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GLACIOLOGICAL AND METEOROLOGICAL MONITORING AT HIGH ALTITUDES FIRN FIELDS

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

Technical report

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Contents

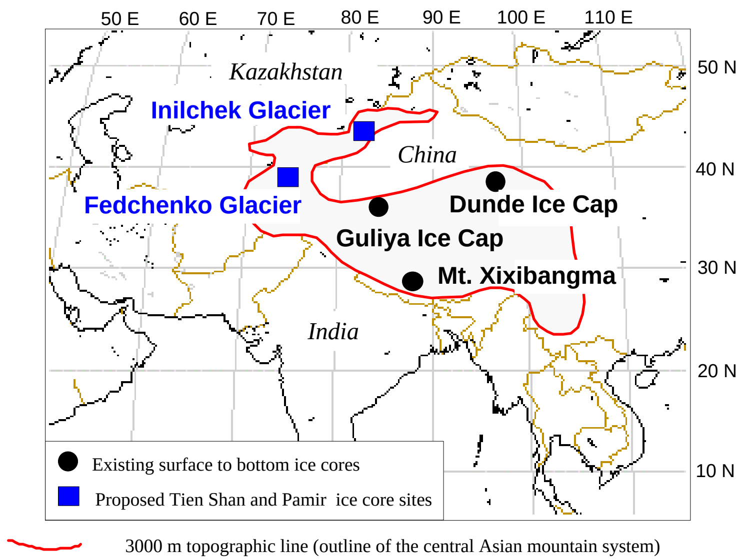
INTRODUCTION

The characterization and modeling of climate variability on annual to century time-scales is a great challenge in the field of climatology. Well-dated, high-resolution ice core records provide the opportunity of extending the climate record back in time thousands to hundreds of thousands of years. Our interest focuses on the Inilchek and Fedchenko Glaciers in the Tien Shan and Pamir on the northwestern periphery of the highlands that define Central Asia (**Fig. 1**) for several reasons.

First, the Inilchek and Fedchenko glaciers are the largest in the Tien Shan and Pamir mountains extending over 80 km in length and covering an total area of 1,500 km^2. The upper accumulation zones are characterized by a gently sloping surface ranging in elevation from 5800 to 6200 m and occupying approximately 300 km^2. Glaciological investigations over fife field seasons in Pamir and Tien Shan, and reconnaissance field season in 1998 of Khan Tengry glaciers (Tien Shan) have determined that little to no melt occurs in the accumulation zone at elevations greater than 5200 m. Furthermore, the relatively low wind speeds and the absence of snow redistribution by avalanches in the snow/firn fields provide a favorable environment for the accumulation of undisturbed horizontal layers of snow, and therefore these sites are suitable locations for the recovery of ice cores and subsequent development of paleoclimatic records.

Second, the location of the Tien Shan and Pamir on the north western margin of the Tibetan Plateau provides a unique opportunity to develop records relating to major circulation systems such as the westerly jet stream and the Siberian High. As the Tien Shan and Pamir represents a significant montane barrier to northern and western air masses moving in central Asia, it plays an important role in determining the climatic processes in northern Central Asia, similar to that of the Himalayas and Karakoram to the south and south west.

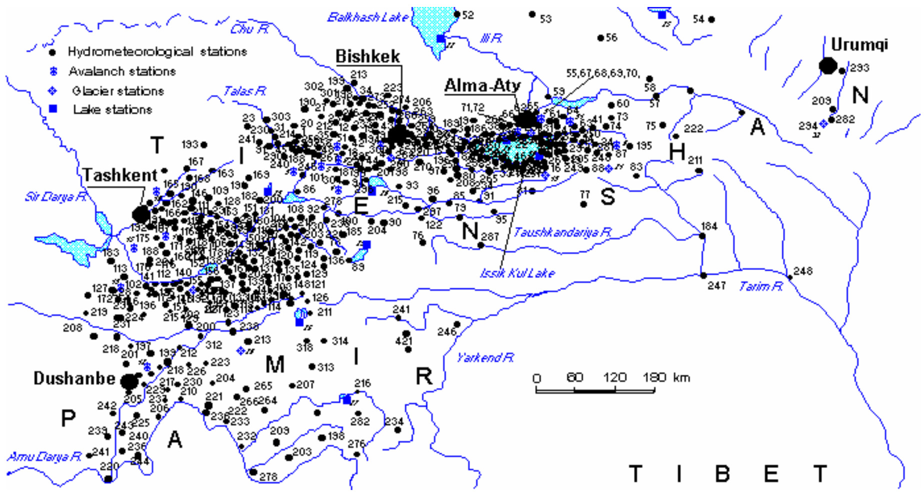
Fig. 1. Map of the Central Asia and ice-coring sites



Head of Inilchek Glacier (5400 m) snow/firn fields, Central Tien Shan, August 1998

Third, there exists an extensive network of hydrometeorological stations (**Fig. 2**) that have been in operation for the past 60-100 years in the Tien Shan and Pamir. Meteorological and hydrological data are available from over 2,000 stations and provide sufficient data for detailed climatological analyses as well as providing a broad array of data that can be used to compare with and calibrate ice core records.

Fig. 2. Central Asian hydro-meteorological network



Fourth, in addition to preserving valuable climate records in their accumulation zones, glaciers of Central Asia hold the greatest concentration of snow and ice in the low-mid latitudes and constitute a source of fresh water shared by fifteen countries. In the Tien Shan, glaciers store approximately 1,180 km^3 of fresh water, roughly equivalent to the combined mean annual runoff of the Yangtze and Huan He rivers and therefore play a critical role in the water cycle in this closed drainage region.

CLIMATIC VARIABILITY AND ATMOSPHERIC CIRCULATION PATTERNS

Before our study on deep ice-coring program we prospected a preliminary research on large scale atmospheric circulation variability and patterns of precipitation change over the Central Asia and Siberia. This research is based on data from 86 stations. We required that all stations had homogeneous data through the period from 1931 to 1990. We used the Quasi-Newton method to provide estimates for periods of missing data and to maximize data coverage. To minimize the inherent temporal and spatial noise of high-resolution time series we analyzed seasonal and annual time scales over large regions. Our analysis on temporal variability in precipitation includes statistical evaluation of their means, variances, moving-averaged time series patterns, periodicity, and patterns of spatial and temporal correlation. Average statistics for the whole period, and for periods with a predominance of atmospheric circulation patterns were calculated, and significance in precipitation deviations associated with atmospheric circulation was examined by F- tests.

Linear Trend. A statistically significant increase in precipitation occurred in Siberia, northern, western regions of Tien Shan, Pamir and plain regions of Central Asia. In the northern region of Tien Shan and Siberia, annual amount has increased up to 108 mm for the past sixty years. The rise in annual precipitation was attributed mainly to winter precipitation increases. A positive trend in precipitation could be a result of displacement to the northwest of the Siberian High reducing its impact on Western Siberia, and northern regions of Tien Shan strengthing or displacing western streams that bring moisture laden air masses. A positive trend in Siberia, and northern regions of Tien Shan suggests that for the last century impact of western jet stream on amount of precipitation increased there.

Fig. 3. 500mb trought position for the ZAP, and $M_{1,2}$AP of *Baidal* (*1961*)

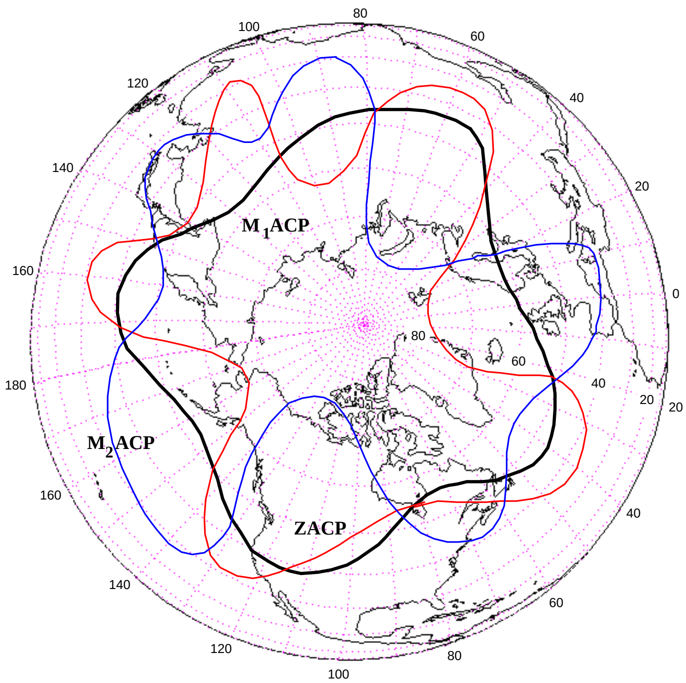


Fig. 4. The centrally weighted moving averages of long-term deviations in annual (ΔP_a), winter (ΔP_w), and summer (ΔP_s) precipitation in the Tien Shan, Pamir, plains of Central Asia and Western Siberia

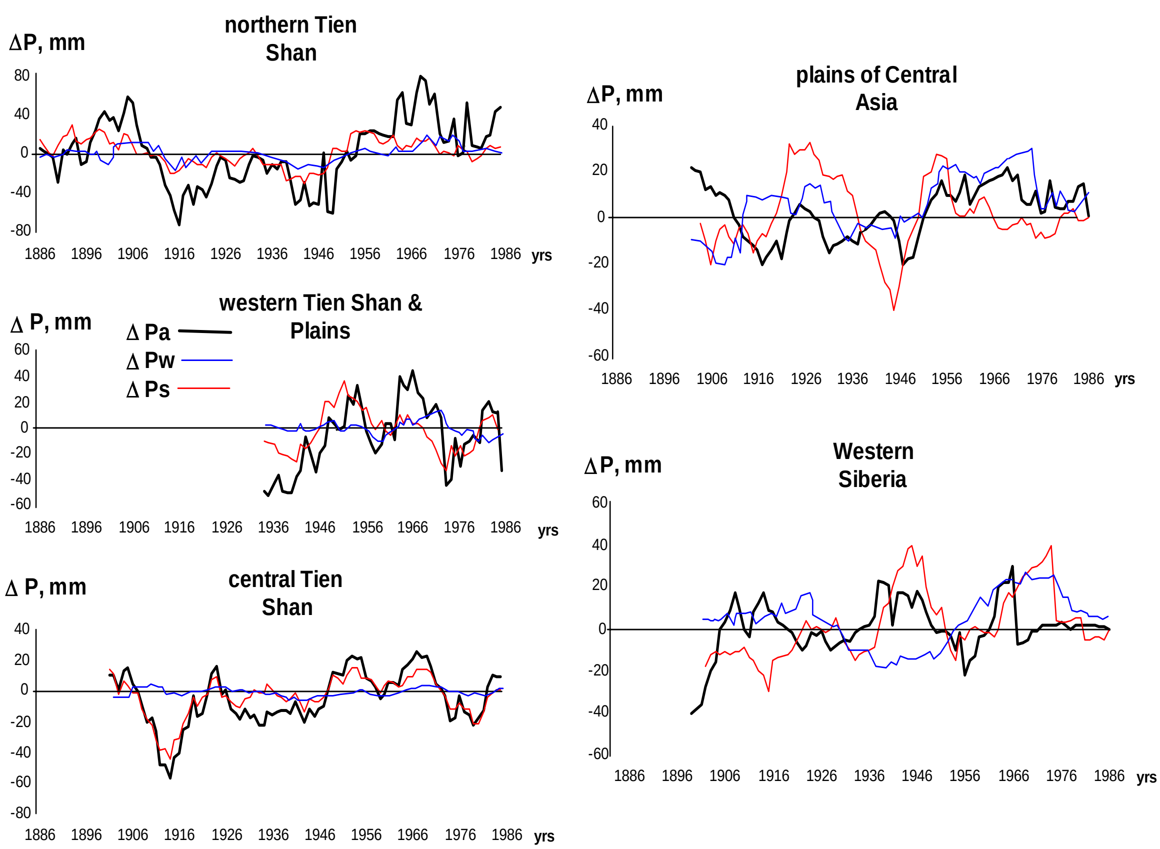
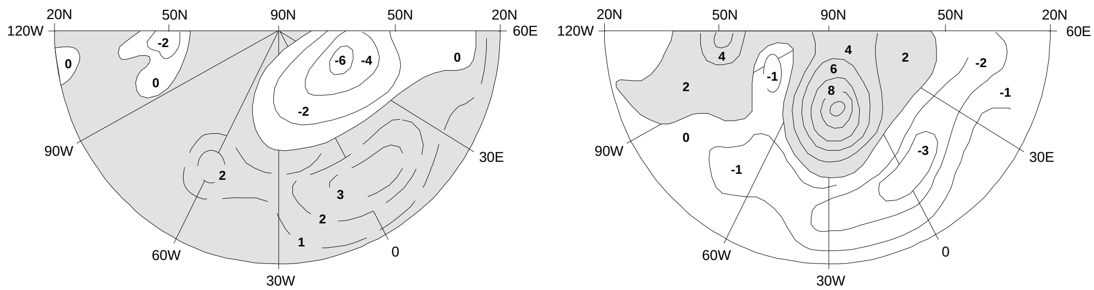


Fig. 5. The extreames of the NAO: The long-term mean sea-level-pressure anomaly pattern (mb) when 'Greenland below' (1) and when 'Greenland above' (2) (from *Lamb and Pepple, 1987*)



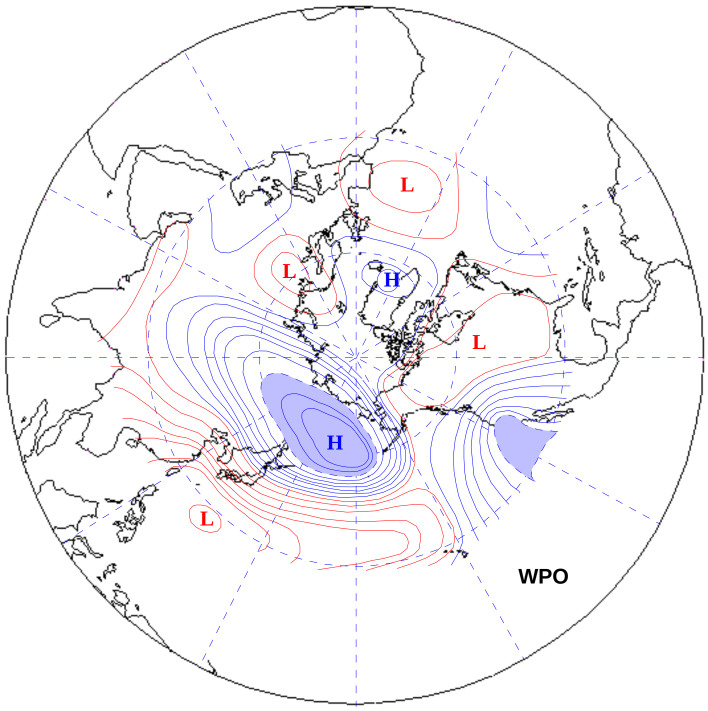
Associations Between ZACP, MACP (Fig. 3), Synoptic Processes and Regional Precipitation. During the period of ZACP predominance, negative deviations in annual, seasonal and monthly maximum amount of precipitation occurred everywhere in the Central Asia and Western Siberia. During the period of MACP predominance, all deviations in precipitation were positive. The correlation between values of precipitation with synoptic circulation conditions were established. Increased frequency of synoptic processes with weak-mobile cyclones, large-amplitude stationary waves, and low-pressure system with small barometric gradients and decreased frequency of S-SW cyclonic circulation, N-NW cold influxes resulted in a rise of annual amount of precipitation from 1960 to 1990, and vice versa during the period 1930 to 1960. Long-term variations on annual and winter precipitation are in phase throughout the Tien Shan and Pamir. Fig. 4 identifies the period with negative deviations in annual and summer precipitation from the 1910 to 1950. Positive values of moving average deviations occurred from the beginning of sixth decade to the beginning of eighth decade. The synchronous periods of positive and negative deviations corresponded to the deviations in frequency of synoptic processes and are about in accordance with predominance of Zonal or Meridional ACP. During the cold season, synoptic processes bringing precipitation to the Siberia and Central Asia are the same, therefore, the long-term variability of precipitation during cold season has synchronous changes (Fig. 4). During the warm season, synoptic processes in the Siberia and Central Asia are different. Thus, the source of moisture, time, intensity and amount of precipitation are different in the Siberia and Central Asia.

Association between NAO (Fig. 5), WPO (Fig. 6), ENSO, PNA, NA and Regional Precipitation The NAO and WPO atmospheric patterns are the dominant modes of circulation over mid-latitudes of mountains and plains in continental Asia. The NAO has statistically significant negative correlation. While any precipitation category was equally likely for negative and intermediate indices of the NAO, there was not more than one winter with above average precipitation among fourteen ones when the NAO was positive. WPO has negative correlation with annual and seasonal amount of precipitation. During the years with positive anomalies of WPO, probability of occurrence below average and normal winter precipitation reached up 84%. We did not find any significant impact of PNA and NA on precipitation in the Central Asia. We expect that ENSO has inversely influenced in the precipitation in the Tien Shan and Pamir mountains. A possible influence of ENSO on the precipitation at the mid-latitudes of Asia is supported by same periods from 2 to 8 years in their fluctuations. Our results suggest that NAO and WPO are potentially useful prognostic tool for precipitation at vast areas of mid-latitudinal Asia and their oscillations can be recorded in annual accumulation layers at high altitudes ice/firn fields of Central Asian Mountains.

METEOROLOGICAL AND SYNOPTIC PROCESSES

We carried out the field measurements and observations at four points: the active ablation zone 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 four automatic mini-met stations "Grant Instruments" (Cambridge)Ltd., England. The data loggers of the stations recorded hourly

Fig. 6. Spatial patterns of the leading rotated EOF modes of 500 hPa geopotential height anomalies during the Northern Hemisphere cold season (October-March) from 1946-89. Contor interval is 0.025 in relative units and negative values are denoted by dashed lines. (from *Nishimori and Kawamura, 1993*). Heavy and light shading denote significant positive and negative anomalies of WPO.

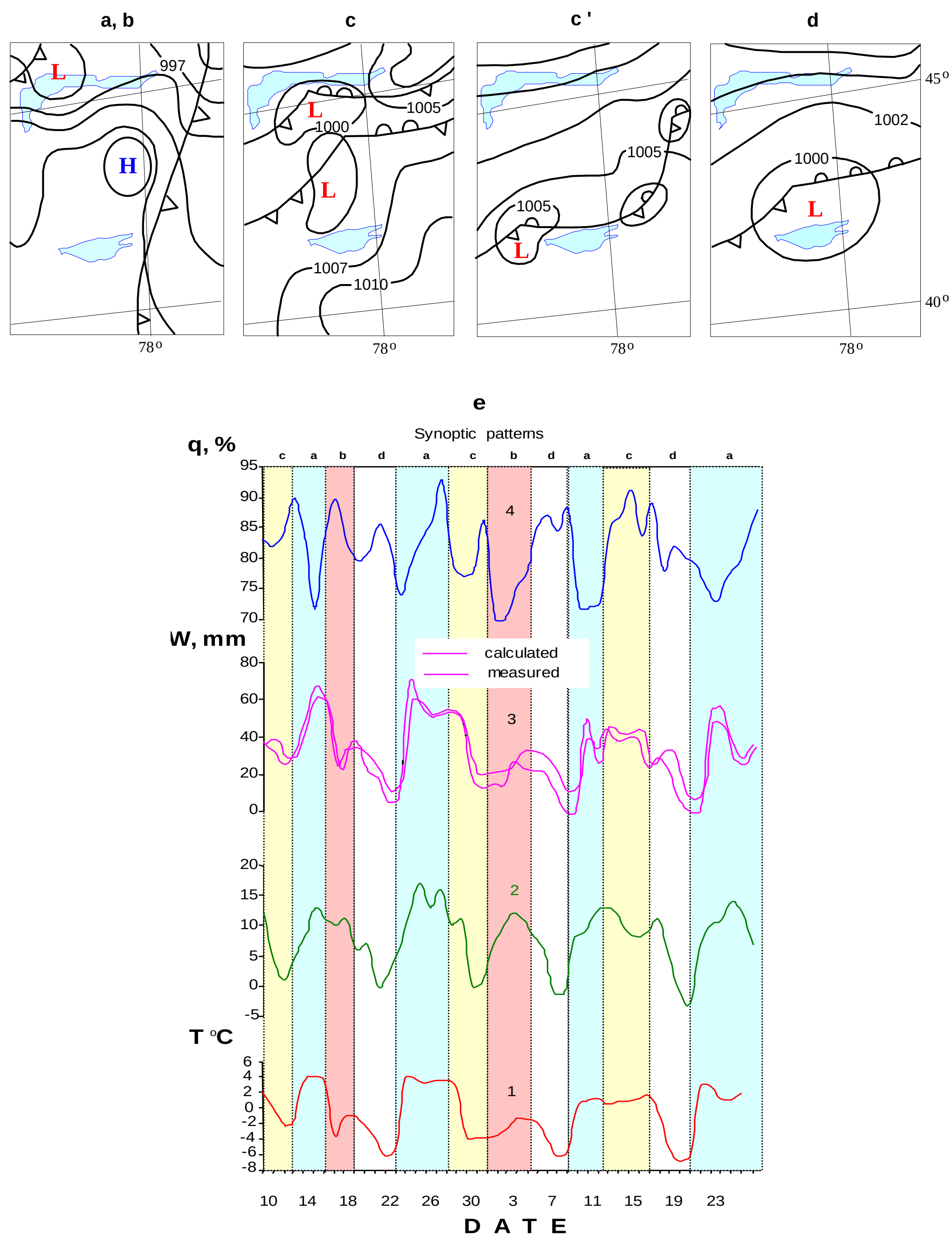


measurements of net total radiation, total incoming radiation, reflected radiation, atmospheric pressure, snow and ice temperature, and discharge from ablation plots. Measurements were recorded at two levels (0.5 and 2.0 m) above the surface for air temperature, relative humidity, and wind speed. Wind 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 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. Discrepancy between measured ablation and discharge averaged 5 mm.

According to our field observations on the Inylchek glacier and the analyses of synoptic maps, there are four main synoptic processes (**Fig. 7**):

Anticyclonic weather with foehn development is the most favorable synoptic process for glacier ablation, observed with 33% frequency during two expeditionary summers. Dry foehns 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. Air temperature can rapidly increase 5°C on the glacier. A great amount of loess dust is brought into the valley with foehns from central Asian deserts. The atmosphere becomes less transparent and long-wave radiation increases. The total radiation balance reached its maximum of 15 MJ $m^{-2}\cdot day^{-1}$ and albedo its minimum (34%). Glacier melt intensified abruptly because of heat advection and was maximum, did not stop even at night and reached 82 $mm\cdot day^{-1}$. Turbulent heat exchange in heat balance was 6%, 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. High humidity and aerosol dust provide the formation of intermass cloudiness and local precipitation, especially at elevations above 5000 m.

Fig. 7. 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).



Anticyclonic cold weather, 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. 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 -3.3^{o}C. During this weather, latent heat and turbulent exchange did not play any significant role in heat balance, and refreezing occurred.

Cyclonic, warm weather occurred with a frequency of 24%. The regime is associated with N-W intrusions, when the cold front lingering near the mountains develops wave activity 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 0.9^{o}C. Evaporation in such periods prevails over condensation reaching 13%. Melt amounted to 15 mm$\cdot$day^{-1}.

Cyclonic cold weather had 24% frequency. Cyclonic activity develops in mid-latitudes of central Asia. Cold intrusions bring precipitation . 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$\cdot$day^{-1}, from radiation alone with little turbulent exchange (only 2%).

STUDIES IN THE ACCUMULATION AREA

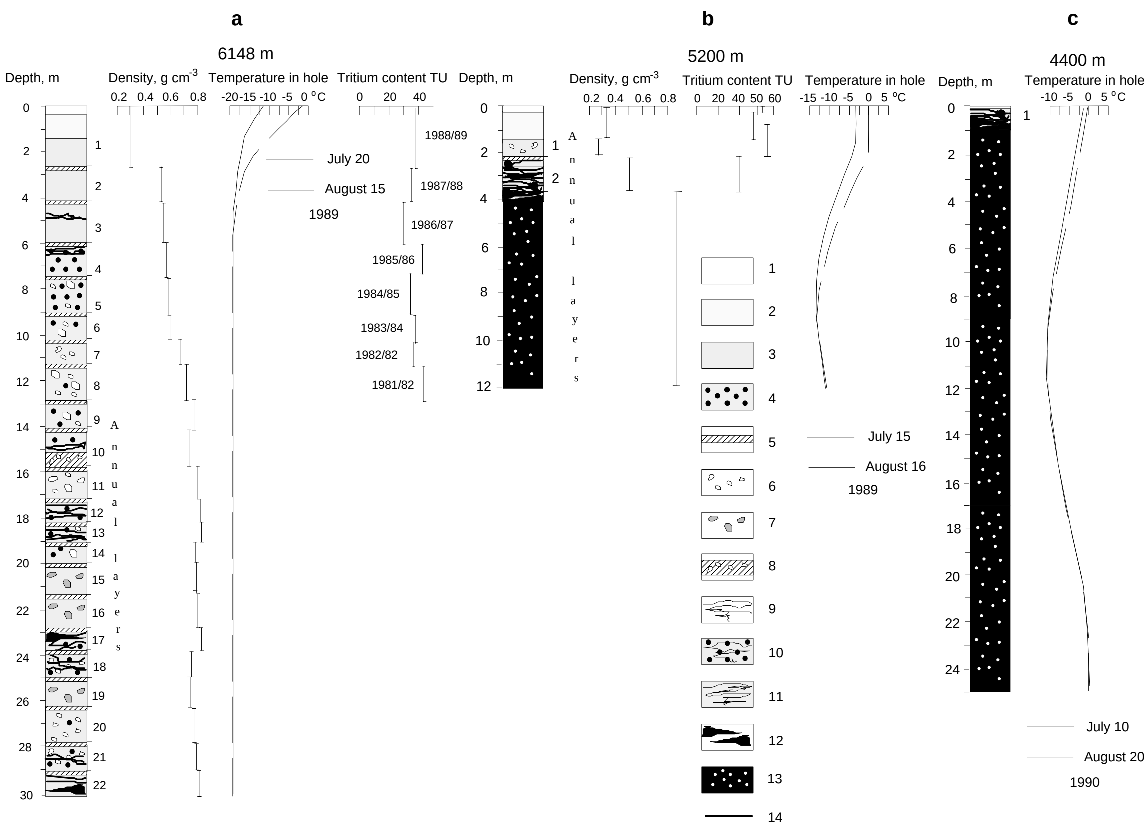
Measurements of accumulation were carried out in the accumulation zone at the beginning and end of summer because maximum precipitation occurs during summer in this region. Depth of snow cover was measured five times at more than 400 points located 50 m from one another. The measuring error was about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

We analyzed the tritium concentration (^{3}H) in 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. Precision of the samples data was 1-10 TU.

Mechanical electric-drill assemblage, Inilchek Glacier, 5400 m, August 1998

The firn fields of the southern Inylchek glacier stretch from southeast to northwest. The area is more than 30 km^2 and the difference between lowest and highest points is 1900 m. 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}).

Fig. 8. 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.



Verification of annual layers was made also by tritium (^3H) sampled from the strata (Fig. 8). 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 at 6148 m. Results of stratigraphic analyses is justified by a good correlation between annual accumulation measured at 6148 m and annual precipitation measured at Tien Shan station.

Increase of precipitation with altitude is not a linear function. 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.

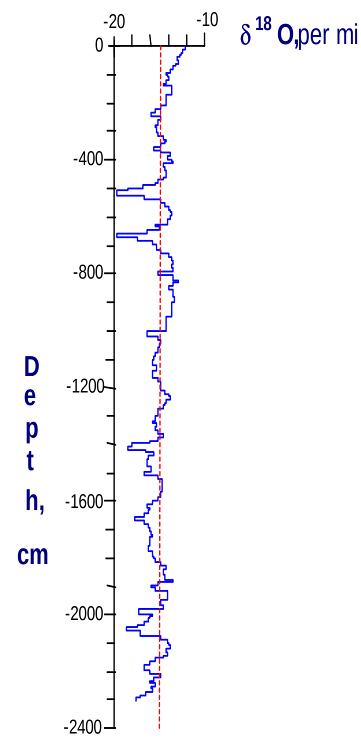
Four ice formation zones have been revealed in the Inylchek accumulation area. The icefall dividing the accumulation area into two parts seems to lie in the cold infiltration-recrystallization zone where the meltwater becomes ice due to infiltration. Stratification analysis of snow firn layers has shown 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.

In the 30 m hole drilled at 6148 m, diurnal temperature changes were observed only in the top layer of annual accumulation (**Fig. 8a**). At greater depths, the temperatures were constant, and at the bottom temperature was -21°C, that is about annual mean air temperature at this elevation. Heat flux brought by foehns was not significant there. High humidity, observed especially at night (85-95%), was favorable for hoarfrost forming. 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}.

ISOTOPIC MEASUREMENTS OF PRECIPITATION

Isotope-geochemical measurements were made during expeditions at all points of observation. Plastic sample collectors with a diameter of 500 mm were used for isotopic measurements of precipitation. Every morning after precipitation occurred the collectors were emptied into polyethylene bottles in which the samples were melted and stored until $\delta^{18}O$ and δD measurements on mass spectrometer Delta - E (Finnigan MAT) in the Institute of Geology, Estonian Academy of Sciences. Samples were obtained from snow and firn pits, and also by mechanical drilling. The collection interval varied from 5 to 30 cm depending on homogeneity of the layers. The collection spots were located on northern, shadowed slopes above the zone of snow and ice melting. Precision of the data was ±0.1%o. The results are presented conventionally as relative deviations per mil ($\delta^{18}O$) from international SMOW standard.

Fig. 9. Oxygen isotope records in ice core from the Inylchek Glacier, 4800 m

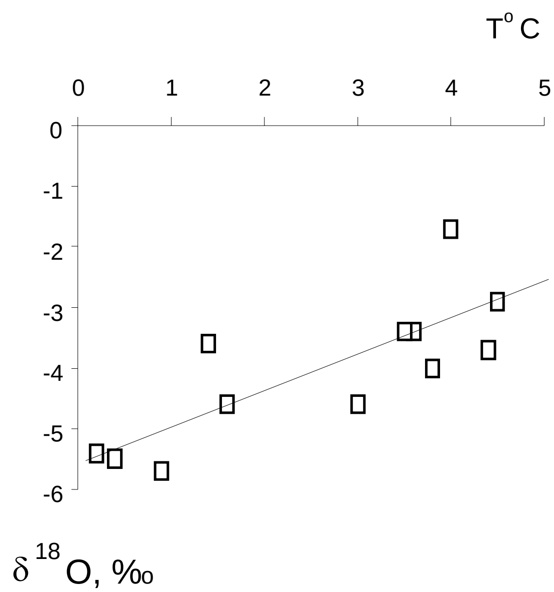


In the observational period on the Inylchek glacier at 4100 m, the mean of $\delta^{18}O$ in atmospheric precipitation was -7.2%o with mean air temperatures of -0.1°C. The maximum difference of $\delta^{18}O$ ratios was -7.5%o. Relatively small variation of oxygen ratios in atmospheric precipitation during expeditionary observations, and the absence of apparent periodic anomalies of $\delta^{18}O$ composition in a 23 m ice core (Fig. 9) in central Tien Shan suggest only one source of moisture. Their relatively heavier ratios (-2%o) under more negative air temperatures than on the Himalayas and Tibetan glaciers indicates a close source. $\delta^{18}O$ values derived from individual samples of surface precipitation collected over a range of elevations showed no apparent trends with elevation. The air temperatures during deposition of precipitation can strongly affect the isotopic composition of snow in mountain areas. There exists a good relationship between mean air temperature during deposition and $\delta^{18}O$ for the samples collected from Inylchek (Fig. 10, eq.1) glaciers.

$$\delta^{18}O = 0.6 \cdot T - 5.6; \qquad r = 0.77,\ F = 12.9,\ se = 0.16 \qquad (1)$$

where T°C is air temperature during precipitation; $\delta^{18}O$,%o is oxygen isotope composition of new precipitation; r is of coefficient correlation, F statistics are observed values to determine a confidence level for the model, se, in %o, is standard error of $\delta^{18}O$ estimation.

Fig. 11. Relations between $\delta^{18}O$ in atmospheric precipitation and air temperature on the Inylchek Glacier.



The analysis a 23 m ice core with 186 strata (**Fig. 10)** revealed a statistically significant decrease in $\delta^{18}O$ ratios from the top occurred with an average rate of 0.009 %o per stratum that could be explained by an increase of air temperatures in central Tien Shan.

THE PURPOSE OF 1988 TIEN SHAN RECONNAISSANCE

was a preliminary survey of the drill site on the Inilchek Glacier for paleo-climatic deep ice coring program development on Tien Shan and Pamir in 1999-2002:

- Checking the local logistics (helicopter facility, porters, guides, medical and rescue groups, freezer etc.) and to realize a preliminaries with Central Asia scientific Institutions for further collaboration;
- Radio-echo sounding survey of the entire upper accumulation zone (between 5000 m and 6000 m) to determine ice thickness and bedrock topography in order to identify the best location to recover the surface to bottom ice core in 2000;
- Setting up automatic weather station in the vicinity of the drill site;
- Collection and analysis of a shallow core (20 m); and sampling from several 3 - 4 m snowpits over a range of elevations in the accumulation zone for chemical-isotopic analyses and microparticle content;
- Collection meteorological and synoptic data from the local met-stations extending back 60-100 years for further ice core data comparison and calibration.

1999 proposed drilling site at the head of South Inilchek Glacier 5400 m, Tien Shan, August 10, 1998.

SNOW CHEMISTRY

In this paragraph we show the first results of our reconnaissance in 1998. Sixteen samples were analyzed from new snow precipitated in August 7, 8, 9, and from the four snowpits located at 5300, 5340, 5390 m and 5460 m. Snow samples were obtained from undistributed snow at four-five levels in 3m pits which accumulated precipitation for 1997/1998 and 1996/97. We considered annual accumulation from September to August according to dust layer. The foehn winds development that brought the main dust to the Inylchek Gl. observed on average at the end of summer.

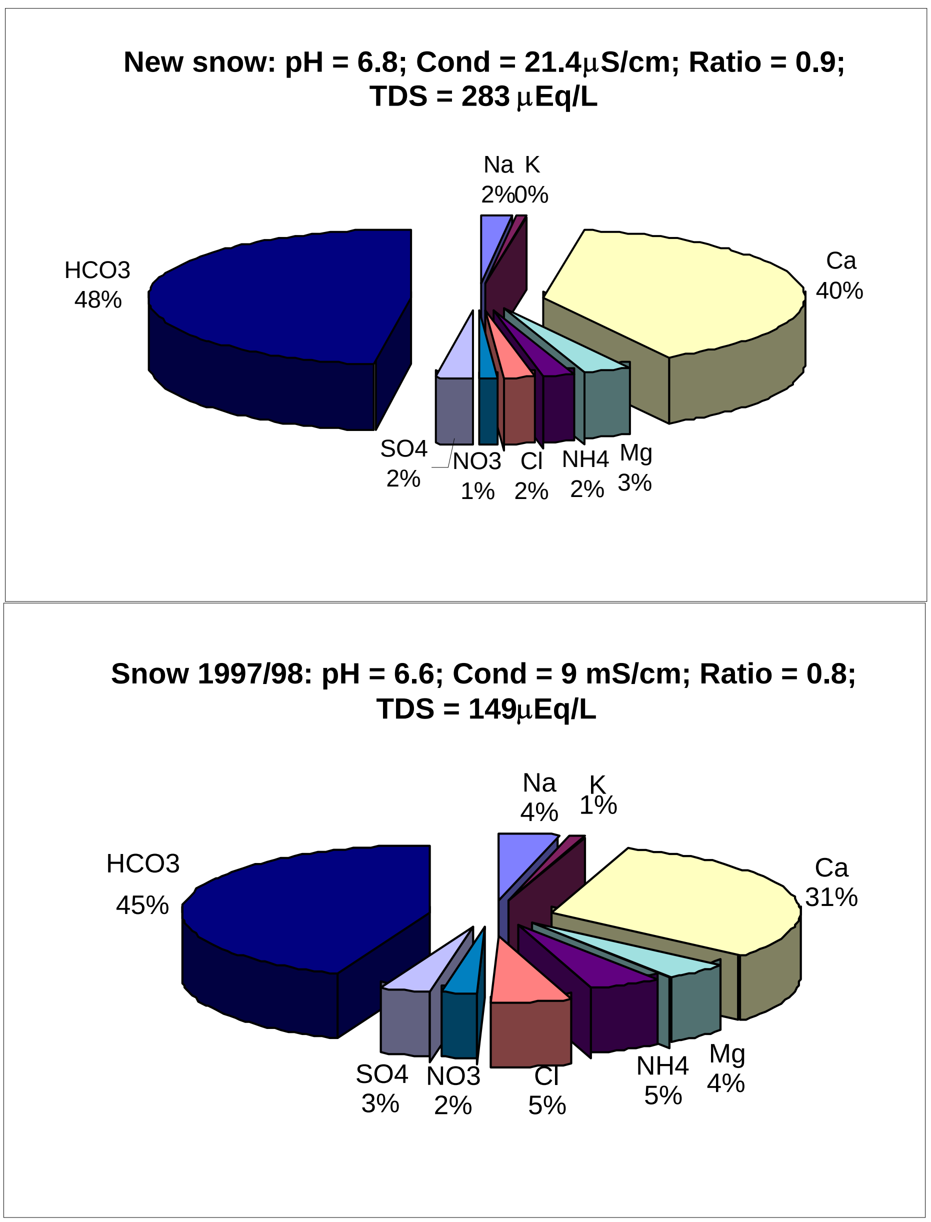
We used a 500 mm-long, 50-mm diameter acrylic tube. Cores from the tubes were emptied into 100ml clean polyethylene bottles. Snow samples were moved to Bishkek and melted in the collection bottles and then transferred to the UCSB for chemical analysis. The pH electrode was calibrated with 7.0 and 4.0 buffers, and conductance meter was calibrated with a 0.0005 M KCI standard. Conductance values were standardized to 20.3ºC. Laboratory analysis of chloride, nitrate, and sulfate was conducted by ion chromatography (Dionex Model 1010I). Calcium, magnesium, sodium, and potassium were analyzed with a Variant AA6 atomic absorption spectrophotometer.

We calculated the ionic balance for each sample (in ❍Eq/L) using the following equation:

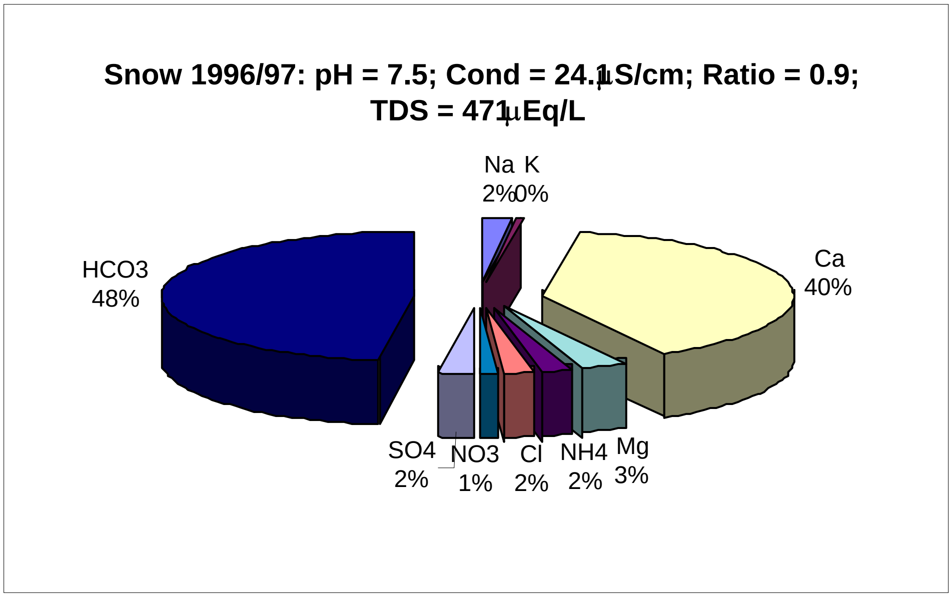
$$[Na^{+}] + [K^{+}] + [NH_4^{+}] + [Ca^{2+}] + [Mg^{2+}] = [SO_4^{2-}] + [NO_3^{-}] + [Cl^{-}] + [HCO_3^{-}] \qquad (2)$$

For comparative purposes, the analytic results were grouped as new snow, snow 1996/97 and snow 1997/98 (**Fig. 1).** 1996/97 was dry warm year while 1997/98 was cold above and wet. As we mentioned, snowmelt in the accumulation area occurred to 5200 m, all samples were obtained from dry deposition.

Fig. 11. Average relative ionic composition (%), pH, conductivity (cond.), ratio between cation and anion composition, and solute concentration (TDS), in snow samples from the Inylchek Gl. from 5300, 5340, 5390 m and 5460 m.



Our measurements of snow chemistry on the Inylchek Gl. Generally support findings elsewhere in Central Asian glaciers, these samples did not display any particularly unusual characteristics. Values of pH ranged on average from 6.6 in 1997/98 snow deposition to 7.5 in older snow of 1996/97 year, indicating neutral to slightly alkaline snow water. Higher pH values were found in snow containing visible dust layers reaching 9.0. Values of specific conductance were variable between 2.7 and 48.2 ❍S cm^{-1}, on average higher conductance values were found in older snow layers of 1996/97 amounting 24.1 ❍S cm^{-1} and in new snow amounting 21.4 ❍S cm^{-1}, while in



1997/98 conductance value was on average 9.0 ❍S cm^{-1}. Despite on extremely elevated and entire location of the Inylchek Glacier, the high ionic concentration for the data set occurred in the samples reaching up to 471 ❍Eq L^{-1} in older snow of 1996/97 and surpassingly up to 283 ❍Eq L^{-1} in new snow. In snow of 1997/98 its value was 149 ❍Eq L^{-1}. The high ionic concentration could be associated with aeolian dust brought from Central Asian deserts. This data is in accordance with results of *Wake et al. (1992)* and *Williams et al. (1992)* in the eastern Tien Shan. There is some diversity in chemical quality of snow as seen by variation by dissolved solids content that is depend on source and trace of moisture. The major chemical constituents were found in snow from the Inylchek Gl. Bicarbonate and calcium were the dominant ions in entire data set of samples (**Fig. 1).** The greatest concentration of calcium ions (up to 296 ❍Eq L^{-1}) was found in snow layers containing dust. The strong continental climate with large variations in air temperature at the high mountains causes the intensive weathering deposits even at high altitudes, when the composition of rocks is formed by conglomerates, sandstone, marlstone, limestone, marbles, fluorite, granites, porphyries and diorites. Combustion of the organic matter containing in down spread alluvial, alluvial fan deposits and shale outcrops also in the bicarbonate type. The cations of Mg^{2+} is less spread than of Ca^{2+}. High sulphate concentration (up to 16.6 ❍Eq L^{-1}) could be associated with aeolian dust brought from the fertilized Tarim valley. These sulfate concentrations were up to three times greater than concentration reported in other remote regions of the world *Williams et al. (1992)*. The large concentration of sulfate and nitrate ions and observed ions of ammonium in glacial snow is a result of industrial pollution. We did not found decreased solute concentration with increasing elevation in snow samples.

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