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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 firm 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 Ca2+, Mg2+, NH4+, SO42− and NO3− were measured over the 10 years of snow accumulation captured in the firm core. The seasonal variations of δ18O 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 δ18O values are controlled by the amount effect, with more negative (i.e. lighter) δ18O values representing summer monsoon precipitation characteristic of tropical regions. Higher concentrations of Ca2+, Mg2+ and SO42− 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 NH4+ and NO3− 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; Domross and Peng, 1988). Unfortunately, the longest continuous instrumental climate records for the region extend back only to AD1935, and most records are available only from AD1950. However, the Tibetan Plateau possesses a diversity of natural archives from which detailed paleoclimatic records can be developed. The development and interpretation of paleoclimatic 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 δ18O and major ions in precipitation (Lyons and Mayewski, 1983; Mayewski and others, 1983; Wake and others, 1990, 1992, 1993, 1994a; 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) δ18O values (Dansgaard, 1964; Rozanski and others, 1993). Furthermore, at many tropical stations, mean monthly δ18O is inversely correlated with monthly temperature, confirming the dominant role of the amount effect in controlling the seasonality of δ18O 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 δ18O in precipitation (e.g., Wusiki, 1977; Wake and Stievenard, 1995). In the northeastern regions of the plateau, however, air temperature appears to be the controlling factor in temporal fluctuations of δ18O (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, 1988; 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 long core was recovered from a relatively flat portion of Dasuopu glacier (28°23' N, 55°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 δ18O and major-ion (Ca2+, Mg2+, NH4+, SO42- and NO3-) 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 handling and processing 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 δ18O, respectively. A total of 305 samples were obtained from the core.

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 δ18O and concentrations of dust-source ions (Ca2+, Mg2+ and SO42-) and biogenic-source ions (NH4+ and NO3-). Profiles of δ18O and major-ion concentrations against water-equivalent depth are shown in Figure 2. In general, high concentrations of major ions correspond to less negative δ18O values. The core was dated down to the summer of 1988 by counting annual peaks of δ18O 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 δ18O and major ions were selected to study seasonal variability. Instrumental data from the closest meteorological station (Yalam station, 28°11' N, 85°30' E; 3810 m a.s.l.; 20 km southeast of the drill site) were used to compare with the core data. At Yalam station, the mean annual surface air temperature and precipitation are 3.5°C and 626 mm, 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 Yalam station. This assumption is supported by two

![Fig. 1. Location map of drilling site located on the northern flank of Xixabangma Feng.](image)

**Fig. 2. Depth profiles of δ18O and chemical-species concentrations with depth (water equivalent) in the Dasuopu firm core. Dating was performed by counting annual peaks of δ18O values and major-ion concentrations. The course solid line shows the smoothing trend using weighted smoothing (five-point smoothing). Dashed lines indicate annual layers.**
The correlation coefficients between $\delta^{18}O$ and major ions in the Dassoupu firn core 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 $-14.1\%o$ and $-20.8\%o$, 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 Nixabangma 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 Stüvenard, 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 Dassoupu core with those of $\delta$D 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 $\delta$D value at Lhajung appears a little earlier than the lowest $\delta^{18}O$ value at Dassoupu.

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

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<td>Month</td>
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<td>Temperature (°C)</td>
<td>-3.7</td>
<td>-2.9</td>
<td>-0.6</td>
<td>2.7</td>
<td>5.9</td>
<td>9.2</td>
<td>10.5</td>
<td>10.3</td>
<td>8.3</td>
<td>3.8</td>
<td>0.0</td>
<td>-2.0</td>
<td>3.5</td>
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<tr>
<td>Precipitation (mm)</td>
<td>32.6</td>
<td>52.5</td>
<td>63.5</td>
<td>46.5</td>
<td>28.8</td>
<td>61.7</td>
<td>78.2</td>
<td>84.6</td>
<td>78.1</td>
<td>61.4</td>
<td>11.4</td>
<td>15.9</td>
<td>63.1</td>
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<tr>
<td>Distribution of annual precipitation (%)</td>
<td>5.3</td>
<td>8.5</td>
<td>10.3</td>
<td>7.6</td>
<td>4.7</td>
<td>10.0</td>
<td>12.7</td>
<td>13.8</td>
<td>12.7</td>
<td>10.0</td>
<td>1.9</td>
<td>2.6</td>
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**Note:** All $R$ are significant at the 95% level.
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 Xizabangma 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 Xizabangma from arid regions (i.e. Tadlimakan 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 2 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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