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A REVIEW OF CENTRAL ASIAN GLACIOCHEMICAL DATA

by

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ABSTRACT

The glaciers of central Asia provide suitable locations from which to recover continuous, high-resolution glaciochemical records on a continental scale. Although the glaciochemical investigations undertaken to date in central Asia are few in number and limited in terms of spatial coverage and length of record, some preliminary observations can be made concerning regional and seasonal trends in snow chemistry in this region.

The sodium chloride ratio for most snow samples collected in central Asia approaches the ratio found in sea water (0.86 in μeq kg^{-1}), reflecting a marine source for these constituents. Sodium and chloride concentrations are, on average, 3–10 times higher in the Himalayas than in the Karakoram, demonstrating the greater influence of monsoonal sources of moisture in the Himalayas. Very high sodium concentrations from Khel Khod Glacier probably reflect a local crustal source from surrounding ice-free areas. Low nitrate concentrations were found in snow collected from the southern margin of the Himalayas and high concentrations in snow deposited on the north margin of the Himalayas. This strong regional trend in the spatial distribution of nitrate suggests the influx of continental aerosols, rich in nitrate, originating from the arid regions of central Asia. High calcium concentrations measured in snow from Mount Everest and the north-west corner of China are also indicative of dust derived from the arid regions of central Asia. Very high sulfate concentrations found in snow from the Tien Shan and the Bogda Shan most likely reflect local anthropogenic sources. The altitude effect on isotopic composition is not apparent from snow samples collected in central Asia.

Understanding the processes which control the chemical content of snow, the local-to-regional scale complexities, and the seasonal variability are fundamental steps necessary to assess the potential for recovering representative long-term glaciochemical records from central Asia.

INTRODUCTION

The recovery and analysis of snow and ice samples from appropriately located snow-pits and ice cores have proven extremely valuable in producing continuous records of atmospheric chemistry and climate (e.g. Lorius and others, 1985; Mayewski and others, 1986a). Furthermore, records from glaciochemical investigations are especially important when direct observations and measurements of the atmosphere are either spatially and/or temporally lacking.

The vast extent of glacierized regions in the high mountains of central Asia (Fig. 1) provide several suitable locations from which to recover glaciochemical records. The recovery of snow and ice samples from elevations in the range of 4500 to 7000 m above sea level (a.s.l.) provides a unique opportunity to describe and understand atmospheric chemistry and processes in the free troposphere. Glaciochemical records can be used to identify patterns of regional circulation, sources of moisture, sources and distribution of chemical species in the atmosphere and regional fluxes of chemical species relatable to biogeochemical cycles (Mayewski and others, in press). Data sets describing the spatial and seasonal variation of snow chemistry in central Asia will provide useful input for ongoing global change research efforts such as the International Geosphere-Biosphere Program (National Academy of Science, 1986) and the Global Tropospheric Chemistry Program (National Academy of Science, 1984). This paper reviews the glaciochemical data which have been collected from central Asia and provides some preliminary observations concerning regional and seasonal trends in central Asian snow chemistry.

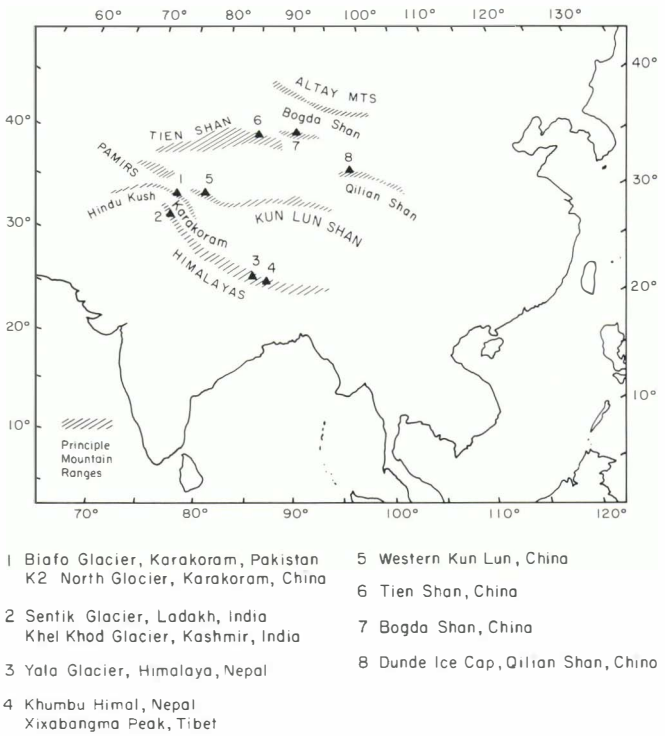

Fig. 1. Principle mountain ranges and glaciochemical collection sites in central Asia.

EXISTING DATA SETS

Table I provides a listing of the glaciochemical investigations that have been undertaken in the high mountains of central Asia and Table II provides a detailed summary of the chemical characteristics of central Asian snow. Perhaps the single most obvious fact that emerges for this vast region is that the existing data set is limited both spatially and temporally. However, data are now available also from the Dunde (Thompson and others, this issue) and Chongce (Nakawo and others, this issue) ice cores.

Glaciochemical data are currently available only for sites on the southern margin of the mountain ranges of central Asia (sites 1 through 4, Fig. 1) and from the Tien Shan and Bogda Shan in north-west China (sites 6 and 7, Fig. 1). Additionally, only the records from the Biafo,

TABLE I. SUMMARY OF GLACIOCHEMICAL INVESTIGATIONS IN CENTRAL ASIA

Location	Elevation (m a.s.l.)	Number of samples	Type of sample	Period of record	References
Karakoram					
Biafo Glacier	4650–5520	198	snow-pits	1983–86	Wake (1987, 1989, unpublished)
K2 North Glacier	4440/5320	83	2 cores	??	
Western Himalaya					
Sentik Glacier	4908	104	core	1962–80	Mayewski and others (1984); Lyons and Mayewski (1983)
Khel Khod Glacier	4695	19	core	1977–79	Mayewski and others (1981)
Dunagiri	4400–6050	16	surface snow	8/78	Niewodniczanski and others (1981)
Central Himalaya					
Yala Glacier	5400	55	core	~70 years	Watanabe and others (1984)
Xixabangma peak	5850	6	fresh snow	5/84	Mayewski and others (1986b)
Mt. Everest	5600–7100	120	fresh snow	4/86–5/86	Spencer (unpublished); Jenkins and others (1987)
Kumjung village	3900	6	surface snow	12/82–1/83	Davidson and others (1986)
Kongma Glacier	5650	12	snow cliff	??–11/74	Wushiki (1977a)
Western Kun Lun					
Chongce Ice Cap	6130/6366	??	2 cores	~30/60 years	Nakawo and others (1990)
Tien Shan					
Urumqi R.–Glac. 1	3450–4110	37	surface snow	9/88–4/89	Wake and Mayewski (in preparation)
Bogda Feng	1940–3550	38	surface snow	9/88–4/89	Wake and Mayewski (in preparation)
Qilian Shan					
Dunde Ice Cap	5250–5400	60	snow-pits	1981–86	Thompson and others (1988)
Dunde Ice Cap	5450	??	3 cores	??	Thompson and others (1989)

Sentik, Khel Khod and Yala glaciers extend for more than one year (Table III). Snow chemistry data recovered from the other southern margin areas (i.e. Kumjung village, Mount Everest and Xixabangma peak) represent samples of an individual, or a series of individual snowfall events covering a rather short period of time (i.e. less than one month). In addition, the types of chemical species and stable isotopes analyzed differ between studies, limiting comparison among the investigations.

SAMPLE LOCATIONS

The glaciochemical sample locations listed in Table II fall into three broad climatic zones. The Biafo, Khel Khod and Sentik glaciers are characterized by precipitation sources from both the west and the south. In this region, snow accumulation increases toward the west as a result of increasing influence of precipitation derived from westerly moisture sources. The upper Biafo Glacier consists mainly of extensive open and gently sloping accumulation areas covering over 500 km^2. The percentage of ice-free area surrounding the accumulation zone is minimal. Glaciochemical samples were collected from snow-pits excavated from 4650 to 5520 m a.s.l. The aspect of these collection sites varied from east to south to west. The northward-facing Sentik Glacier is one of several glaciers emanating from the Nun Kun Plateau (325 km^2). While the plateau is largely ice-covered, extensive areas surrounding the plateau are ice-free. Khel Khod Glacier is one of several relatively small (<10 km^2) glacier basins in Kashmir. It faces south-westward and is surrounded by ice-free areas.

Sample collection sites in the central Himalayas, including Yala Glacier, Xixabangma peak, Mount Everest and Kumjung village are characterized by a monsoonal maritime type of climate (Li and Xu, 1980). This region experiences heavy precipitation during the summer monsoonal period. Yala Glacier covers an area of 2.6 km^2, flows in a north-easterly direction, and is surrounded by extensive ice-free areas. Fresh snow samples from Xixabangma peak and Mt. Everest were collected from relatively high elevation sites (6300 m and 5600–7100 m a.s.l., respectively) on the north side of the mountain, in an elevation band where perennial snow and ice dominate. The Kumjung village fresh snow samples were collected at a much lower elevation (4900 m a.s.l.) adjacent to a small village.

The Tien Shan and Bogda Shan mountains in north-west China experience an inland continental climate. Moisture is derived primarily from the west and the north (Li and Xu, 1980). Both Glacier No. 1 at the headquarters of the Urumqi River and Bogda Feng Glacier are small (<2 km^2), and surrounded by extensive ice-free areas.

The preservation of chemical records in snow and ice deposited in high altitude/low–mid latitude glaciers depends upon glacier basin morphology and local meteorological conditions. Sample locations which are removed from the effects of avalanches, little affected by redistribution of snow by the wind, experience low mean annual temperatures, and high rates of annual snow accumulation are most likely to develop relatively undisturbed glaciochemical records. A qualitative assessment of the degree of post-depositional alteration of snow and ice samples collected in central Asia appears in Table IV.

TABLE II. DETAILED SUMMARY OF CHEMICAL CHARACTERISTICS OF CENTRAL ASIAN SNOW. For references see Table I

	Biafo Glacier	Sentik Glacier	Khel Khod Glacier	Yala Glacier	Xixabangma peak	Everest*	Kumjung village	Tien Shan	Bogda Shan
No. of samples	198	104	19	55	6	120	6	51	26
Ca^{2+} min	–	–	–	–	–	1.5	–	9.2	5.1
max	–	–	–	–	–	176	–	332	405
mean	–	–	–	–	–	32.1	19.0	60.7	66.7
std. dev.	–	–	–	–	–	32.2	–	77.7	86.5
Na^+ min	0.1	0.03	0.1	–	2.2	0.1	–	0.6	0.4
max	27	28	79	–	12	83	–	316	604
mean	1.1	3.0	15.6	10.9	5.2	7.5	3.9	27.9	44.0
std. dev.	2.2	4.1	22.5	9.6	4.0	14.2	–	65.5	120
Cl^- min	0.1	0.5	–	–	1.9	0.2	–	0.5	0.5
max	11	30	–	–	15	64	–	74	86
mean	1.1	3.0	–	9.9	5.3	6.1	–	9.3	9.0
std. dev.	1.1	4.7	–	7.3	4.9	8.8	–	16.4	15.7
NO_3^- min	0.1	0.1	–	–	2.7	1.3	–	1.1	1.1
max	12	4.4	–	–	9	18	–	13	16
mean	2.9	1.4	–	2.1	6.3	4.5	4.7	3.7	6.0
std. dev.	2.0	1.0	–	1.6	2.7	2.7	–	2.7	3.5
SO_4^{2-} min	0.1	–	–	–	1.9	0.6	–	2.0	5.0
max	12	–	–	–	12	39	–	187	557
mean	2.2	–	–	4.8	7.7	5.7	2.9	23.3	51.1
std. dev.	1.9	–	–	4.4	4.6	5.4	–	40.9	102
SiO_2 min	–	0.01	0.05	–	–	0.04	–	–	–
max	–	97	12	–	–	3.4	–	–	–
mean	–	7.1	2.8	–	–	0.5	–	–	–
std. dev.	–	14.0	3.3	–	–	0.5	–	–	–
Na : Cl mean	0.88	1.24		1.08	1.05	–	–	2.3	2.6

Calcium, sodium, chloride, nitrate and sulfate concentrations in $\mu eq\ kg^{-1}$; reactive silicate concentration in $\mu mol\ kg^{-1}$; Na : Cl ratio in $\mu eq\ kg^{-1}$ (in sea water Na : Cl ratio is equal to 0.86).

* These data correspond to the full 120 samples analysed and not to the 100 samples presented by Jenkins and others (1987).

TABLE III. TEMPORAL EXTENT OF ION CONCENTRATION RECORDS RECOVERED FROM CENTRAL ASIAN GLACIERS

Period of record — ion concentrations

Location*	1960–	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89
Biafo Glacier															———						
Sentik Glacier	———																				
Khel Khod Glacier										———											
Yala Glacier	(~1910) <<	———																			
Xixabangma peak																–					
Mt. Everest (N side)																		–			
Kumjung village															–						
Tien Shan																				———	

* Only eight of the investigations listed in Table I have published ion concentration data.

DISCUSSION

Although the glaciochemical investigations undertaken to date are few in number and limited in terms of spatial coverage and length of record, some preliminary observations can be made concerning regional and temporal trends in snow chemistry and their importance in improving our understanding of regional atmospheric circulation and atmospheric chemistry in central Asia. Figure 2 illustrates the mean concentrations of sodium, chloride, nitrate and sulfate in snow collected from the mountains in central Asia. The columns in the histograms, from left to right, are roughly arranged west to east (except for the Tien Shan and Bogda Shan sample locations). In interpreting the data, more weight is given to the glaciochemical data recovered from the Biafo and Sentik glaciers since the records from these two regions extend for more than one year and were recovered from areas that experienced minimal post-depositional alteration, and since sodium, chloride and nitrate concentrations were determined for both studies.

Both sodium and chloride show strong regional trends with the lowest values in the Karakoram, and progressively higher values toward the south-east. This regional trend clearly demonstrates the increased influence of

TABLE IV. PHYSICAL PARAMETERS AFFECTING QUALITY OF GLACIOCHEMICAL SAMPLES COLLECTED IN CENTRAL ASIA

Location	Morphology of collection site	Elevation	Mean annual temperature	Annual accumulation	Relative influence of: wind	avalanches	meltwater infiltration	Type of sample
		m a.s.l.	C *	m w.e.				
Biafo	acc. basin	4650–5520	−4.5**	0.9–2.5	low	none	low	snow-pits
K2 North	acc. basin	5320	–	–	low	high	high	ice core
Sentik	acc. basin	4908	−3.0	0.62	low	none	low	ice core
Khel Khod	circ glacier	4695	–	0.48	low	low	low–med	ice core
Dunagiri	ridge	4400–6050	–	–	low	none	low	fresh snow only+
Yala Glacier	acc. basin	5400	0.0	0.60	?	?	high	ice core
Xixabangma	acc. zone	5850	–	–	low	none	low	fresh snow only+
Everest	acc. zone	5600–7100	–	–	low	low	low	fresh snow only+
Kumjung	near village	3900	–	–	low	low	low	fresh snow only+
Kongma	ice cliffs	5650	–	0.58	?	?	med–high	ice cliff
Tien Shan	acc. basin	3450–4110	−5.4***	0.43	low	low	low	winter snow only
Dunde	ice cap	5250–5400	−5.4	0.20	?	low	low–med	snow-pits/ice core

* from ~10 m bore hole temperature measurements.
** measured at 5450 m.
*** from meteorological records at 3590 m.
+ collected within 24 hours of snowfall.

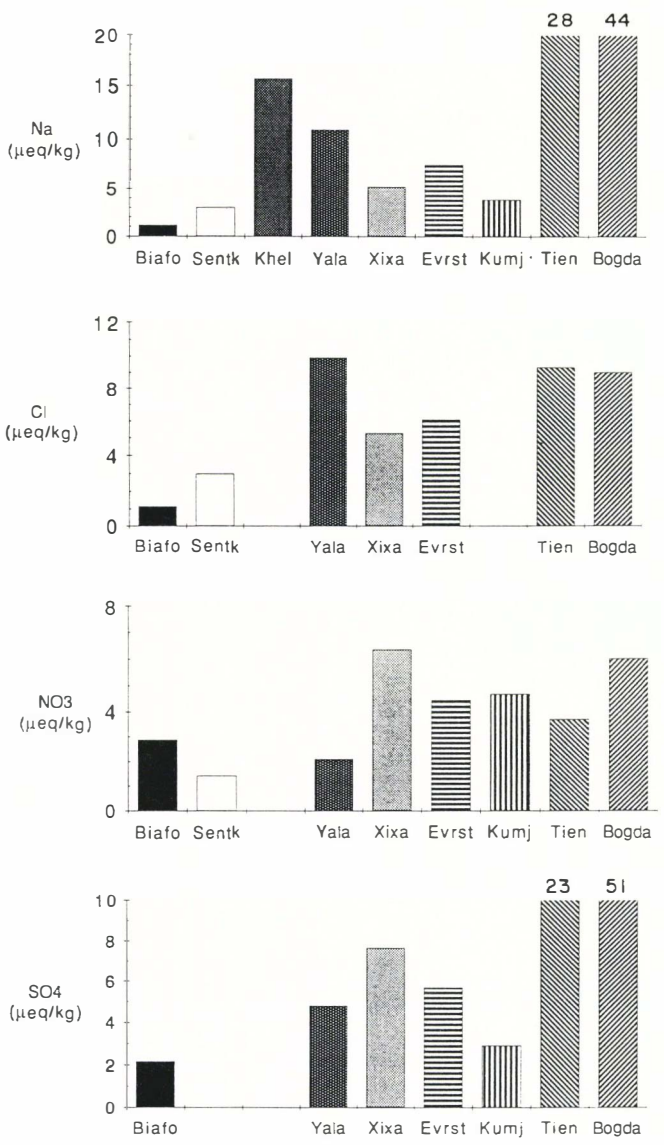

Fig. 2. Comparison of mean ion concentrations of snow collected in central Asia. The columns, from left to right, are arranged roughly west to east (except for the Tien Shan and Bogda Shan sample locations).

monsoon-derived moisture in the Himalayas when compared with the Karakoram. Seasonal signals apparent in records from the Karakoram (Wake 1989, unpublished) and western Himalaya (Mayewski and others, 1984) are characterized by relatively higher concentrations of sodium and chloride in summer strata. This is indicative of the influx of moisture derived from the Arabian Sea which is then transported to the mountains by summer monsoonal circulation. Winter strata are characterized by overall lower concentrations of sodium and chloride, reflecting moisture derived from distant marine sources such as the Mediterranean Sea and/or Atlantic Ocean. The sodium : chloride ratios for samples collected from the Biafo and Sentik glaciers, Xixabangma peak and Mount Everest (Table II) approach the ratio found in sea water (0.86 in $\mu eq\ kg^{-1}$). Thus, most of the sodium and chloride entering the region is derived from marine sources. The slightly higher sodium : chloride ratio for the Sentik Glacier samples implies an additional source of sodium. Snow from Sentik Glacier is also characterized by high concentrations of reactive silicate (Table II). The elevated sodium and reactive silicate values suggest inputs of crustally-derived material. The very high sodium values observed in samples from Khel Khod Glacier cannot easily be interpreted in terms of a regional trend as they most likely reflect a local crustal source from surrounding ice-free areas. The high sodium and chloride concentrations of snow from the Tien Shan and the Bogda Shan most likely represent an input of sodium- and chloride-rich dust originating from the extensive evaporite deposits to the north and west of these mountain ranges.

Low nitrate concentrations were found in snow collected from the southern margin of the Himalayas (Sentik and Yala glaciers) and high concentrations in snow deposited on the northern margin of the Himalayas (Biafo Glacier, Xixabangma peak and Mount Everest). This strong regional trend in the spatial distribution of nitrate suggests the influx of terrestrial dust, rich in nitrate, originating from the extensive arid regions of central Asia. From an analysis of nitrate values in snow around the world, Lyons and others (in press) found that aerosols derived from continental interiors tend to be rich in nitrate. In addition, snow samples from Mount Everest and the north-west corner of China show extremely high calcium concentrations (Table II), indicative of dust derived from the arid regions of central Asia.

Sulfate values

samples collected from Yala Glacier, Kumjung village, Xixabangma Peak, and Mt. Everest compared to samples from Biafo Glacier. Excess sulfate (non sea-salt) accounts for 90–95% of the total sulfate measured at all five sites. The elevated sulfate concentration in these samples could be

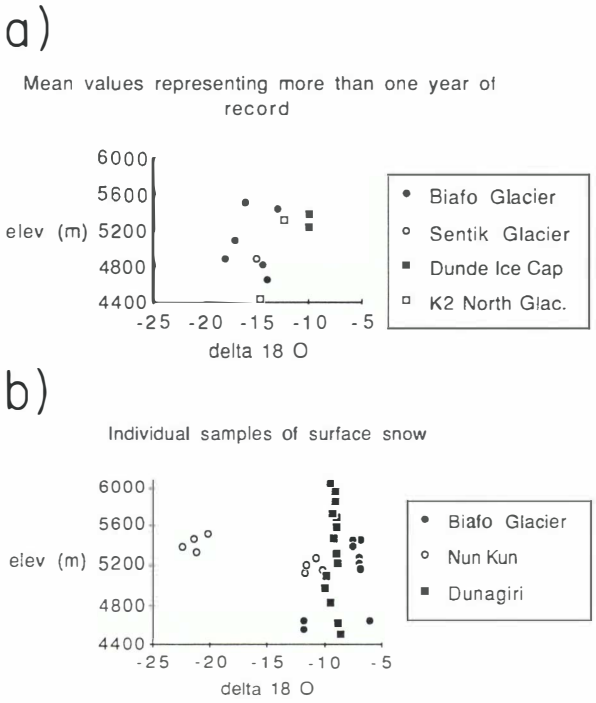

Fig. 3. $\delta^{18}O$ values derived from central Asian snow plotted against elevation: upper plot represents mean values derived from more than one year of record; lower plot represents individual samples of surface snow collected over a range of elevations.

due to an influx of anthropogenic emissions from the Indian subcontinent, transported to the Himalayas with monsoonal circulation. However, Mayewski and Lyons (1983) suggest that monsoonal air masses tend to dominate at lower elevations with more pristine air aloft. The calcium : sulfate ratio in snow from Mt. Everest is 0.17, suggesting that about one-fifth of the calcium and sulfate could enter the region in the form of gypsum-rich ($CaSO_4 \cdot 2H_2O$) dust from the arid regions of central Asia. Very high sulfate concentrations found in snow from the Tien Shan and Bogda Shan most likely reflect local anthropogenic sources (Wake and Mayewski, in preparation).

Strong seasonal signals are present in $\delta^{18}O$ records from both the Sentik (Mayewski and others, 1984) and Biafo (Wake, 1987, 1989, unpublished) glaciers, and have proven very useful in identifying seasonal stratigraphy. Strong seasonal variations of δD values were observed in precipitation collected in the Khumbu Himal; low δD values occurring in summer monsoonal rains are caused by removal of the heavy isotopic component in steady monsoon rains as they track across the Indian subcontinent (Wushiki, 1977a, b). $\delta^{18}O$ values derived from longer term records (i.e. greater than one year) and from individual samples of surface snow collected over a range of elevations, albeit from a limited number of sites, show no apparent trend with elevation (Fig. 3). This is not surprising as factors other than temperature, such as transport history and local meteorological conditions, can strongly affect the isotopic composition of snow in mountain areas (Niewodniczanski and others, 1981; Grootes and others, 1989). There exists a good relationship between mean annual temperature and $\delta^{18}O$ values for samples collected from Biafo, Sentik and Yala glaciers (Fig. 4). On the other hand, the Dunde Ice Cap experiences a very different climatic regime as it lies in the centre of a very arid region of central Asia. It is classified as an inland continental glacier (Li and Xu, 1980), with a net annual accumulation of 0.2 m w.e. This might explain the poor relationship with the Biafo and Sentik data.

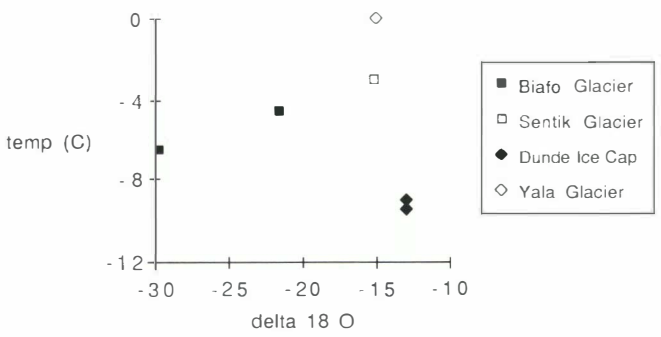

Fig. 4. $\delta^{18}O$ values derived from central Asian snow plotted against mean annual temperature.

CONCLUSIONS AND PERSPECTIVES

While limited in spatial and temporal distribution, the glaciochemical data thus far collected reveal local and regional trends, including a marine influence (sodium and chloride), a local crustal dust influence (sodium and reactive silica), a regional dust influence (nitrate and calcium) and an anthropogenic influence (sulfate) on snow deposited in central Asia.

As our knowledge of central Asian snow chemistry evolves, it is apparent that new programs ought to incorporate analyses of a wider variety of chemical species in order to determine the relative importance of various sources (e.g. marine, crustal, biogenic, anthropogenic, volcanic). For example, marine sulfate could be quantified by measuring methyl sulfonic acid. Inputs from the arid regions of central Asia and local crustal debris could be identified by measuring the aluminium, sodium, calcium, magnesium, reactive silica and iron content of the samples. A potential volcanic source of sulfate could be identified by looking at microparticle, chloride and fluoride concentrations, and sulfur isotope ratios. The remaining excess sulfate would most likely be due to anthropogenic activity. Anthropogenic influence could be quantified by analyzing the snow for such constituents as ammonium, nitrogen and sulfur isotopes, and various trace metals. Stratospheric versus tropospheric inputs can be distinguished using ^{7}Be as a tracer. In addition, we must also improve our understanding of the air/snow fractionation processes which dominate in the different climatic regimes of the area. We are in the process of developing this type of data set for snow samples collected from selected sites throughout central Asia.

The glaciochemical record in central Asian glaciers represents an extremely valuable, yet virtually untapped, resource. However, depending upon the sample location, glaciochemical records recovered from central Asian glaciers could potentially be swamped by high levels of marine, continental dust and/or anthropogenic inputs; a problem less prevalent in polar regions. Therefore, understanding the processes which control the chemical content of snow, the local to regional scale complexities, and the seasonal variability are fundamental steps necessary in order to assess the potential for recovering representative long-term glaciochemical records from central Asia.

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