a
March	trend		0.13	0.88		0.41	-0.58		-0.16
	F		4.79	5.08		3.8	7.6		2.57
	r		-0.43	-0.45		-0.59	0.72		0.41
April	trend					0.29	-0.5		
	F					3.27	4.33		
	r					-0.46	0.51		
May	trend					0.42	-0.36	0.65	
	F					5.14	4.04	5.39	
	r					-0.44	0.44	-0.51	
June	trend	-0.07		0.8	0.29	0.45	-0.24	0.21	
	F	7.23		50.16	9.25	6.82	3.75	7.73	
	r	0.54		-0.7	-0.53	-0.63	0.43	-0.46	
July	trend					0.32			
	F					8.81			
	r					-0.65	0.44		
August	trend					0.73	-0.35	0.41	
	F					31.1	3.75	4.43	
	r					-0.79	0.45	-0.51	
September	trend						-0.38	0.38	
	F						4.65	7.94	
	r						0.48	-0.41	
Year	trend			5.12	1.0	1.2	-3.21		
	F			25.52	5.83	5.22	10.09		

seasons when the frequency decreased by more than 50 percents of the long-term average (Table 4). Among six types of synoptic processes, which associated with precipitation (*Manual on short-term weather forecast, 1986*) (Table 4), only frequency of influxes of air masses entering from the west has statistically significant correlation with amount of precipitation. Frequency of north-northwestern (N-NW) cold air advection (5 type) which brought intensive precipitation with decreasing air temperatures (see Table 1) also has decreased more than twice during warm season (Table 4) of 1985-1998. However, the mean number of entrance of western cyclones increased during the last thirteen years over the long-term average more than twice (Table 4) that is also favorable for precipitation development (type 14) in the Central Tien Shan. The frequency of synoptic processes with location of the southeastern periphery of the Siberian High (9a type, Table 1) has increased 13 events for the thirteen years (Table 3). This pattern of synoptic process is not favorable for the development of precipitation.

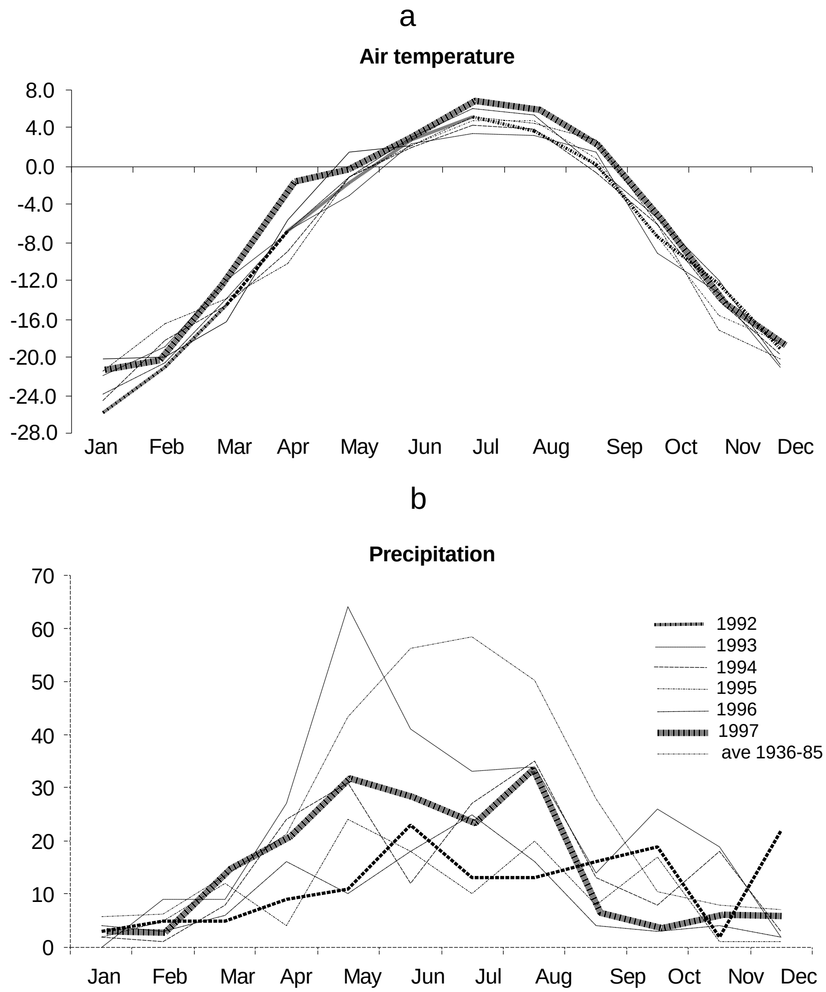


Fig. 4. Monthly mean of precipitation (a); and air temperature at the Tien Shan station, 3614 m (b).

Isotopic and Soluble Ionic Composition in Firn Core and Climatic Conditions

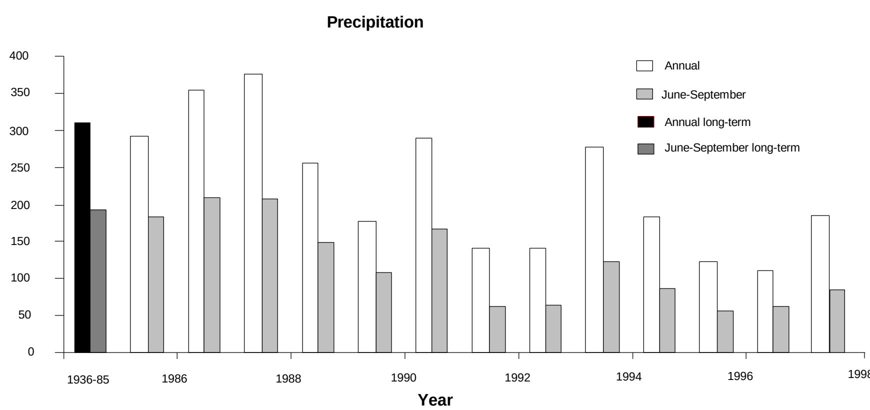
Annual Accumulation. First identification of annual layers in the ice core, which looked very natural, was presented by *Kreutz (in review)* and based on variability of $\delta^{18}O$ signal. In this identification the meteorological, glaciological and hydrological data have not been used because these data were not available that time. According to the results obtained by *Kreutz (in review)* the mean annual snow accumulation for the period from 1992 to 1998 was found to be 1463 mm at 5100 m, which was quite surprising for us because the long-term net annual accumulation rate at these elevations is not more than 800 mm (*Javjarov, A. A. 1935; Zabirov, R.D. 1947; Racek, V.I. 1954; Annual Technical Report on Snow Survey, 1958-1974; Dikih, 1993; Aizen, 1993, 1996, 1997, Kotlyakov, 1998*). At the outset, we expected that extremely wet decade was catch

Table 4. Mean frequency of the synoptic processes($\bar{f}$) associated with precipitation over the central Tien Shan for the two periods 1949-1984 and 1985-1998. Synoptic maps of the main processes are shown on the Figure 3.

Month	Synoptic process	1	2	3	5	10	14
May	$\bar{f}_{1969\text{-}84}$	0.1	0.5	0.1	2.7	13.0	0.2
	$\bar{f}_{1985\text{-}97}$	0.0	0.6	0.7	0.8	6.5	2.6
June	$\bar{f}_{1969\text{-}84}$	0.5	0.1	0.1	2.9	13.3	0.1
	$\bar{f}_{1985\text{-}97}$	0.3	0.0	0.1	0.5	4.7	2.1
July	$\bar{f}_{1969\text{-}84}$	0.0	0.0	0.5	1.9	11.8	0.1
	$\bar{f}_{1985\text{-}97}$	0.0	0.0	0.2	1.0	7.5	2.6
August	$\bar{f}_{1969\text{-}84}$	0.3	0.0	0.0	1.3	13.9	0.1
	$\bar{f}_{1985\text{-}97}$	0.0	0.0	0.2	0.9	5.4	1.5
September	$\bar{f}_{1969\text{-}84}$	0.1	0.4	0.6	2.5	11.9	0.1
	$\bar{f}_{1985\text{-}97}$	0.0	0.0	0.1	1.4	4.9	1.8

but after we received the meteorological and hydrological data for the last thirteen years from Kyrgyzstan we realized that 1463 mm net accumulation is sheer impossible especially during the extremely dry last decade.

a



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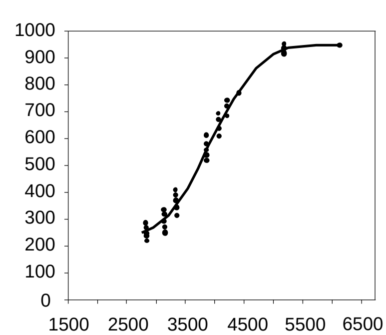

Fig. 5. Long-term, annual and summer mean of precipitation at the Tien Shan station, 3614 m(a) and long-term altitudinal distribution of precipitation at the Inylchek valley (b) (*Aizen et al., 1997*).

The evidences of this conclusion were based on: (a) the altitudinal distribution of precipitation (Fig. 5b) for the years of higher amount of precipitation at the Tien Shan meteorological station, precipitation sites located up to 5000 m, and snow surveys in Inilchek glacier basin in different years (*Alexandrov, A.I., 1893; Merzbacher, G. 1904; Demchenko, M.A., 1934, 1935; Javjarov, A. A. 1935; Zabirov, R.D. 1947; Racek, V.I. 1954; Grudzinskiy, M.A. 1959; Annual Technical Reports, 1958-1974*; *Mount Tuomuer, 1982, Aizen at al., 1997*). There is no any topographical or other factors, which could so significantly increase precipitation in the head of Inilchek Glacier. (b) If we assume that average accumulation of 1463 mm is appropriate value for the elevations over 5000 m, the elevational position of equilibrium line should be significantly under its present long-term average (4476 m). As a result, the Inylchek Glacier mass balance must be positive and the glaciers should be in a progressive phase. However, the glacier degradation is continuing especially during the last decade; (c) according to the known glaciological postulate, at the level of equilibrium line the mean annual ablation has to be equal accumulation, and to the mean runoff from the glacier. It is difficult to check runoff from the Inilchek Glacier due to periodical outburst flows from the Merzbacher Lake but observations at the firn line position proved that ablation was not exceed 800 mm there (*Zabirov, R.D. 1947; Racek, V.I. 1954; Grudzinskiy, M.A. 1959, Dikih, 1993, Aizen, 1993, 1997).*

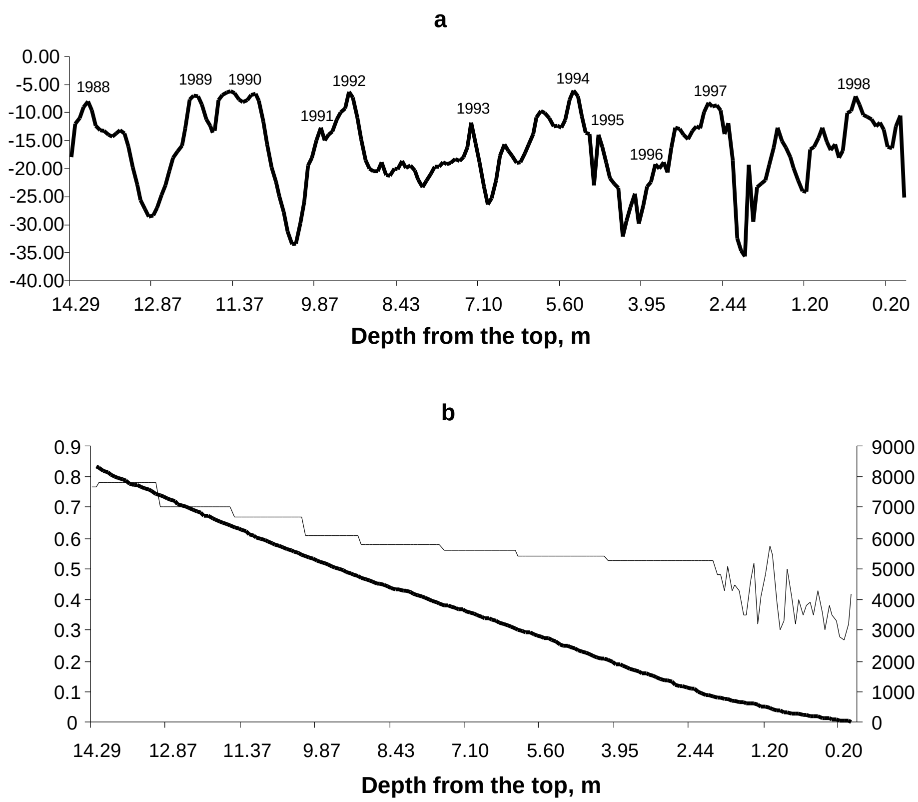

Fig. 6. (**a**) Distribution of isotopic composition; (**b**) snow-firn density (*?*) and snow accumulation (Ac) in the shallow firn core from the Inylchek glacier obtained at 5100 m

According to the data we obtained from the Kyrgyz Hydrometeorological Bureau we reestablished a depth/age scale for the ice core (Fig. 6) taking into account the changes in annual monthly variability of precipitation and air temperatures (Fig. 4). The data on distribution of snow and firn density in the core were taken from the measurements in snow pits, crevasses and from ice core on the Inilchek glacier in 1989, 1990, 1992 (*Aizen et al., 1997*) and 1998 (Fig. 7). The identification of annual records in the ice core based on isotopic analyses can be correlated to annual accumulation measured at 5100 m and annual precipitation measured at Tien Shan station using equation 1 (Fig. 8). The coefficient of correlation between snow accumulation calculated by eq.1 and recovered from firn core is 0.82. In sequences to identification of annual layers in the ice cores, the mean annual snow accumulation for the period from 1988 to 1998, was found to be 757 mm (Table 5) at 5100 m. These results are in accordance with our previous observations on the Inylchek Glacier firn fields at 6148 m (eq.2) (*Aizen et al., 1997*). Taking into account an altitudinal decrease of precipitation we calculated the rate of accumulation at 5100 m through the eq.2 (Table 5). The coefficient of correlation between snow accumulation calculated by eq.2 and recovered from firn core is 0.84.

$$A_{c\ 5100} = 3.7 \cdot P + 51.3 \tag{1}$$
$$A_c'_{6148} = 27.7 \cdot P^{0.61} \tag{2}$$

where A_c and A_c' are annual net accumulation on Inylchek Glacier at 5100 m and 6148 m, P is annual precipitation measured at Tien Shan station. The mean of accumulation we received is also in accordance with calculated accumulation presented on maps of the World Atlas of Snow and Ice Resources *(Kotlyakov, 1998)*.

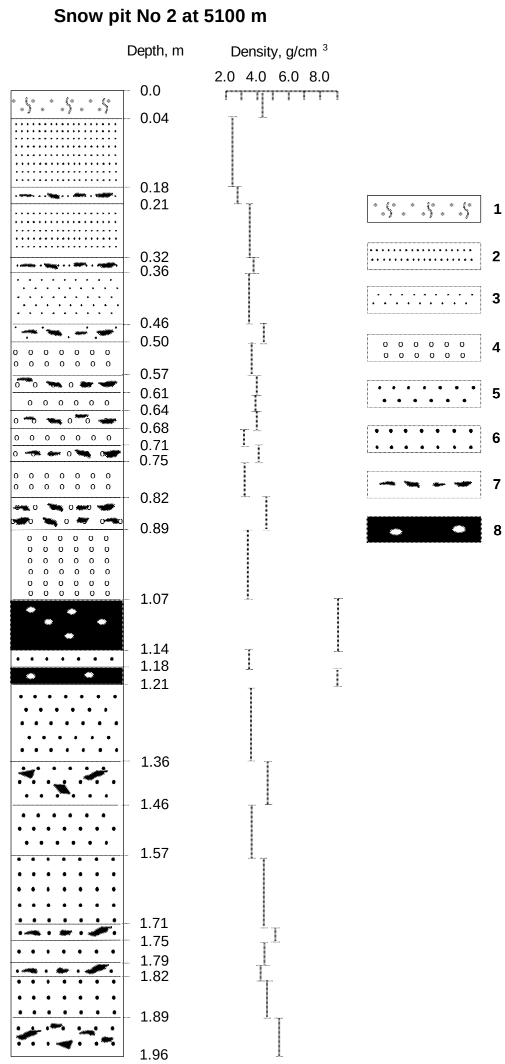

Fig.7. Snow stratigraphy and snow density in pit No2 at 5100 m on the Inilchek Glacier. 1 – get wet layer of new snow, 2 – fine grained snow, 3 – medium grained snow, 4 - coarse grained snow, 5 – medium grained firn, 6 – fine graned firn, 7 – ice lenses, 8 – dense ice layer with dust.

In addition, we made the independent validation of the equation (1), that supports reestablished annual layers in the ice core. Observations on stratigraphy in five snow pits revealed a dense ice dusted layer with density of 0,9 g/sm^3. As example we presented data from snow pit No2 obtained in August, 7 1998 (Fig. 7) where ice dusted layer is observed at the 1.07 m of depth from the top, which could be caused by insignificant melt. Analyzing air temperature at the 5100 m, which calculated on the basis of data from the Tien Shan station, and using air temperature gradient 0.54°C per 100 m (*Aizen et al., 1997*) we found that during the summer 1998 a positive air temperatures occurred only in July, 10 at the 5100 m. The total amount of precipitation observed at the Tien Shan station from the July 10 to August 7, 1998 was 75 mm that equaled 386 mm at 5100 m on the Inilchek Glacier according to calculation through eq.1. Due to the data on snow density and thickness from snow pit, total accumulation from the surface (August, 7) to the ice layer (July, 10) was 368 mm, which is comparable with data from the Tien Shan station and calculation by equation 1 (i.e., 386 mm at 5100 m).

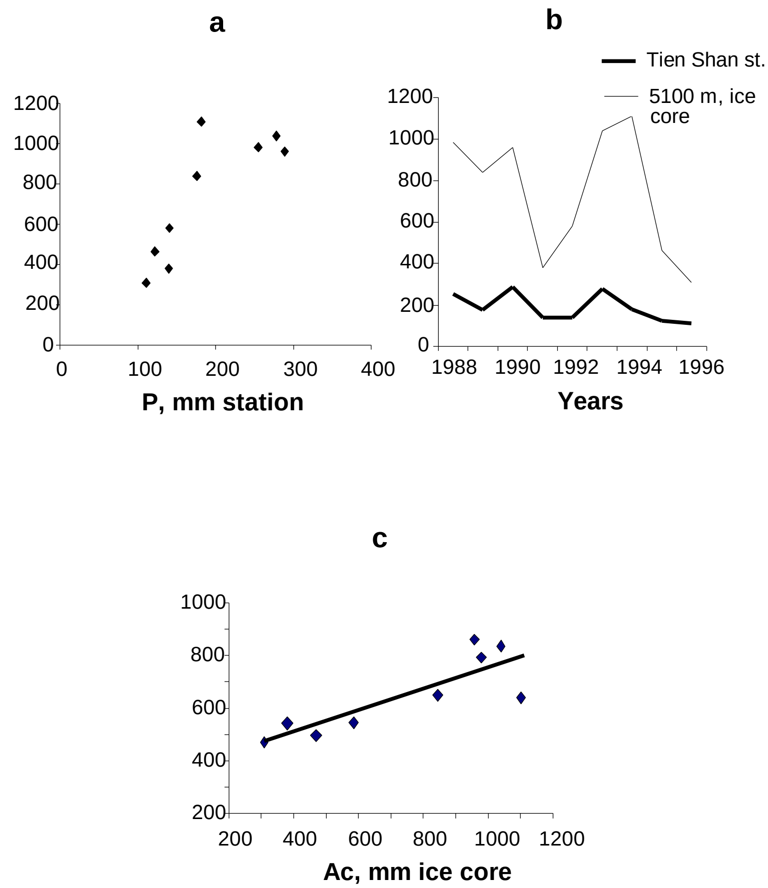

Fig. 8. Relationship between (a) annual precipitation (P) observed at the Tien Shan station (3614 m) and annual snow accumulation layer (Ac) recovered from the firn core of the Inylchek glacier at 5100 m; (b) annual precipitation observed at the Tien Shan St. and recovered from the firn core and, (c) between annual snow accumulation layer (Ac) and snow accumulation calculated from eq.2 (*Aizen et al., 1997*).

Isotopic Composition and Air Temperature. The isotopic composition of precipitation is correlated with environmental parameters characterizing a given sampling point (*Dansgaard, 1964; Siegenthaler and Oeschger, 1980, Jouzel et al., 1997*). Altitudes and latitudes of precipitation deposition, air-cloud-surface temperature, distance from a source of moisture, elevation of moisture transferring, isotopic composition of moisture source are the main factors impacted on relative concentration of δ^{18}O. Distinct changes in the oxygen-isotope variability could be considered as indicators of seasonal variations of precipitation, air temperature or a regular pattern of circulation variations (*Yao and Thompson, 1992; Lin et. al., 1995; Yao et al., 1995; Aizen, 1996*).

Table 5. Annual mean precipitation (P), maximum mean monthly air temperature (T_{max}°C) from the Tien Shan station (3614 m); firn core data recovered from the Inylchek glacier at 5100 m: Ac is snow accumulation; $\delta^{18}O$ are maximum and minimum composition of oxygen isotopes; and A'c is snow accumulation calculated through equation (1).

	P, mm station	Ac, mm ice core	A'c, mm Equation	T_{max} station	$\delta^{18}O_{max}$ ice core	$\delta^{18}O_{min}$ ice core
1998				5.7	-7.11	-35.64
1997	188	787	747	6.6	-8.17	-20.7
1996	111	309	470	5.1	-18.92	-29.7
1995	122	463	499	4.7	-13.93	-22.92
1994	182	1111	642	6.1	-6.03	-26.41
1993	278	1039	838	3.5	-11.77	-20.49
1992	141	581	547	5.1	-6.27	-14.95
1991	140	380	544	4.7	-12.69	-33.48
1990	289	961	858	4.4	-6.48	-35.5
1989	176	840	651	6.3	-6.94	-28.5
1988	255	984	794	5.7	-7.99	-17.95

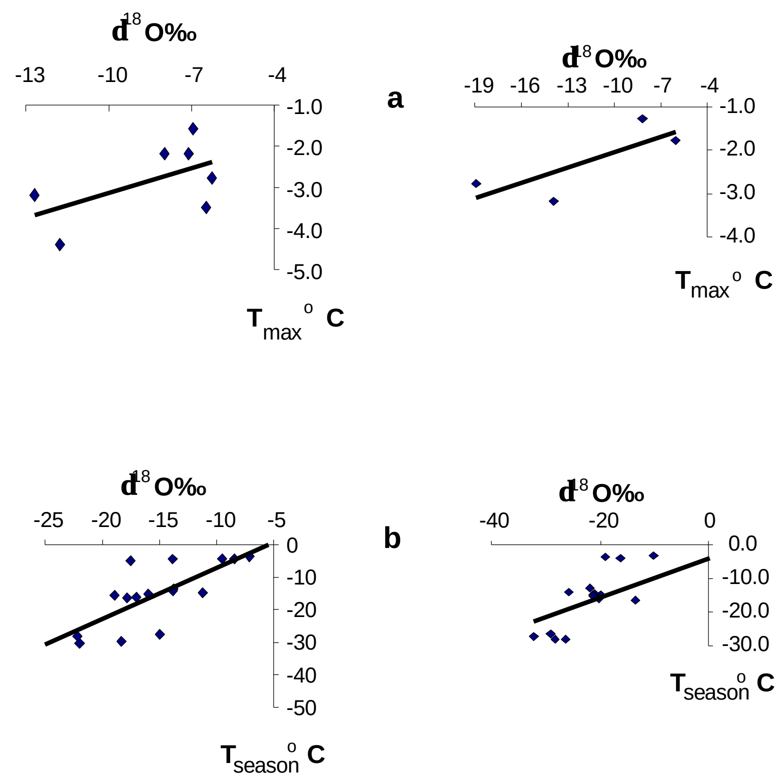

Fig. 9. Relations between $\delta^{18}O$ in firn core and (**a**) maximum and (**b**) seasonal mean air temperature at 5100 m of Inylchek Glacier. R_{10}, R_{14} is ratio between annual frequency of 10th and 14th types of synoptic processes and -their long-term monthly and seasonal average.

Small winter precipitation (Fig. 4a) is distinctive characteristics of the Central Tien Shan. Development of convection currents and strengthening of unstable atmospheric stratification results in a summer maximum of precipitation caused mainly by moist air mass influxes from the west (*Aizen et al., 1996*). At the same time summer air temperatures exceed spring, autumn, and winter values. Taking into account that the air mass with higher temperatures is characterized by relatively heavy $\delta^{18}O$ isotopic ratios (*Yao and Thompson, 1992; Lin et. al., 1995; Yao et al., 1995; Aizen, 1996*), we assume that the highest $\delta^{18}O$ composition corresponds to summer seasons when the maximum precipitation observed (Fig. 6). During the period 1985-1998 the maximum monthly air temperature observed in July. Since that, we compared the highest $\delta^{18}O$ composition in annual layer with maximum mean air temperatures, observed in July, at the Tien Shan station (Table 5). For the periods 1994-1998 and 1988-1993 the relationships between the highest $\delta^{18}O$ composition and maximum mean air temperatures are different (Fig. 9a, eq.3). Therefore, the prevailing synoptic processes brought moisture to Central Tien Shan were considered for these two periods to understand the difference in moisture origination and moisture transferring. To analyze the variability in frequency of the main synoptic processes brought moisture we calculated the ratio between annual frequency of synoptic processes and their long-term average (R_{type})

$$R_{type} = f_{type} / \overline{f}_{type} \qquad (3)$$

here f_{type} is annual frequency of a synoptic process for a month or season; $\overline{f}_{type}$ is long-term average frequency of synoptic process per month or season for the period 1969-1998 (Table 6). During July months from 1988 to

Table 6. Ratio (R) between annual frequency of synoptic processes and their long-term average in July (Number of events).

	3	5	7	8	9b	9a	9	10	14
				Average					
1969-1997	0.4	1.5	3	8	4.4	2.6	2.3	10.1	1.1
				Ratio					
1997	0	0.2	0.4	0	1.6	1.4	0.9	1.1	0.8
1996	0	0	0	0.5	0	1.2	1.1	1.7	0
1995	0	1.3	0.7	0	0.2	0	0	1.1	0
1994	0	0	0	0	0.5	0	0	1.4	0
1993	0	1.3	0	0.9	0.2	0.4	0.9	0.7	2.7
1992	0	1.3	0.7	0	0	1.2	1.7	0.5	2.7
1991	0	1.3	0	0	0	0.8	0.9	0.3	9.1
1990	0	0.1	0.3	0	0	0.4	0.9	0	4.5
1989	5	1.4	0	0.4	0.2	1.2	4.3	0.1	4.5
1988	0	1.3	0	0	0.5	0	0.9	0.3	1.8

1993 the frequency of the synoptic process with influxes of air masses entering from the west (10 type) was below average about 70% and the frequency of western cyclones (14 type) and N-NW cold air advection (5 type) was above average. (Table 6). The main synoptic process that brought moisture to the Central Tien Shan is the influxes of air masses entering from the west (the correlation coefficient of 0.72 for March, Table 3). The air mass influxes entering from the west are formed over the Atlantic Ocean then transferring along the middle latitudes over the Mediterranean, Caspian and Black seas at high altitudes. Western cyclones and N-NW air advection bring less precipitation to the Central Tien Shan (Table 3). The moisture in the western cyclones originates over the Caspian, Black, and Mediterranean seas and is transferred to the Middle Asia at low altitudes and latitudes. During development of the N-NW advection, the main source of moisture brought to Tien Shan is the Caspian Sea. The relationships between air temperatures and $\delta^{18}O$ composition in ice core are different because during prevailing of different synoptic patterns the distance from moisture source, latitudes of moisture origination, elevation and latitudes of moisture transferring are different.

Using equation 1, the seasonal snow accumulation (summer, autumn, winter and spring) at 5100 m was calculated, and the corresponding $\delta^{18}O$ composition of layers in the firn core was averaged. Out previous results establishing relationship between the $\delta^{18}O$ composition and air temperatures *(Aizen et al., 1996*) is not appropriate for the ice core records because it was calculated based on limited information from new precipitation and air temperature during snow deposition of two summer months of 1991, 1992. According to the distribution of annual air temperatures (Fig. 4b), significant variations in the average seasonal composition of $\delta^{18}O$ reflects different synoptic situation for the moisture precipitation. The ratio calculated by eq. 3 between annual seasonal frequency of synoptic processes (influxes of air masses from the west - 10 and western cyclones - 14 types) and their long-term average differentiates the two relationships between seasonal composition of $\delta^{18}O$ and seasonal air temperatures (Fig. 9). The deviations of these relationships can be represented by (eqs.4-5):

$$T_{max} = \begin{cases} -1.10 + 0.20\,(\delta^{18}O_{max}) \text{ when } R_{10} < 1 \text{ and } R_{14} > 1 & (r = 0.61) \\ -0.86 + 0.18\,(\delta^{18}O) \quad \text{ when } R_{10} > 1 \text{ and } R_{14} < 1 & (r = 0.78) \end{cases} \qquad (4)$$

$$T_{season} = \begin{cases} -8.60 + 1.60\,(\delta^{18}O_{season}) \text{ when } R_{10} < 1 \text{ and } R_{14} > 1 & (r = 0.73) \\ -4.20 + 0.57\,(\delta^{18}O_{season}) \text{ when } R_{10} > 1 \text{ and } R_{14} < 1 & (r = 0.71) \end{cases} \qquad (5)$$

where T_{max}°C is the maximum monthly air temperature; T_{season}°C is the average season temperature at 5100 m calculated with data from the Tien Shan station and the average altitudinal gradient in air temperature (equal to 0.0053°C m^{-1}, (*Aizen et al.*, 1997)); $\delta^{18}O_{max}$ is the maximum value of the oxygen isotope composition in the annual layer of the firn core; $\delta^{18}O_{season}$ is the average value of the oxygen isotope composition in the seasonal layer of firn core; R_{10} is the ratio between annual frequency of 10^{th} synoptic processes with influxes of air masses from the west and their long-term mean; r is the coefficient of correlation.

It is known that at the equal altitudes of moisture precipitation, more negative $\delta^{18}O$ value corresponds to a longer distance from the atmospheric moisture source, higher latitudes of moisture origination, lower air temperatures, or higher elevation of moisture transferring (*Dansgaard, 1964; Siegenthaler and Oeschger, 1980*). According to our results (Fig. 9), at the same air temperatures more negative $\delta^{18}O$ values observed during prevalence of influxes of air masses from the west (R_{10}>1 in 1994-1997) than during prevalence of western cyclones (R_{14}>1 in 1988-1993). These results are in accordance with description of the considered synoptic processes (Table 1), i.e. the air mass influxes entering from the west are formed over the Atlantic Ocean, transferred along middle latitudes over the Mediterranean, Caspian and Black seas at high altitudes, while the moisture in the western cyclones originates over the Caspian, Black, and Mediterranean seas and is transferred to the Middle Asia at low altitudes and latitudes.

Major ions and Synoptic Processes. Mean ion concentrations in the 1998 Inylchek Glacier firn core is presented by *Kreutz et al.,* (*in review*). Based on the calculated through eq.1 seasonal snow accumulation at 5100 m the corresponding means of major ion concentrations composition of layers in the firn core were averaged for seasons (summer, autumn, winter and spring). The soluble ionic content of precipitation reflects the moisture source and areas over moisture was transferred. Hence, the deposited precipitation can be considered as an indicator of the synoptic process. To identify different sources of moisture, the mean seasonal soluble-ions content in the ice core was compared with the frequency of fourteen synoptic processes using correlation analyze (Table 7). During winter the soluble content of snow depositions in the firn core can be only associated with changes in frequency of development of southeastern periphery of Siberian High (synoptic processes, type 9a). During this situation the centre of anticyclone is located at the Ust-Urt Plateau, western Kazakhstan and the mouth of the Volga River. The Siberian High is very strong in winter and is the

Table 9. Correlation between seasonal mean frequency of synoptic processes observed over the Central Tien Shan and seasonal mean of major ion content in firn core from the Inylchek Glacier.

	1-3,13	5	8	9	10	11	14
December – February							
Na^+				0.6			
K^+				0.84			
Ca^{2+}				0.55			
Cl^-				0.7			
NO_3^-				0.6			
SO_4^{2-}				0.5			
March – May							
Na^+	0.85						
K^+	0.7			0.66			
Mg^{2+}	0.7			0.82			
Ca^{2+}	0.78			0.82			
NH_4^+				0.72			
Cl^-	0.83			0.56			
NO_3^-	0.53			0.82			
SO_4^{2-}	0.82			0.81			
June – August							
Na^+			0.67			0.69	
K^+			0.54			0.79	
Mg^{2+}		0.63	0.55			0.76	
Ca^{2+}						0.73	
NH_4^+				0.87	0.77		
Cl^-		0.52	0.65			0.7	
NO_3^-				0.81	0.76		
SO_4^{2-}			0.54			0.78	
September –November							
Na^+	0.88						
K^+	0.84						
Mg^{2+}	0.65		0.55				
NH_4^+		0.54					
Cl^-	0.88						
NO_3^-	0.56		0.74				
SO_4^{2-}	0.53						

prevailing atmospheric patterns in the Central Tien Shan (Fig. 10). The main synoptic processes during spring and autumn, are southern cyclones (types 1, 2 and 13) that formed mostly over the south of Caspian Sea, Iran, southern Turkmenia, and western Afghanistan. These cyclones associated with dust storms (*Manual on short-term weather forecast, 1986*). Solonchaks (alkali soils), widespread in deserts of Turkmenia and at the Caspian Low, are the source of soluble salts, carbonates and gypsum. The known mirabilite deposits at Kara Bogaz-Gol Gulf (East Coast of Caspian Sea) (*Adishev, 1987*) may increase content of Na and SO_4^2 ions in surface waters. Since that we assume that increasing content of major ions in seasonal layers of firn core, except of NH_4, may be associated with development of southern cyclones. During spring, increase of the frequency of synoptic processes with position of southeastern and southern periphery of Siberian High (Types 9a and 9b) over the Central Tien Shan are associated with an increase of the major ions content partially NH_4 and NO_3 (coefficient of correlation reaches 0.82, see Fig. 11; Table 7). When southern periphery of Siberian High (type 9b) is located over the Central Tien Shan, strong winds from the east and southeast (Tarim Basin) are observed there; otherwise, during type 9a air mass advection occurred through the western Kazakhstan, and Fergana valley. In autumn, concentration of NO_3 anions is associated with weak-mobile cyclones (type 8) formed over the northern Kazakhstan, and NH_4 is associated with northwestern advection (type 5) which originated over south Urals. During summer, the main synoptic process associated with major ions content (except of NH_4 and NO_3) is the large thermal depression (11 type), when dust from the Kara Kum and Kizil Kum deserts transferred over the Middle Asia region. The NH_4 and NO_3 compounds are associated with air masses formed over Black and Caspian Seas passing through western Kazakhstan and Fergana valley from the west (type 9, 9b 10).

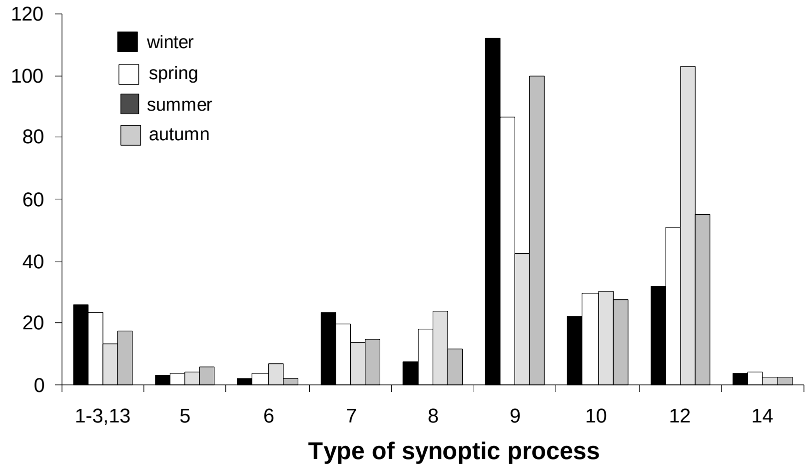

Fig. 10. Long-term average frequency (number of events) for the period 1969 - 1997 of the main synoptic processes observed over the Central Tien Shan (see **Table 1** with description on the types of synoptic processes).

To examine genesis of precipitation, we analyzed a correlation between Na and Cl ions assuming their marine origination. Based on general set of data, Kreutz et al., *(in review)* we found departure of these ions from the seawater ratio. Next, we divided this data for two time set periods: with, and without western cyclones. A scatter plot shows lesser departure from seawater Na^+/Cl^- ratio (Fig. 11) during the years when the frequency of western air masses influxes were above average over Central Tien Shan. This evidence is in accordance with our results on deviation of the relationships between air temperature and isotope content (eqs.3 and 4).

Discussion

Coupling between synoptic-scale climatic patterns and modifications of precipitation and temperature regimes during the period 1988-1998 was examined. We used observational data on frequency of fourteen types of synoptic processes, air temperature, and precipitation over the Central Tien Shan and compared them to the isotopic content of a 14.6-m firn core collected in the accumulation zone (5100m) of the Inylchek Glacier. During the period 1985 to 1998, the increased summer and decreased winter air temperatures under the simultaneous decreasing of precipitation pointed on the strengthening continentality of climate, which can be caused by strengthening influence of Siberian High and weakening impact of Western Jet stream in Central Tien Shan. Increasing degradation of the large sub-continental glacier system, the Khan Tengry massif, over the last ten years may have been a result of this circulation variability caused a decrease in precipitation, more than a quarter of the long-term annual average and increase in summer air temperatures. Intensification in Siberian High impact on the Central Tien Shan may cause glacier degradation despite of lowing the winter temperatures. During this period of years, the month of maximum precipitation shifts to an earlier date because of decreasing summer precipitation. The component of annual precipitation from the spring, summer and autumn seasons has become nearby the same unlike the previous years when the summer maximum of precipitation was observed. The frequency of the main synoptic process associated with precipitation, e.g., influxes of air masses entering from the west, decreased 50% of the long-term average during the period 1988-1998. The frequency of synoptic processes with the location of the south-eastern periphery of the Siberian

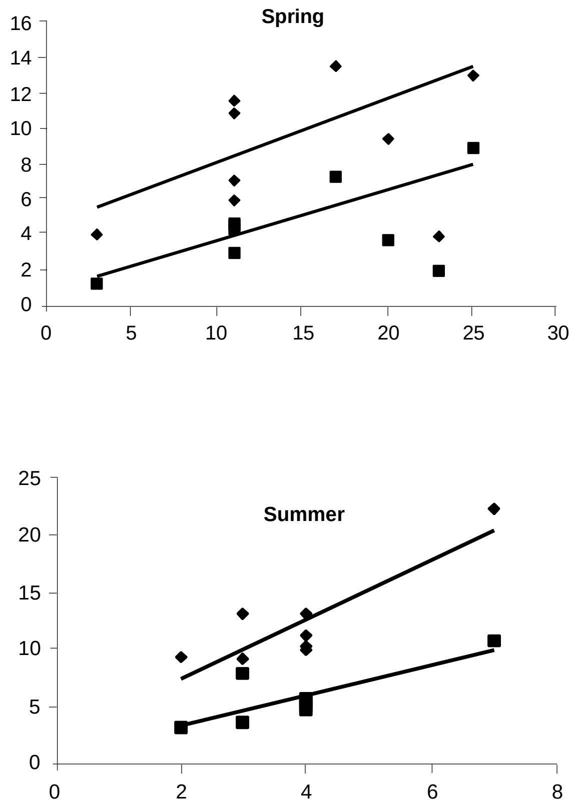

Fig.11 Association between frequency of synoptic processes with position of southeastern and southern periphery of Siberian High (9 type) with NH_4 and NO_3 ion content during spring and summer seasons

High over the Tien Shan has increased at the rate of 1.2 events per year. This synoptic process is not favorable for precipitation development. We expect that during the last decade changes of large-scale atmospheric processes, (i.e. position of the Siberian High and the impacts of the western jet stream) are occurring over the Central Tien Shan. According to identification of annual layers in the cores, the mean annual snow accumulation for the period from 1988 to 1998, was found to be 757 mm at 5300 m that is in accordance with meteorological observational data. There exists a linear relationship between maximum, seasonal mean of air temperature and the highest, seasonal isotopic composition ($\delta^{18}O$) in accumulated precipitation originating from the same moisture source. At the equal air temperatures more removed source of moisture (Atlantic Ocean) resulted in more negative values of isotopic composition ($\delta^{18}O$). During development of influxes entering from west, which originated over the Atlantic Ocean, Mediterranean, Black and Caspian seas, more negative values of $\delta^{18}O$ were observed than during other synoptic processes, which brought moisture from closer sources. Seasonal analyses of major ion concentration and weather conditions during the years from 1988 to 1998 revealed the association between chemical composition in ice core/snow samples and frequency of synoptic processes that will be the basis for the further paleoclimate reconstruction. We associated the increased ionic concentration of NH^4, observed partially in summer and autumn, with agricultural development in the Fergana Valley, and western Kazakhstan and industrial pollution from the southern Urals, southern basin of Volga R and northwestern China.

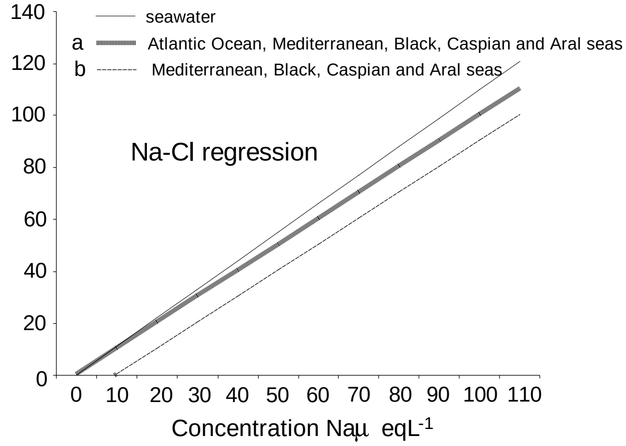

Fig. 12. Relationship between Na^+ and Cl^- composition in the firn core during prevalence different synoptic processes: (a) influxes of air masses from west, (b) western cyclones.

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