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Cameron P. Wake
University of New Hampshire - Main Campus, cameron.wake@unh.edu

Paul A. Mayewski
University of New Hampshire - Main Campus

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Snow and Glacier Hydrology (Proceedings of the Kathmandu Symposium, November 1992).
IAHS Publ. no. 218, 1993.

The Spatial Variation of Asian Dust and Marine Aerosol Contributions to Glaciochemical Signals in Central Asia

C. P. WAKE & P. A. MAYEWSKI
Glacier Research Group, Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, New Hampshire 03824, USA

Abstract Short-term (6 months to 17 years) glaciochemical records have been collected from several glacier basins in the mountains of central Asia. The spatial distribution of snow chemistry in central Asia is controlled by the influx of dust from the large expanse of arid and semi-arid regions in central Asia. Glaciers in the Northern and Western Tibetan Plateau show elevated concentrations and elevated annual fluxes of calcium, sodium, chloride, sulphate and nitrate due to the influx of desert dust from nearby arid and semi-arid regions. Glaciers in the Southeastern Tibetan Plateau show lower concentrations and lower annual fluxes of major ions due to longer transport distances of dust from the arid and semi-arid regions of Western China. Snow from the Karakoram and Western Himalaya show ion concentrations similar to those in Southeastern Tibetan Plateau, but much higher annual fluxes suggesting that much of the aerosol and moisture transported with the westerly jet stream is removed as it ascends the Southwest margin of the Tibetan Plateau. Snow from the Southern slopes of the Eastern Himalayas shows very low concentrations and very low annual fluxes of major ions, indicating that this region is relatively free from the chemical influence of Asian dust. The glaciochemical data suggest that glaciers which are removed from large source areas of mineral aerosol, such as those in the Himalaya, the Karakoram, and the Southeastern Tibetan Plateau, are the ones most likely to contain longer-term glaciochemical records which detail annual to decadal variation in the strength of the Asian monsoon and long-range transport of Asian dust.

INTRODUCTION

The chemical analysis of snow and ice samples recovered from snow pits and ice cores has proven extremely valuable in producing high resolution palaeo-environmental records of atmospheric chemistry and climate over a wide range of time scales (tens to hundreds of thousands of years; e.g. Mayewski *et al.*, 1986a; 1990, 1993; Mayewski & Legrand, 1990; Jouzel *et al.*, 1987; Legrand *et al.*, 1988). While the oldest and best preserved records come from polar regions, limited work on snow and ice samples recovered from high

altitude/mid-low latitude glaciers has shown that these regions also hold valuable records of environmental change (e.g. Mayewski *et al.*, 1984; Wagnebach *et al.*, 1988; Holdsworth *et al.*, 1989; Thompson *et al.*, 1989; Wake, 1989). Glaciochemical records allow us to piece together a detailed history of precipitation chemistry that is not available through any other type of environmental record.

The vast extent of glacierized regions in the high mountains of central Asia (Fig. 1) provide several locations from which to recover glaciochemical records. Prior to 1989 we had collected high resolution, short-term (6 months to 17 years) glaciochemical records from a few glacier basins in central Asia, including Sentik Glacier in the Ladakh Himalaya (site 2 in Fig. 1; Lyons & Mayewski, 1983; Mayewski *et al.*, 1984), Biafo Glacier in the central Karakoram (site 3; Wake 1987a, b; 1989), and two locations in the Eastern Tien Shan (site 10; Wake *et al.*, 1992). In addition, other studies had investigated the chemistry of individual snowfall events (e.g. Jenkins *et al.*, 1987; Mayewski & Lyons, 1983; Mayewski *et al.*, 1986b) and ice cores (e.g. Watanabe *et al.*, 1984; Thompson *et al.*, 1989) in the mountains of central

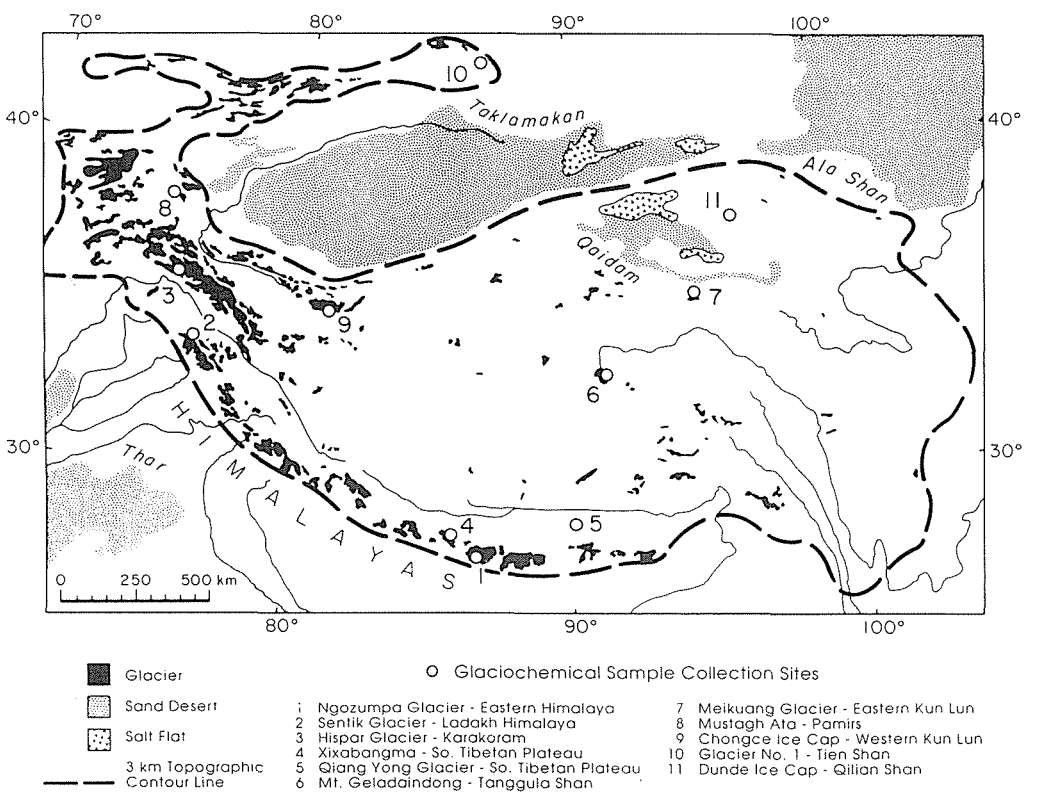

Fig. 1 Location map for glaciochemical collection sites (represented by open circles)in the mountains of central Asia. The heavy dashed line represents the 3000 m contour line and outlines the Tibetan plateau. All samples were collected within the accumulation zone of each glacier basin. Landscape and topographic information were derived from Royal Geographical Society (1987).

Asia. However, interpretation of the spatial variation of snow chemistry in central Asia were clearly hampered by the spatial and temporal limitations of, and lack of consistency in, the existing glaciochemical data set (Wake *et al.*, 1990).

Recently we have collected a number of new glaciochemical records from Ngozumpa Glacier (site 1 in Fig. 1) on the Southern slopes of the Eastern Himalaya; Hispar Glacier (site 3) in the Karakoram; Xixabangma peak (site 4) and Qiang Yong Glacier (site 5) in the Southern Tibetan Plateau; Mt. Geladaindong (site 6) in the Tanggula Shan; Meikuang Glacier (site 7) in the Eastern Kun Lun; Mustagh Ata (site 8) in the Pamirs; and Chongce Ice Cap (site 9) in the Western Kun Lun. These data represent a significant improvement in terms of the spatial coverage and quality of glaciochemical records from central Asia. These new glaciochemical data, in conjunction with results from previous investigations in central Asia (i.e. Mayewski *et al.*, 1984; Thompson *et al.*, 1989; Wake *et al.*, 1992) are used in this paper to define the spatial variation of snow chemistry in central Asia, to determine the influence of marine aerosol and Asian dust on the chemical content of snow in central Asia, and to identify glaciers whose chemical records most likely reflect the annual to decadal variability of the Asian monsoon. In conjunction with glaciochemical sample collection program in central Asia, we have also developed records describing the spatial variation of aerosol chemistry (Wake *et al.*, in press) and dust deposition (Wake *et al.*, in review) in the mountains of central Asia.

Landscape zones and climatic regimes

The glaciochemical sample collection sites cover a wide geographic area (Fig. 1) and represent four distinct regions on the basis of landscape, as defined by Alekseyev *et al.* (1988), and/or on the basis of climatic regime (i.e. relative influence of monsoonal versus westerly air masses) as reviewed by Barry & Chorley (1982), Li & Xu (1984), Hastenrath (1985), Chang & Krishnamurti (1987), Fein & Stephens (1987), and Domrös & Peng (1988):

(i) Ngozumpa Glacier (site 1) lies on the Southern slopes of the Eastern Himalaya. This region is characterized by mixed forest and small scale agriculture below 4000-4500 m asl, while glaciers and mountains dominate above this elevation. Precipitation is derived from monsoonal air masses during the summer and, at high elevations, from westerly depressions during the winter (Inoue, 1976; Barry, 1981).

(ii) Sentik Glacier (site 2) and Hispar Glacier (site 3) lie in the Western Himalaya and Karakoram, respectively. The exceptional elevation and concentration of peaks over 6000 m in the Karakoram produces an effective barrier for air masses transported with the mid-latitude westerlies. Orographic lifting of westerly derived air masses throughout the year results is very high snow accumulation above 4000 m asl (Wake,

1989). Occasionally, substantial summer snowfalls result from the incursion of monsoonal air masses (Finsterwalder, 1960; Wake, 1989). The Western Himalaya receives a greater portion of its precipitation from monsoonal sources (Mayewski *et al.*, 1984; Hastenrath, 1985). Arid and semi-arid conditions predominate below 4000 m asl in the Karakoram and Western Himalaya due to the rainshadow effect and desiccating down-valley wind systems. In addition, arid and semi-arid regions, including the Thar Desert, the upper Indus Plains and Afghan Turkestan, lie to the Southwest of the Karakoram and the Western Himalaya (Middleton *et al.*, 1986).

(iii) Xixabangma Peak (site 4), Qiang Yong Glacier (site 5), and Mt. Geladaindong (site 6) all fall within the grassland steppes which dominate the Southeastern Tibetan Plateau. Mt. Geladaindong lies close to the transition zone between grassland steppes to the South and East and semi-arid/arid regions to the North and West. The Southeastern Tibetan Plateau receives most of its precipitation from summer plateau monsoon circulation (Murakami, 1976; Tang & Shen, 1981)

(iv) The Northern and Western regions of the Tibetan Plateau are characterized by semi-arid and arid regions. In addition, Meikuang Glacier (site 7) and Dunde Ice Cap (site 11) lie adjacent to the Qaidam Basin in the Northeastern regions of the plateau; Mustagh Ata (site 8) and Chongce Ice Cap (site 9) lie adjacent to the Taklamakan desert and numerous loess deposits (Liu, 1985); and Glacier No. 1 (site 10) lies in between the Taklamakan and Junggar deserts. Surface material in central Asian deserts is typically calcareous (Dregne, 1968; McKee, 1979). Furthermore, numerous large depressions in the Qaidam and Taklamakan desert basins contain extensive salt deposits rich in sodium and chloride, among other species (Dregne, 1968; McKee, 1979; Chen & Bowler; 1986).

Atmospheric circulation

Atmospheric circulation in central Asia is characterized by a marked seasonal shift in surface and upper level wind systems associated with the Asian monsoon (Barry & Chorley, 1982; Chang & Krishnamurti, 1987; Fein & Stephens, 1987). During the winter the westerly jet stream is split into two branches, one passing to the North and one to the South of the Tibetan Plateau. Throughout the winter the subtropical westerly jet stream steers depressions towards the Western margin of the plateau and along the Southern slopes of the Himalaya, causing high winds and snowstorms at high elevations in the Pamirs, the Karakoram, and the Himalaya. The interior regions of the Tibetan Plateau, which lie in the rain shadow of the mountains on the Western margin, generally receive limited precipitation during the winter, although the occasional influx of westerly disturbances in winter can result in large snowfall events (Reiter, 1981; Seko & Takahashi, 1991).

In May and June the Southern jet stream slowly weakens, and by mid-June is replaced by an easterly jet stream, as the summertime high level anticyclone develops over the Tibetan Plateau. During the summer, Indian summer monsoon circulation transports moisture from the Bay of Bengal to the Eastern and central Himalaya, and moisture from the Arabian sea to the Western Himalaya and Karakoram. Moisture from the Bay of Bengal is also carried into the Eastern portions of the Tibetan Plateau via summer plateau monsoon circulation (Tang & Shen, 1981; Murakami, 1987; Domrös & Peng, 1988).

Source areas for dust in Asia

Descriptions of dust storm activity in Asia are provided by Goudie (1983), Middleton (1986; 1989), Middleton *et al.* (1986) Merrill *et al.* (1989) and Gao *et al.* (1992). Several arid and semi-arid regions act as source areas for dust in central Asia. Low pressure fronts transport dust from the arid regions in Western China (i.e. Taklamakan Desert and surrounding loess deposits, and the Qaidam Basin) Eastward over the Tibetan Plateau, Eastern China and the Pacific Ocean. Upper level westerly airflow generates point-source dust storms in the Western and Northern regions of the Tibetan Plateau. Low pressure fronts moving easterly also create dust storm conditions in the Kara Kum and other deserts in Tajikistan, Kyrgyzstan and Southern Kazakhstan. In the Thar desert of India and Pakistan, dust is transported easterly and northeasterly as a result of strong pressure gradients prior to the break of the summer monsoon. Katabatic winds, reinforced by topographic funnelling of westerlies, generate point-source dust storms in the Karakoram and Hindu Kush mountain ranges. The peak in dust storm activity throughout Asia occurs during the spring and early summer months, although dust storms do occur at other times of the year.

SAMPLING AND ANALYSIS

Sample collection

Snow and ice samples for this study were collected from snowpits and shallow cores at high elevation sites in the accumulation zones of central Asian glaciers (Table 1). Continuous records extending for one year or longer are available from Ngozumpa Glacier (site 1), Sentik Glacier (site 2), Hispar Glacier (site 3), Xixabangma Peak (site 4), Qiang Yong Glacier (site 5), Mt. Geladaindong (site 6), Mustagh Ata (site 8), and Dunde Ice Cap (site 11). At 5760 m asl at Meikuang Glacier (site 7) and 4140 m asl at Glacier No. 1 (site 10), we sampled shallow snowpacks (<0.2 m water equivalent) which lay directly on top of glacier ice. Seasonal snow accumulation melts completely during the summer ablation season. The longest reliable record available from Meikuang Glacier and Glacier No. 1 is therefore less than one year. During

Table 1 Glaciochemical sample collection sites in the mountains of central Asia.

Site no. (Fig. 1)	Mountain/ glacier	Elevation (m asl)	Lat. (N)	Long. (E)	Period of record**	Years of record	n
SOUTHERN SLOPES- EASTERN HIMALAYA							
1	Ngozumpa Glacier	5700	28.0	86.7	1989-90	1	30
WESTERN HIMALAYA & KARAKORAM							
2	Sentik Glacier*	4908	34.0	76.1	1963-80	17	99
3	Hispar Glacier	5150	36.0	75.5	1985-88	3	76
SOUTH-EASTERN TIBETAN PLATEAU							
4	Xixabangma Peak	6140	28.3	85.2	1990-91	1	30
5	Qiang Yong Glacier	5850	28.8	90.2	1990-91	1	17
6	Mt. Geladaindong	5950	33.4	91.1	1988-90	2	40
NORTHERN & WESTERN TIBETAN PLATEAU							
7	Meikuang Glacier	5480-5769	35.7	94.2	summer 91	half	12
8	Mustagh Ata	5910	38.2	75.1	1990-92	2	30
9	*Chongce Glacier*	6327	35.2	81.6	1980-87§	7§	77
10	Glacier No. 1*	3960-4140	43.1	86.8	spring 89	half	27
11	Dunde Ice Cap*	5325	38.1	96.4	1967-87	20	na

n is the number of samples analysed; here, na means not available.

* Sentik Glacier data from Mayewski *et al.* (1984); Glacier No. 1 data from Wake *et al.*, 1992; Dunde Ice Cap data from Thompson *et al.* (1989).

§ The record from Chongce Ice Cap is discontinuous due to contamination of firn samples during transport. Only chemical data derived from the ice sections of the core are reported.

** Note that the period of record is not the same for all sites. However, the 1-to-3 fold variation from year-to-year in the annual mean ion concentrations of snow at sites for which there is more than one year of record (i.e. Sentik, Hispar, Geladaindong, Mustagh Ata) is much less than the 4-to-80 fold variations observed on a spatial scale (see Fig. 2). In addition, the systematic spatial variation in major ion concentration in central Asian snow suggests that the data provide a representative regional perspective.

transport, a firn/ice core recovered from Chongce Ice Cap (Han *et al.*, 1989) experienced a minor degree of melting; water migration through the firn sections resulted in contamination. The chemistry data from Chongce Ice Cap comes only from the ice sections of the core and therefore represents a discontinuous record.

Extreme care was taken at all times during sample collection, handling and transport to assure that samples remained uncontaminated. Non-particulating clean suits and hoods, plastic gloves and particle masks were worn during all sampling procedures. Prior to use all sample tools and containers were rinsed, soaked, and rinsed again with Milli-Q water (Millipore Corp., Bedford, Massachusetts, USA). Snow and ice samples were collected continuously at 5 or 10 cm depth intervals, depending on the annual snow accumulation. More than 10 samples were collected from each annual layer enabling us to characterize seasonal signals. Analyses of duplicate samples as well as transport and laboratory blanks indicates that sample contamination during sample transfer, transport and subsequent analytical procedures was negligible.

Snow and ice samples collected from glaciers in central Asia were processed in two ways. Where practical, samples were placed in precleaned 125 ml containers, placed in insulated shipping containers with frozen eutectic mixtures and were kept frozen during shipment to the University of New Hampshire. Where keeping samples frozen was not possible, the samples were melted in the field and transferred to precleaned, leakproof 30 ml sample containers. This was done on the glacier itself as the environment in general was cleaner than anything down valley. Analysis of selected duplicate melted and frozen snow samples collected from Glacier No. 1 (site 10) suggests there is little difference in the concentration of dominant ions (i.e. sodium, magnesium, calcium, chloride, nitrate, and sulphate) between samples that were melted in the field and those that were kept frozen until just prior to analysis (Wake *et al.*, 1992). This improves our confidence in comparing the major ion data derived from samples that were melted in the field (i.e. Sentik Glacier, Hispar Glacier, Mt. Geladaindong, Meikuang Glacier, Mustagh Ata and Glacier No. 1) and those that were returned frozen (i.e. Ngozumpa Glacier, Xixabangma, Qiang Yong Glacier and Chongce Ice Cap).

Laboratory analysis

Snow samples were analysed for anions (chloride, sulphate, and nitrate) and cations (sodium, potassium, calcium, and magnesium) using a Dionex™ Ion Chromatograph Model 2010 (Dionex Corp., Sunnyvale, California, USA) with computer driven auto sampler in the laboratories of the Glacier Research Group at the University of New Hampshire. The anion system employed a Dionex™ AS4A anion exchange column in conjunction with an anion guard column. The cation system consisted of Dionex™ cation-I and cation-II fast columns. Ten percent of all samples were analysed in duplicate using two separately drawn aliquots. This procedure resulted in a standard deviation from the mean of less than 5% for anions and less than 7% for cations.

RESULTS

Ion concentrations

Major ion concentrations in central Asian snow exhibit a systematic regional variation. Each of the four landscape/climatic zones in central Asia where snow and ice samples were collected display distinct characteristics with respect to major ions concentrations (Fig. 2). Geometric means are used to characterize ion concentrations, as the data from each site approaches a lognormal distribution. Ngozumpa Glacier on the Southern slope of the Eastern Himalaya shows geometric mean concentrations of calcium, sodium, chloride, and sulphate less than 0.4 μeq kg^{-1}. Glaciers in the Western Himalaya and

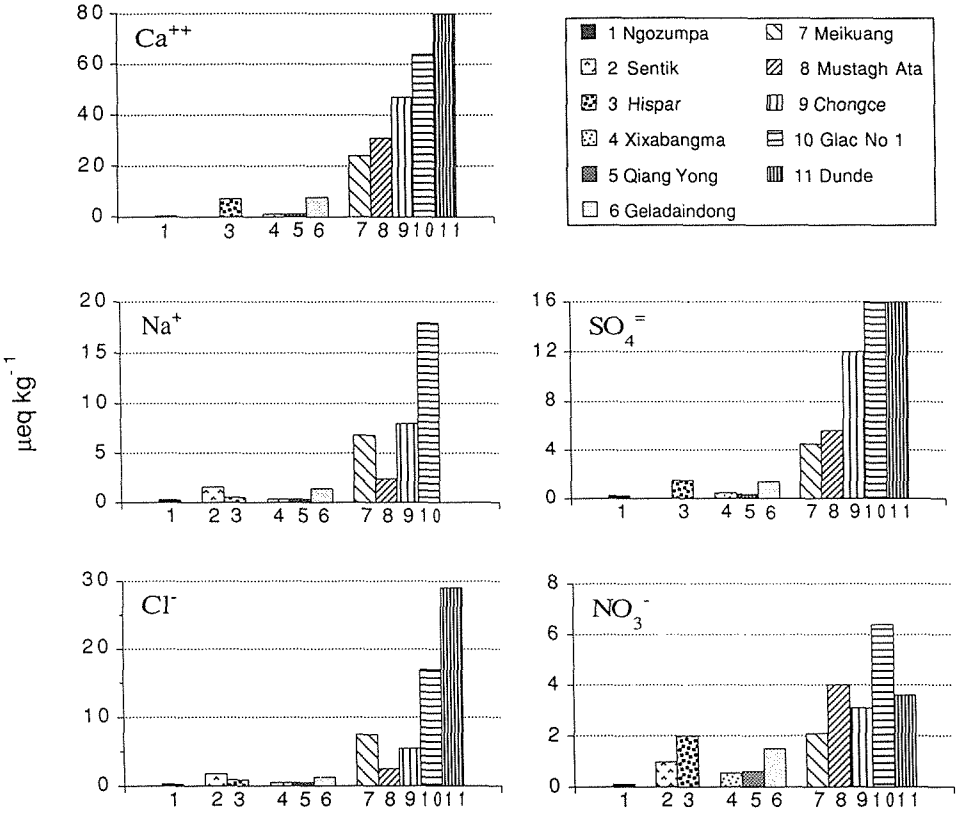

Fig. 2 The spatial variation of geometric mean concentrations of calcium, sodium, chloride, sulphate, and nitrate in central Asian snow. The sites from left to right are arranged roughly from South to North. Numbers beside site names refer to location in Fig. 1.

Karakoram (Sentik and Hispar) show geometric mean calcium concentrations of 7.3 μeq kg^{-1} (Hispar only) and sodium, chloride, and sulphate levels ranging from 0.5 to 2.0 μeq kg^{-1}. Glaciers in the Southeastern Tibetan Plateau (Xixabangma, Qiang Yong, and Mt. Geladaindong) display calcium levels ranging from 1 to 8 μeq kg^{-1}, and sodium, chloride, and sulphate levels ranging from 0.4 to 1.5 μeq kg^{-1}. Glaciers in the Northern regions of the Tibetan Plateau (Meikuang, Mustagh Ata, Chongce, Glacier No. 1, and Dunde) show concentrations of calcium greater than 24 μeq kg^{-1}, and of sodium, chloride, and sulphate greater than 2.4 μeq kg^{-1}. In contrast to the species discussed above, nitrate concentrations show less variation over the Tibetan Plateau and bordering mountain regions, indicative of a separate and more distant source. However, higher concentrations of nitrate are still associated with glaciers which show elevated levels of calcium, sodium, chloride, and sulphate.

Annual fluxes

Annual layers in the glacier were delineated in the field using the location of

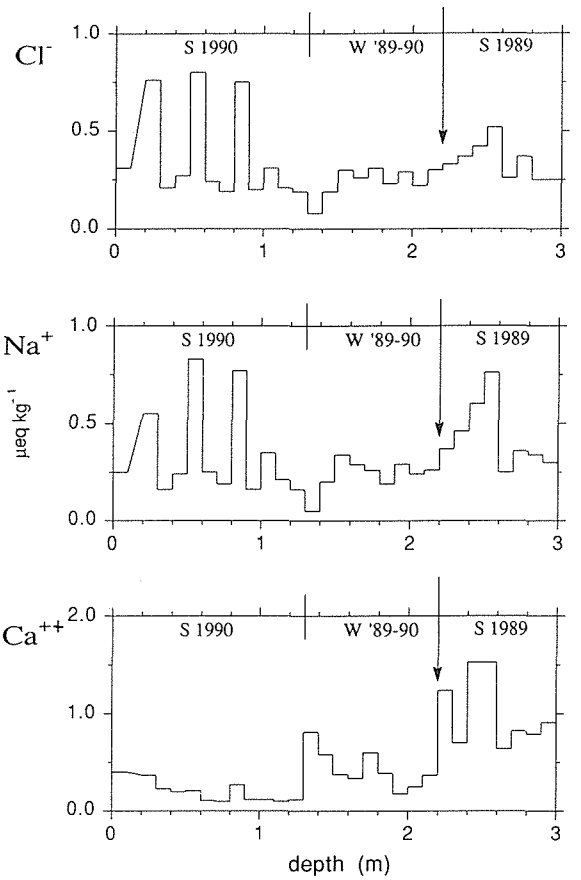

Fig. 3 Depth profiles of chloride, sodium, and calcium from Ngozumpa Glacier (site 1) on the Southern slopes in the Eastern Himalaya. "End of summer" surfaces are identified with vertical arrows. Summer layers are identified with an "S" while winter layers are identified by a "W".

visible dust layers, ice layers and ice lenses, as well as variations in snow density, snow colour and grain size. In addition, available meteorological records for each region were reviewed and patterns of seasonal precipitation identified to help delineate seasonal layers. Following analyses of major ion and particle concentrations of snow samples, depth profiles of these parameters were compared with each other, and with the chronology that had been established using the physical characteristics of the snowpack. Strong seasonal signals in major ion chemistry and particle concentrations were then used to help define transitions between different seasonal layers in the glacier. Depth profiles of sodium, chloride, and calcium for samples from Ngozumpa Glacier (site 1) Hispar Glacier (site 3) and Mt. Geladaindong (site 6) appear in Figs. 3, 4, and 5, respectively. End of summer surfaces, as determined from both physical and chemical stratigraphy, are identified with vertical arrows.

The mass depositional flux of major ions was calculated by multiplying the water equivalent thickness by the ion concentration for each sample. Annual

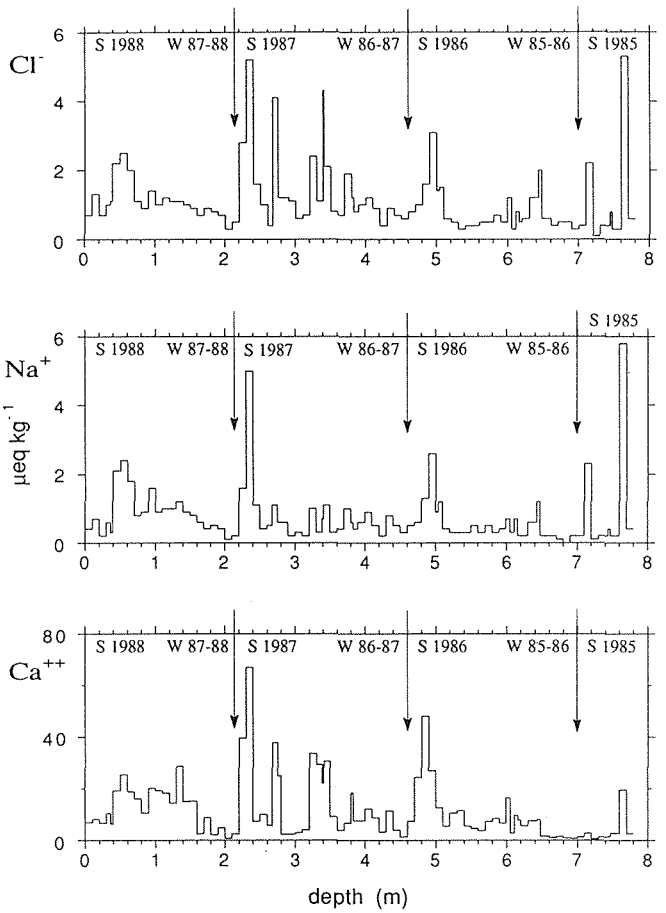

Fig. 4 Depth profiles of chloride, sodium, and calcium from Hispar Glacier (site 3) in the Karakoram. "End of summer" surfaces are identified with vertical arrows. Summer layers are identified with an "S" while winter layers are identified by a "W".

fluxes represent the sum of fluxes for all samples in an annual layer. Annual deposition of snow and major ions is available for seven sites (Table 2). Annual fluxes could not be calculated for Meikuang Glacier (site 7) or Glacier. No 1 (site 10) because the records extend for only 6 months. The discontinuous record from Chongce Ice Cap does not allow for accurate annual flux calculations. No flux data is yet available for the Dunde Ice Cap (Thompson *et al.*, 1989).

The annual flux data displays similar spatial patterns to those apparent in the major ion concentration data. Ngozumpa Glacier (site 1) shows an intermediate value for annual snow accumulation, but very low annual fluxes for all ions. Hispar Glacier in the Karakoram and, to a lesser extent Sentik Glacier in the Western Himalaya, show high annual snow accumulation rates and high annual fluxes of calcium, sodium, chloride, sulphate, and nitrate. Annual ion fluxes measured on glaciers in the South-eastern regions of the Tibetan Plateau (Xixabangma, Qiang Yong and Mt. Geladaindong) are

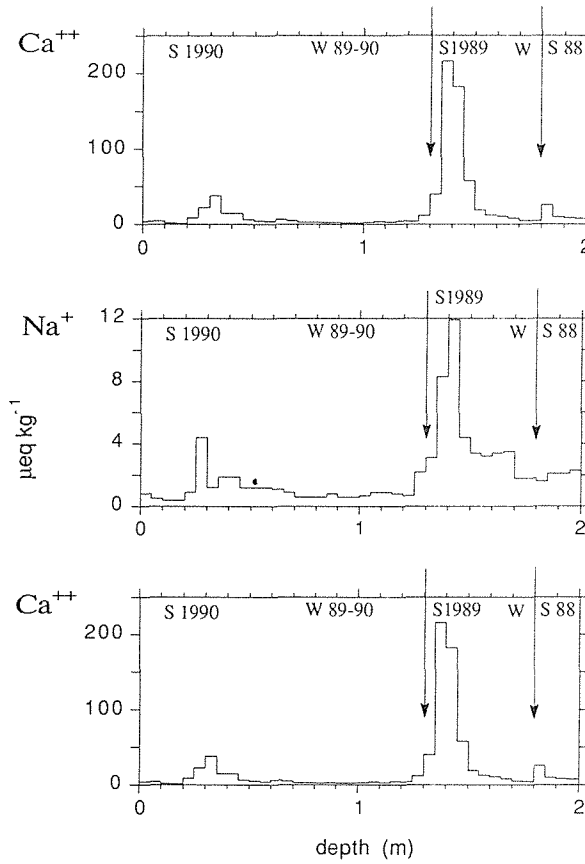

Fig. 5 Depth profiles of chloride, sodium, and calcium from Mt. Geladaindong (site 6) in the central regions of the Eastern Tibetan Plateau. "End of summer" surfaces are identified with vertical arrows. Summer layers are identified with an "S" while winter layers are identified by a "W".

intermediate between the high values in the Western Himalaya and Karakoram and the very low values at Ngozumpa Glacier. Mustagh Ata in the Western Tibetan Plateau shows low annual snow accumulation rates but relatively high annual fluxes of calcium, sodium, chloride, and sulphate.

DISCUSSION

Snow from Southern slopes in the Eastern Himalayas (site 1), in comparison to snow collected from other glaciers in central Asia, shows very low major ion concentrations (Fig. 2) and annual fluxes (Table 2). In fact, major ion concentrations and annual fluxes at Ngozumpa Glacier are comparable to those measured in pre-1900 A.D. snow from central Greenland and in snow collected 38 km upwind of the South Pole (Whitlow *et al.*, 1992). Low calcium levels suggest that high elevation glaciers on the Southern slopes of the Eastern Himalaya are relatively free from the chemical influence of Asian dust which

Table 2 Annual accumulation of snow and major ions in central Asia.

Site no (Fig. 1)	Mountain/ glacier	Elevation (m asl)	Snow accumulation (g cm^{-2} a^{-1})	Years of record	(neq cm^{-2} a^{-1}) Ca^{++}	Na^{+}	Cl^{-}	$SO_4^{=}$	NO_3^{-}
SOUTH SLOPE - EASTERN HIMALAYA									
1	Ngozumpa	5700	56	1	26	22	23	13	9
WESTERN HIMALAYA & KARAKORAM									
2	Sentik	4908	60	17	na	152	146	na	70
3	Hispar	5150	130	3	1580	273	146	273	390
SOUTH-EASTERN TIBETAN PLATEAU									
4	Xixabangma	6140	68	1	169	34	43	45	45
5	Qiang Yong	5850	62	1	137	24	30	24	44
6	Geladaindong	5950	30	2	794	78	64	62	74
NORTHERN & WESTERN TIBETAN PLATEAU									
8	Mustagh Ata	5910	24	2	1400	115	108	182	93

Here, na means not available.

tends to dominate snow chemistry at some of the other sites (see discussion below). The calcium time series from Ngozumpa Glacier (Fig. 3) displays peaks in summer of 1989 and winter of 1990, but not during the summer 1991 layer. Conversely, the sodium and chloride profiles (Fig. 3) show summertime peaks rising 0.5 μeq kg^{-1} above background ($\approx$0.3 μeq kg^{-1}). The Southern slopes of the Eastern Himalaya are strongly influenced by precipitation derived from the influx of monsoonal air masses during the summer (Miller *et al.*, 1965; Inoue, 1976; Yasunari, 1976; Yasunari & Inoue, 1978). The sodium and chloride time series appear to reflect the influx of marine air masses, rich in sodium and chloride, associated with summer monsoon circulation.

In stark contrast to the low levels of major ions in snow from Ngozumpa Glacier, glaciers in the Northern and Western Tibetan Plateau (Meikuang, Mustagh Ata, Chongce, Glacier No. 1 and Dunde) show very high concentrations of calcium, sodium, and chloride. This is primarily a result of the influx of desert dust from the arid and semi-arid regions which dominate the landscape on the Northern and Western margins of the Tibetan Plateau. The seasonal variability in chemical signals at these sites is strongly related to the variability of dust rich layers. High concentrations of ions are associated with visible dust layers and/or layers with high microparticle content (Nakawo *et al.*, 1990; Thompson *et al.*, 1989; Wake et al, 1992).

The high concentration of sulphate in snow from Northern and Western Tibetan Plateau are associated with high levels of calcium, sodium, and chloride (Fig. 2). This pattern suggests that desert derived mineral aerosol is also the dominant source of sulphate in central Asia. Regional precipitation investigations in North America (Junge & Werby, 1958; Munger & Eisenreich,

1983; Barrie & Hales, 1984) and North Africa (Rognon, 1979) have shown that arid regions are commonly source areas for sulphate. However, anthropogenic sources of sulphate are also clearly recorded in the Tien Shan (Wake *et al.*, 1992) and in seasonal snow throughout the former Soviet Union (Belikova *et al.*, 1984), suggesting that anthropogenic emissions also play an important role in the regional sulphur cycle in central Asia. Sodium and chloride signals in the North-eastern region of the Tibetan Plateau (i.e. Meikuang Glacier and Dunde Ice Cap), which potentially relate to monsoon precipitation (i.e. peaks of ≈ 1 μeq kg-1), are effectively masked by sodium and chloride derived from the Qaidam and/or Taklamakan desert basins.

Lower concentrations and annual fluxes of calcium, sodium, chloride, sulphate and nitrate measured in glaciers in the Southeastern Tibetan Plateau (Xixabangma, Qiang Yong and Geladaindong), compared to values for glaciers in the Northern and Western Tibetan Plateau, are indicative of a decrease in the mineral aerosol input as a result of longer transport distance from large desert basins in Western China. Time series for calcium, sodium and chloride from Mt. Geladaindong (Fig. 4) show strong seasonality. Peaks in all three species occur in the spring/summer layers of the snowpack. This likely results from the transport of dust, raised during the springtime dust storm period in the Taklamakan Desert, Qaidam basin and/or arid and semi-arid region in the Northern and Western Tibetan Plateau, to the central and Southern Tibetan Plateau by persistent northwesterly surface winds (Luo & Yanai, 1983; Murakami, 1987). Higher concentrations and annual fluxes of calcium at Mt. Geladaindong are consistent with this interpretation as this glacier lies closer to the mineral aerosol source regions to the North and West (Fig. 1). Note that the winter of 1989-90 shows much greater snow accumulation than the previous winter (Fig. 4). According to local shepherds the winter of 1989-90 was a period of abnormally high snow accumulation and, as a result of the deep snowpack, they lost several thousand head of sheep. Summertime peaks which are unique to the sodium and chloride time series are thought to represent the influx of sodium and chloride rich marine air masses associated with plateau monsoon circulation (Tang & Shen, 1981; Murakami, 1987).

The high annual flux of snow and major ions at Hispar Glacier, and to a lesser extent at Sentik Glacier, suggests that much of the aerosol and moisture transported with the westerly jet stream is removed as it ascends the Southwest margin of the Tibetan Plateau. Calcium time series from Hispar Glacier (Fig. 5) do not show a strong seasonal signal which are indicative of inputs of dust throughout the year. Conversely, sodium and chloride show peaks in spring/summer layers suggesting inputs of evaporite rich dust transported from the Thar desert during the springtime dust storm period and/or inputs of marine aerosol from monsoonal air masses.

CONCLUSIONS

The glaciochemical data set presented here confirms that chemical signal recorded in glaciers from the Northern and Western Tibetan Plateau are dominated by desert dust derived from the vast arid and semi-arid regions of central Asia, while glaciers in the Karakoram, the Western Himalaya, and the South-eastern Tibetan Plateau record inputs of both continental dust and marine aerosol. Glaciochemical records from the Southern slopes of the Eastern Himalaya are characterized by very low ion burdens representative of relatively clean free tropospheric air, and are therefore are sensitive to inputs of marine aerosol associated with summer monsoon circulation.

Aside from an analysis of glacier fluctuations since 1850 AD (Mayewski *et al.*, 1980), paleoclimatic records that have been recovered from the Himalayas and the Tibetan Plateau (e.g. Bryson *et al.*, 1981; Kutzbach, 1981; Wang & Fen, 1987; Thompson *et al.*, 1989; Gasse *et al.*, 1991; Lister *et al.*, 1991) have not yet provided information concerning the annual to decadal variability of the Asian monsoon. Our regional glaciochemical survey in central Asia suggests that chemical signals relating to the Asian monsoon are most clearly recorded at sites, such as the Eastern Himalaya, which are well removed from the influence of Asian dust, while glaciers in the Western Himalaya, Karakoram and Southern Tibetan Plateau record combined monsoonal and Asian dust signals. Any snow chemistry signals of regional significance recorded in glaciers in the Northern and Western regions of the plateau are most likely obscured by dust derived from the Taklamakan and Qaidam desert basins. High elevation glaciers in the Himalayas, the Karakoram and Southern Tibetan Plateau are therefore most likely to contain longer-term glaciochemical records which reflect regional to hemispheric climatic signals, such as the annual to century scale variation in the strength of the Asian monsoon and the long-range transport of Asian dust.

In response to the results of our glaciochemical research in the mountains of central Asia, and in conjunction with the Department of Hydrology and Meteorology in Nepal, we are working to develop a high resolution (i.e. seasonal) palaeo-environmental record of the Asian monsoon through the collection and analysis of ice cores recovered from glacier basins in the Nepalese Himalaya. Chemical analysis of the soluble, insoluble and gas phases contained in these ice cores should provide the most detailed record of climate change available for the mountains of central Asia over the last 1000 to perhaps 10 000 years. The data generated by this program will be used to, for example: (1) determine annual to century scale variations in the strength of the summer Asian monsoon; (2) determine the variation in the position and/or strength of the westerly jet stream as recorded by wintertime snow and dust deposition; (3) develop an anthropogenic emission inventory for Southeast Asia at a site that is sensitive to regional change and not influenced by local sources; and (4) quantify the water balance in glacier basins (i.e. at elevations where snowfall

represents a vital component of the hydrological cycle in Nepal) where little or no traditional meteorological data exists

In conjunction with the glaciochemical investigations, we also plan to collect atmospheric aerosol samples on a daily basis during the field program, and on a monthly basis throughout the remainder of the year. Chemical analysis of these aerosol samples will provide direct measurements of the seasonal variation in air quality in the Nepalese Himalaya. Furthermore, comparison of aerosol and snow chemistries will allow us to determine the extent to which snow chemistry reflects that in the atmosphere and thereby improve the confidence with which we can interpret snow and ice chemistry records.

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