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Monsoon and Dust Signals Recorded in Dasuopu Glacier, Tibetan Plateau

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ABSTRACT. During summer 1997, a 15 m firn core was recovered from Dasuopu glacier (28°23′ N, 85°44′ E; 7000 m a.s.l.) on the northwest margin of Xixabangma Feng in the central Himalaya. Oxygen isotope values and concentrations of Ca^{2+}, Mg^{2+}, NH_4^+, SO_4^{2-} and NO_3^- were measured over the 10 years of snow accumulation captured in the firn core. The seasonal variations of $\delta^{18}O$ values and major-ion concentrations in the Dasuopu core indicate that summer monsoon and dust signals are clearly recorded in Dasuopu glacier. Annual variations in $\delta^{18}O$ values are controlled by the amount effect, with more negative (i.e. lighter) $\delta^{18}O$ values representing summer monsoon precipitation characteristic of tropical regions. Higher concentrations of Ca^{2+}, Mg^{2+} and SO_4^{2-} reflect the influx of mineral aerosols from the vast arid and semi-arid desert regions to the north and west during the spring dust-storm period. High spring concentrations of NH_4^+ and NO_3^- appear to reflect changes in regional biogenic-source strength.

INTRODUCTION

The Tibetan Plateau is one of the most imposing topographic features on the surface of the Earth. The sensible-heat flux and latent heat released over the Tibetan Plateau drives Asian monsoon circulation and strongly influences global circulation patterns (Luo and Yanai, 1983; Murakami, 1987; Domröss and Peng, 1988). Unfortunately, the longest continuous instrumental climate records for the region extend back only to AD 1935, and most records are available only from AD 1950. However, the Tibetan Plateau possesses a diversity of natural archives from which detailed paleoclimatic records can be developed. The development and interpretation of paleoclimate records is especially significant given the critical role that the highlands of central Asia play in the development and intensity of the Asian monsoon, and the importance of the Asian summer monsoon in providing life-sustaining rain to much of the world's population.

The physical and chemical analysis of ice cores recovered from glaciers on the Tibetan Plateau provides some of the best records of past climate change in the region (e.g. Mayewski and others, 1984; Thompson and others, 1989, 1995, 1997; Yao and Thompson, 1992; Yao and others, 1995). In order to better understand the climatic and environmental records preserved in snow and ice on the Tibetan Plateau, several studies have been performed to investigate the spatial and temporal variation of $\delta^{18}O$ and major ions in precipitation (Lyons and Mayewski, 1983; Mayewski and others, 1983; Wake and others, 1990, 1992, 1993, 1994b; Lyons and others, 1991; Yao and others, 1996) and the relationship between aerosol and precipitation chemistry (Wake and others., 1994a; Shrestha and others, 1997; Shrestha, 1998).

The isotopic content of precipitation in polar regions is dominated by the temperature effect (Dansgaard, 1964; Jouzel and others, 1987; Dansgaard and others, 1993), although complications may arise due to, for example, the scouring of winter snow (Fisher and others, 1983; Fisher and Koerner, 1988) or changes in the seasonality of snow accumulation (Steig and others, 1994). Conversely, in tropical regions there exists a good correlation between the amount of monthly precipitation and its isotopic content (termed the "amount effect"), with summer (maximum) precipitation characterized by the more negative (i.e. lighter) $\delta^{18}O$ values (Dansgaard, 1964; Rozanski and others, 1993). Furthermore, at many tropical stations, mean monthly $\delta^{18}O$ is inversely correlated with monthly temperature, confirming the dominant role of the amount effect in controlling the observed seasonal variations of $\delta^{18}O$ in precipitation. Measurements of precipitation and snow-pit samples in the Himalaya and southern regions of the Tibetan Plateau clearly show that the amount effect dominates seasonal variations of $\delta^{18}O$ in precipitation (e.g., Wushiki, 1977; Wake and Stiévenard, 1995). In the northeastern regions of the plateau, however, air temperature appears to be the controlling factor in temporal fluctuations of $\delta^{18}O$ (Yao and others, 1996).

The vast extent of glaciers in the mountains of the Tibetan Plateau provides a convenient means to measure the depositional flux of atmospheric dust over a wide geographic area. The arid and semi-arid regions of central Asia are a major source area for wind-blown dust to the Northern Hemisphere (Liu and others, 1981; Parrington and others, 1983; Gao and others, 1992). The peak in dust-storm activity throughout China occurs from mid-February until late May, with a strong maximum in late April–early May (Merrill and others, 1989). Investigations of the chemistry of snow, ice and aerosol samples collected from glacier

basins indicate that the spatial variation of snow chemistry in the mountains of central Asia is controlled primarily by the influx of desert dust derived from the arid and semi-arid regions of Asia (Wake and others, 1990, 1992, 1993, 1994a, b; Shrestha and others, 1997).

METHODOLOGY

During summer 1997, a 15 m firn core was recovered from a relatively flat portion of Dasuopu glacier (28°23′ N, 85°44′ E; 7000 m a.s.l.) on the northwest margin of Xixabangma Feng in the central Himalaya (Fig. 1). This paper focuses on the high-resolution $\delta^{18}O$ and major-ion (Ca^{2+}, Mg^{2+}, NH_4^+, SO_4^{2-} and NO_3^-) records developed from this core, in order to better understand the seasonal monsoon and dust signals preserved in snow in this region. The core was drilled using a Polar Ice Coring Office (PICO) shallow drill. It was packed into polyethylene sleeves and placed in freezers for transport to the Lanzhou Institute of Glaciology and Geocryology. Samples were collected at intervals of 5 cm (equivalent to about 30 samples per year) in a clean cold room. Extreme care was taken at all times during sample collection and handling to assure samples were not contaminated. For example, non-particulating suits, polyethylene gloves and masks were worn at all times during sampling. Tabletops were covered with pre-cleaned plastic. After sectioning of the core, each sample had its outer 1 cm scraped using a clean stainless-steel scalpel. Once scraped, samples were placed into pre-cleaned plastic bags. After melting, each sample was transferred to 20 and 60 mL pre-cleaned high-density polyethylene bottles for analysis of major ions and $\delta^{18}O$, respectively. A total of 305 samples were obtained from the core.

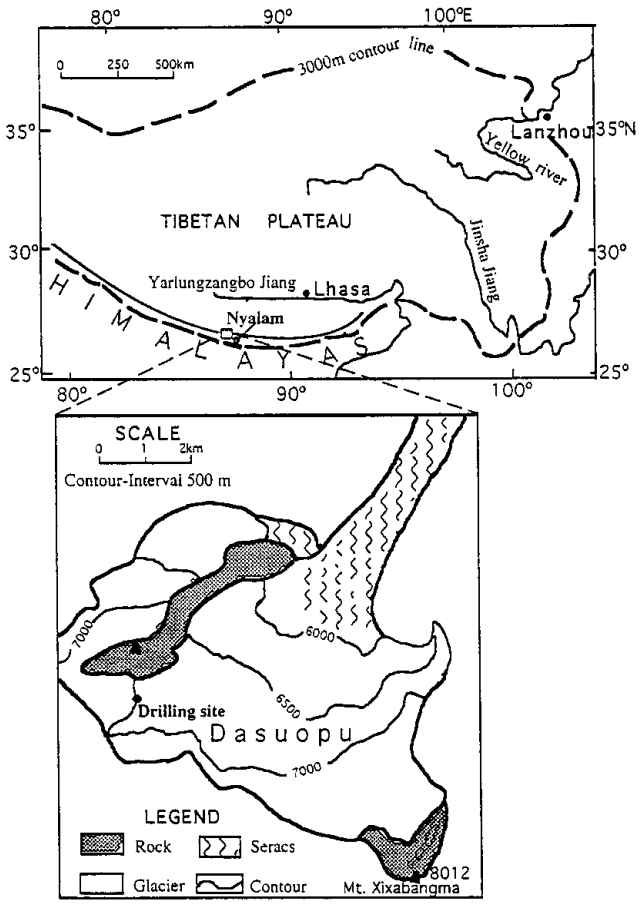

Fig. 1. Location map of drilling site located on the northern flank of Xixabangma Feng.

Oxygen isotope analysis was performed using a Finnigan MAT-252 Spectrometer (accuracy of 0.5%) in the Laboratory of Ice Core and Cold Regions Environment, Chinese Academy of Sciences. The 20 mL bottled samples were transported to the Climate Change Research Center, University of New Hampshire, and analyzed for anions (chloride, sulfate and nitrate) and cations (sodium, potassium, calcium, magnesium and ammonium) using a Dionex Ion Chromatograph model 2010. Detailed methods are described by Buck and others (1992) and Wake and others (1992).

This paper focuses on the seasonal variation of $\delta^{18}O$ and concentrations of dust-source ions (Ca^{2+}, Mg^{2+} and SO_4^{2-}) and biogenic-source ions (NH_4^+ and NO_3^-). Profiles of $\delta^{18}O$ and major-ion concentrations against water-equivalent depth are shown in Figure 2. In general, high concentrations of major ions correspond to less negative $\delta^{18}O$ values. The core was dated down to the summer of 1988 by counting annual peaks of $\delta^{18}O$ and major-ion concentrations. Average annual accumulation rate in the past decade is 0.75 m w.e.

The 8 years for which there exists a complete annual record of $\delta^{18}O$ and major ions were selected to study seasonal variability. Instrumental data from the closest meteorological station (Nyalam station, 28°11′N, 85°58′ E; 3810 m a.s.l.; 20 km southeast of the drill site) were used to compare with the core data. At Nyalam station, the mean annual surface air temperature and precipitation are 3.5°C and 0.62 m, respectively, for the period 1967–93. We have assumed that the seasonal distribution of precipitation at the drill site is the same as that at Nyalam station. This assumption is supported by two

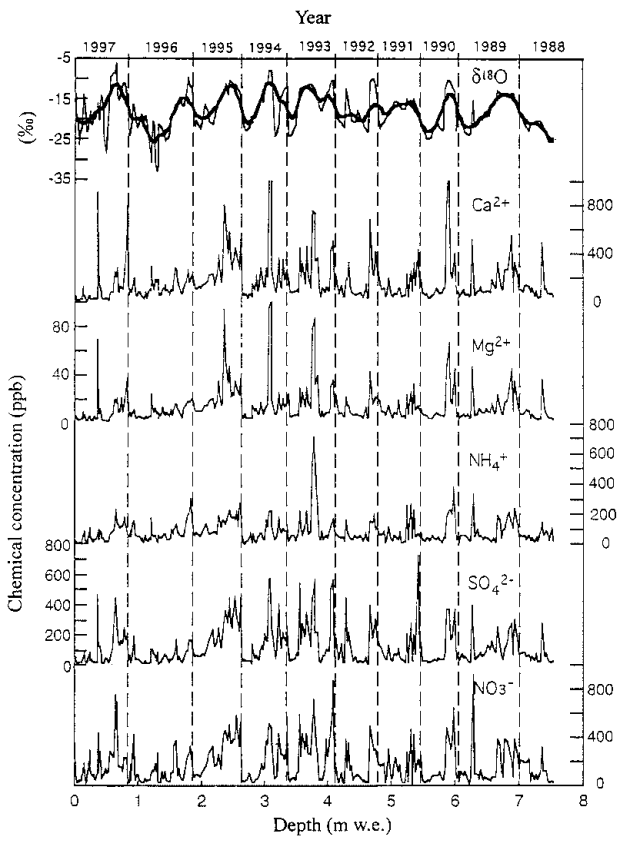

Fig. 2. Depth profiles of $\delta^{18}O$ and chemical-species concentrations with depth (water equivalent) in the Dasuopu firn core. Dating was performed by counting annual peaks of $\delta^{18}O$ values and major-ion concentrations. The coarse solid line shows the smoothing trend using weighted smoothing (five-point smoothing). Dashed lines indicate annual layers.

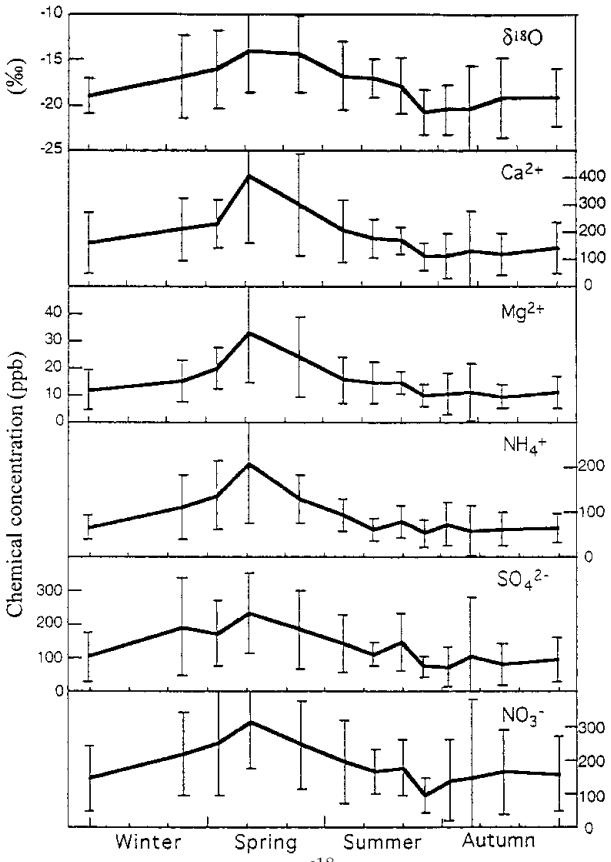

Fig. 3. Seasonal variations of $\delta^{18}O$ and major-ion concentrations in the Dasuopu firn core. Error bars represent ± 1 std dev. ($n = 8$).

factors. First, the source of precipitation is similar for both sites. The region is strongly influenced by the Indian summer monsoon and receives the major part of annual precipitation during the monsoon season (Inoue, 1976), while winter and spring precipitation is derived from low-pressure systems which are steered along the southern slope of the Himalaya by the westerly jet stream (Barry, 1992). Second, the annual mean accumulation at the drill site (0.75 m w.e.) is close to the annual mean precipitation at Nyalam (0.62 m w.e.).

In order to compare seasonal signals in the firn core with meteorological data, $\delta^{18}O$ value and major-ion concentrations for each year (defined by the depth–age relationship) were combined into 12 groups, with each group representing 1/12 of the annual accumulation. The time period of snow accumulation represented by each "group" was then calculated using the average seasonal distribution of annual precipitation for the period 1967–93 at Nyalam station (Table 1).

RESULTS

Profiles of $\delta^{18}O$ and major-ion concentrations with water-equivalent depth reveal fluctuations in $\delta^{18}O$ similar to that in the major-ion series (Fig. 2). Correlation coefficients

Table 2. Correlation coefficients between $\delta^{18}O$ and major ions in the Dasuopu firn core

	$\delta^{18}O$	Ca^{2+}	Mg^{2+}	NH_4^+	SO_4^{2-}
Ca^{2+}	0.50				
Mg^{2+}	0.49	0.95			
NH_4^+	0.55	0.65	0.73		
SO_4^{2-}	0.61	0.83	0.80	0.72	
NO_3^-	0.65	0.70	0.69	0.75	0.84

Note: All R are significant at the 95% level.

(Table 2) reveal that significant positive correlations exist between $\delta^{18}O$ and major ions, and that Ca^{2+}, Mg^{2+}, NH_4^+, SO_4^{2-} and NO_3^- concentrations are highly positively correlated with each other.

Average seasonal variations of $\delta^{18}O$ are shown in Figure 3. The least negative $\delta^{18}O$ values (i.e. isotopically heavier) occur in spring, and the most negative values in late summer. Oxygen isotope values then increase slowly from autumn to winter. The highest and lowest $\delta^{18}O$ values in the year are −14.1‰ and −20.8‰, respectively. Note that the error bars for $\delta^{18}O$ show decreased variability in summer layers, and increased variability in spring and autumn layers.

The most distinctive characteristic in the seasonal variations of $\delta^{18}O$ is the more negative values which occur during the summer monsoon season. In summer and early autumn, there is a strong inverse relationship between $\delta^{18}O$ values and monthly precipitation at Nyalam station (Fig. 4). The lowest $\delta^{18}O$ value corresponds to the highest precipitation, indicating that the amount effect is dominant at 7000 m a.s.l. in the Xixabangma region during the monsoon season. This agrees with other studies in the region (Wushiki, 1977; Grootes and others, 1989; Rozanski and others, 1993; Wake and Stiévenard, 1995). From late winter to mid-spring, both $\delta^{18}O$ and mean monthly temperature at Nyalam station increase, suggesting that $\delta^{18}O$ values reflect air temperature during this period, although the rise in $\delta^{18}O$ occurs prior to the rise in temperature. Comparing seasonal variations of $\delta^{18}O$ in the Dasuopu core with those of δD in precipitation at Lhajung station, located on the southern slope of the Himalaya (Wushiki, 1977), the same seasonal variation can be seen, the only difference being that the lowest δD value at Lhajung appears a little earlier than the lowest $\delta^{18}O$ value at Dasuopu.

The highest concentrations of major ions (Ca^{2+}, Mg^{2+}, NH_4^+, SO_4^{2-} and NO_3^-) occur during spring, while the lowest values occur in late summer (Fig. 3). Among seasonal variations of major ions, Ca^{2+} has the largest fluctuation range of any ion. In general, seasonal variations of cations are more distinct and abrupt than those of anions. Furthermore, the standard deviation of major-ion concentrations shows large variability during the spring, and reduced variation during the summer.

Table 1. Monthly mean temperature, precipitation and distribution of annual precipitation at Nyalam meteorological station

	Month												Annual mean
	1	2	3	4	5	6	7	8	9	10	11	12	
Temperature (°C)	−3.7	−2.9	−0.6	2.7	5.9	9.2	10.5	10.3	8.3	3.8	0.0	−2.0	3.5
Precipitation (mm)	32.6	52.3	63.5	46.5	28.8	61.7	78.2	84.6	78.1	61.4	11.4	15.9	615.1
Distribution of annual precipitation (%)	5.3	8.5	10.3	7.6	4.7	10.0	12.7	13.8	12.7	10.0	1.9	2.6	

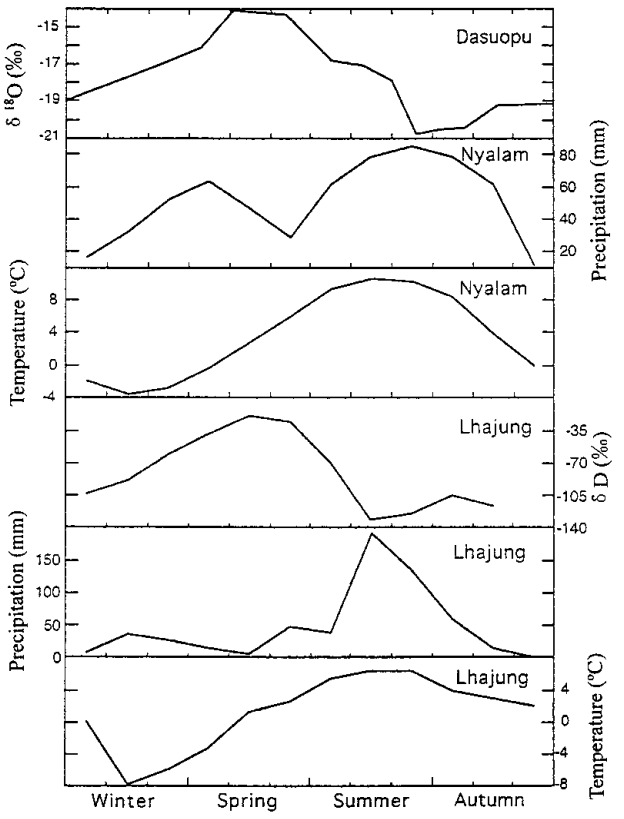

Fig. 4. Seasonal variations of $\delta^{18}O$ in the Dasuopu firn core, compared with monthly air temperature and precipitation at Nyalam meteorological station, 1967–93, and monthly δD, air temperature and precipitation at Lhajung, April 1974–March 1975.

DISCUSSION

The main crest of the Himalaya represents the climatic boundary between a region dominated by the influence of the Indian summer monsoon to the south, and the relatively cold, dry and continental climate which characterizes much of the Tibetan Plateau to the north. The location of Dasuopu glacier on the boundary of the two climatic regions, combined with the high elevation of the site, well above the influence of the boundary layer, provides a unique opportunity to describe and understand atmospheric chemistry and processes in the free troposphere.

As in many tropical and subtropical locations, the more ^{18}O-depleted snowfall (i.e. more negative $\delta^{18}O$ values) at Dasuopu glacier occurs during the summer monsoon period due to the strong removal of the heavy-isotopic component during the intense monsoon rains spreading from the Indian coast to the Himalaya. In the pre-monsoon period (spring), less negative $\delta^{18}O$ values in precipitation may be attributed to the direct transport of water vapor from the Bay of Bengal almost without rainfall over the southern slope of the Himalaya, and may in fact be dominated by the temperature effect. The greatest depletion of ^{18}O occurs in the snow layers which accumulate during the summer monsoon season, and therefore the amount effect is clearly the primary control on the seasonal oxygen-isotope record preserved in snow and ice layers on high-elevation glaciers in the Xixabangma region. We expect that any long-term changes in $\delta^{18}O$ at this site (and perhaps in the Himalaya as a whole) would primarily reflect changes in precipitation regimes locally or regionally. This is in contrast to the interpretation of $\delta^{18}O$ records from the regions further north on the Tibetan Plateau, which fall under a different climatic regime and appear to provide records of temperature changes (e.g. Lin and others, 1995; Yao and others, 1996).

The records of seasonal variations of dust-deposition signals in the Dasuopu core provide evidence of seasonal changes in dust transportation in the troposphere on the southern margin of the Tibetan Plateau. The highest concentrations of Ca^{2+}, Mg^{2+} and SO_4^{2-} occur in spring in Dasuopu glacier, suggesting they result from dust deposition during the peak in the dust-storm activity (Liu and others, 1981; Parrington and others, 1983; Merrill and others, 1989; Gao and others, 1992) and therefore represent a change in the dust-storm activity in regions upwind from the site. Dust can be transported southward to Xixabangma from arid regions (i.e. Taklimakan Desert and the Qaidam basin) by persistent northwesterly surface winds which dominate during spring (Luo and Yanai, 1983; Murakami, 1987). In the monsoon season, lower ion concentrations result from a decreased dust deposition. It is unlikely the seasonal variations in the dust-related major-ion concentrations are due to changes in precipitation (e.g. Hansson, 1994), as monthly precipitation in the region changes only 2–3-fold (Table 1), while dust-related ion concentrations vary by two orders of magnitude or more (Fig. 2).

The correlation coefficients (Table 2) and depth profiles (Fig. 2) indicate that the NH_4^+ and NO_3^- signals recorded in the snowpack differ from those for the dust-related species. High spring concentrations of NH_4^+ and NO_3^- may reflect changes in biogenic-source strength. For example, increases in NH_4^+ and NO_3^- during spring may reflect the agricultural- and pastoral-based lifestyles of the local population in the Himalaya and the Yarlung Zangbo river valley (e.g. nitrogen species derived from livestock urine, fertilizer, biomass burning and emissions from soil) (Mayewski and others, 1983; Davidson and others, 1986; Wake and others, 1994a; Meeker, and others, 1997; Shrestha and others, 1997).

CONCLUSIONS

Values of $\delta^{18}O$ and concentrations of Ca^{2+}, Mg^{2+}, NH_4^+, SO_4^{2-} and NO_3^- have been measured as a function of depth in a 15 m Dasuopu firn core representing 10 years of snow accumulation. Strong seasonal variations of $\delta^{18}O$ values in the Dasuopu core were used to establish a depth–age relationship for the core. Seasonal variations of $\delta^{18}O$ values are controlled primarily by the amount effect, with more negative $\delta^{18}O$ representing summer monsoon snow. Seasonal variations of major-ion concentrations in the Dasuopu core indicate that dust deposition is dominated by spring dust storms which transport dust from the vast arid and semi-arid desert regions to the north and west. High concentrations of NH_4^+ and NO_3^- in spring may reflect more local/regional changes in biogenic-source strength. Thus ice-core records from Dasuopu provide a unique opportunity to reconstruct changes in monsoon and dust-storm activity in the past.

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