

Changes in ionic concentrations and $\delta^{18}\text{O}$ in the snowpack of Zhadang glacier, Nyainqentanglha mountain, southern Tibetan Plateau

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ABSTRACT. To investigate the effects of depositional and post-depositional processes on chemical records in the snowpack, seven monthly snow pits were sampled at the same site on the pass of Zhadang (ZD) glacier (30°28.079' N, 90°39.032' E; 5800 m a.s.l.), Nyainqentanglha mountain, southern Tibetan Plateau, between April and October 2006. Meteorological data from an automatic weather station at the sampling site showed that the annual mean air temperature was -5.6°C on the pass and that monthly air temperature was above 0°C from June to August, indicating that snowmelt could occur in this high-elevation region during the summer. An analysis of $\delta^{18}\text{O}$ and major-ion variability in snow pits suggests that glaciochemical records were influenced by both meltwater percolation in mid-summer (July and August) and seasonal deposition. Less negative $\delta^{18}\text{O}$ values and high concentrations of major ions occurred during the spring. The trends of $\delta^{18}\text{O}$ variations in the ZD snow pits were consistent with those in precipitation sampled at the nearby Nam Co station for all months except for July and August, suggesting that climate signals are well preserved in the snow-pit $\delta^{18}\text{O}$ records during the non-summer months. However, these climate signals were destroyed by strong percolation of meltwater during mid-summer.

INTRODUCTION

Chemical records from ice cores are a valuable source of information for interpreting paleoclimatic change. Not only are the atmospheric chemical composition and depositional processes recorded, but post-depositional processes within the snow–firn stratum, especially when snowmelt occurs, are also recorded (Thompson and others 1995; Ginot, 2001; Li and others, 2006). However, when meltwater percolates through the previous seasonal layers, the glaciochemical signals can be significantly altered (Huang and others, 1996; Hou and Qin, 1999; Eichler and others, 2001; Hou and others, 2002).

Research focused on climate change as reconstructed by ice-core records in the southern Tibetan Plateau has taken place over the past decade (e.g. Thompson and others, 2000; Kang and others, 2002a, 2006, 2007; Qin and others, 2002; Yao and others, 2002; Hou and others, 2007). Recent meteorological observations in the upper glacier area on Qomolangma (Mount Everest) show that the daily maximum air temperature during summer was above 0°C , indicating that snowmelt might occur during the summer at high elevations where ice cores have been retrieved (Xie and others, 2007). Therefore, investigating the effect of summer meltwater percolation on glaciochemical signals is crucial to the accurate interpretation of ice-core records in the region. Additionally, accurate dating of ice cores is essential to the reconstruction of ice-core climatic records. A primary dating method is based on seasonal variations in chemical species. To validate seasonal timings of chemical species, it is necessary to establish the input timing. Snow-pit studies provide a useful tool to investigate such properties (Mayewski and others, 1990; Kreutz and others, 1999; Kang and others, 2004; Wake and others, 2004; Yalcin and others, 2006).

The meteorological and pluviometric regime of the Asian continent is controlled mainly by polar air masses from the Arctic, continental air masses from central Asia and maritime air masses from the Pacific and Indian Oceans (Bryson, 1986). The location of Zhadang (ZD) glacier, Nyainqentanglha mountain (30°28' N, 90°39' E) (Fig. 1) at the boundary of the South Asian monsoon (Indian monsoon) and the continental climate of central Asia, combined with the high elevation (5800 m), offers a unique opportunity to describe and understand changes in climate and the chemistry of the atmosphere over the Tibetan Plateau.

To investigate the effects of depositional and post-depositional processes on chemical species within the snow–firn pack, snow samples were collected once a month from snow pits at the same site on the pass of ZD glacier from April to October 2006. Meteorological data were also recorded at the sampling site by an automatic weather station (AWS). Precipitation samples were collected from each precipitation event at the Nam Co Station for Multisphere Observation and Research (hereafter Nam Co station) about 50 km away from the ZD pass (Fig. 1). The purpose of this study is to understand the seasonality of $\delta^{18}\text{O}$ and major ions and the effects of meltwater percolation on glaciochemical records on the pass of ZD glacier. This is achieved by comparing monthly changes of $\delta^{18}\text{O}$ and major-ion concentrations in snow pits, as well as $\delta^{18}\text{O}$ values between snow pits and precipitation at Nam Co station. This research provides the basis for further interpretation of ice-core records in the region.

METHODS

Between April and October 2006, snow pits were sampled to the glacial ice surface once a month (for a total of seven

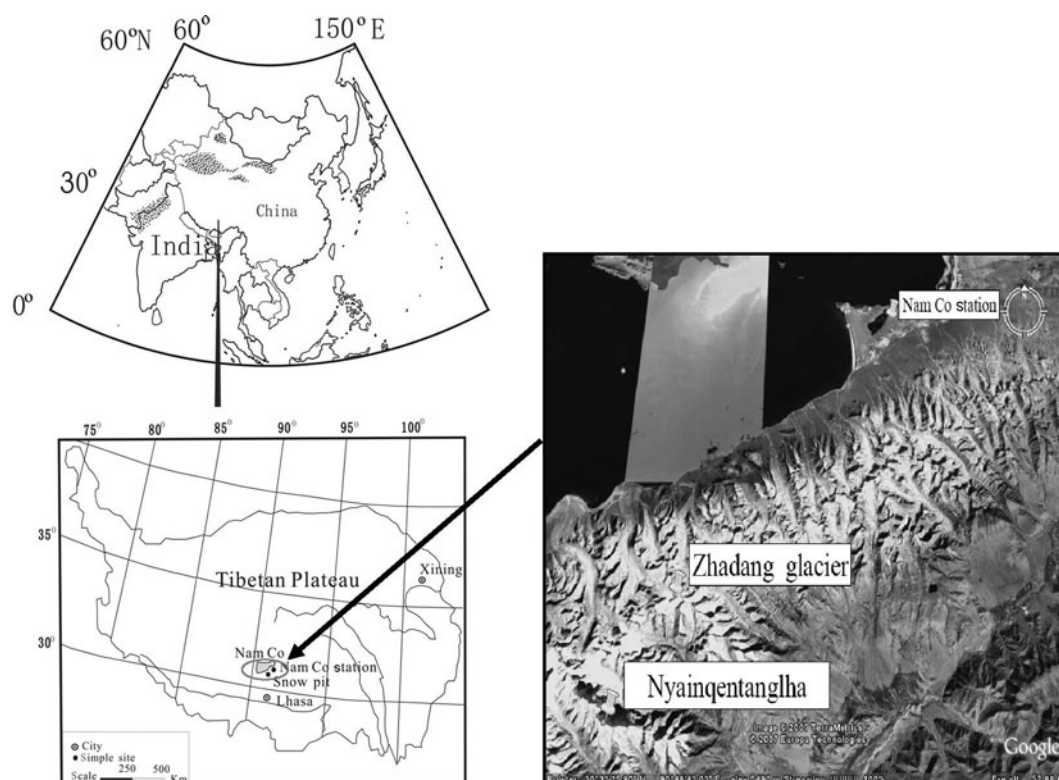


Fig. 1. Location map of sampling site on the pass of ZD glacier and Nam Co station, Nyainqentanglha mountain, southern Tibetan Plateau.

snow pits) at the same site on the pass of ZD glacier on the east of Nyainqentanglha (Fig. 1). The snow pits were sampled at 5 cm intervals on the wall of the snow pits, for a total of 137 samples. Detailed summaries of snow pits are located in Table 1. Extreme care was taken during sample collection and handling to ensure samples were not contaminated. Non-particulating suits, polyethylene gloves and masks were worn during sampling. Pre-washed, high-density polyethylene (HDPE) containers were used as sample scoops (Kang and others, 2004). Field blanks were collected, filled with ultrapure water in the laboratory, opened during sample collection and handled as samples. Samples were kept frozen in the field, during transport and in the laboratory until analysis. All samples were analyzed at

the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. Major cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+ and NH_4^+) were analyzed by a Dionex ISC 2000 ion chromatograph using an IonPac CS12A column, 20 mM MSA (methanesulfonic acid) eluent and CSRS suppressor. Major anions (Cl^- , NO_3^- and SO_4^{2-}) were analyzed by a Dionex ISC 2500 ion chromatograph using an IonPac AS11-HC column, 25 mM KOH eluent and anion self-regenerating suppressor. The detection limits were 1 ng g^{-1} for all ions. Analysis of field blanks showed that contamination during the sampling procedure, transport and treatment was negligible. Oxygen isotope analyses were performed with a method based on isotopic equilibrium exchange between oxygen of CO_2 with a known isotopic composition and the water sample using

Table 1. Information of snow pits at ZD glacier during 2006 (average $\delta^{18}\text{O}$ values and major-ion concentrations, with \pm for standard deviation)

	Snow pit						
	SP4	SP5	SP6	SP7	SP8	SP9	SP10
Sampling date	13 Apr.	11 May	17 June	17 July	10 Aug.	10 Sept.	14 Oct.
Depth (cm)	85	150	110	90	85	80	85
Sample number	17	30	22	17	17	16	17
$\delta^{18}\text{O}$ (‰)	-16.0 (± 3.1)	-13.1 (± 3.1)	-13.4 (± 4.2)	-13.4 (± 1.3)	-14.8 (± 0.3)	-16.5 (± 5.3)	-12.0 (± 5.9)
Ca^{2+} (ng g^{-1})	859.1 (± 1268.5)	694.0 (± 635.6)	482.9 (± 1050.1)	106.8 (± 67.2)	178.5 (± 202.0)	76.5 (± 88.9)	117.7 (± 186.6)
Mg^{2+} (ng g^{-1})	30.0 (± 35.2)	38.2 (± 26.5)	28.5 (± 43.7)	13.3 (± 6.8)	14.8 (± 14.7)	8.0 (± 7.2)	8.2 (± 4.6)
Na^+ (ng g^{-1})	60.1 (± 80.9)	108.0 (± 135.3)	54.7 (± 64.7)	42.3 (± 52.8)	25.1 (± 17.6)	12.1 (± 12.1)	21.9 (± 25.2)
K^+ (ng g^{-1})	41.4 (± 45.2)	54.7 (± 42.3)	28.7 (± 29.0)	34.3 (± 29.0)	11.0 (± 5.4)	14.8 (± 14.7)	16.4 (± 21.0)
NH_4^+ (ng g^{-1})	71.6 (± 91.0)	167.7 (± 86.6)	126.4 (± 188.5)	47.6 (± 32.3)	21.8 (± 7.1)	65.6 (± 33.8)	73.2 (± 34.8)
SO_4^{2-} (ng g^{-1})	169.7 (± 245.8)	248.9 (± 179.4)	47.7 (± 67.5)	35.3 (± 30.2)	49.1 (± 69.3)	75.4 (± 61.9)	100.7 (± 58.8)
NO_3^- (ng g^{-1})	135.9 (± 170.2)	248.9 (± 200.8)	88.8 (± 72.5)	37.5 (± 21.1)	44.9 (± 32.7)	183.2 (± 141.0)	262.1 (± 225.1)
Cl^- (ng g^{-1})	56.1 (± 62.0)	162.4 (± 209.1)	38.0 (± 33.9)	66.9 (± 79.1)	77.4 (± 153.8)	16.0 (± 14.9)	25.8 (± 34.1)

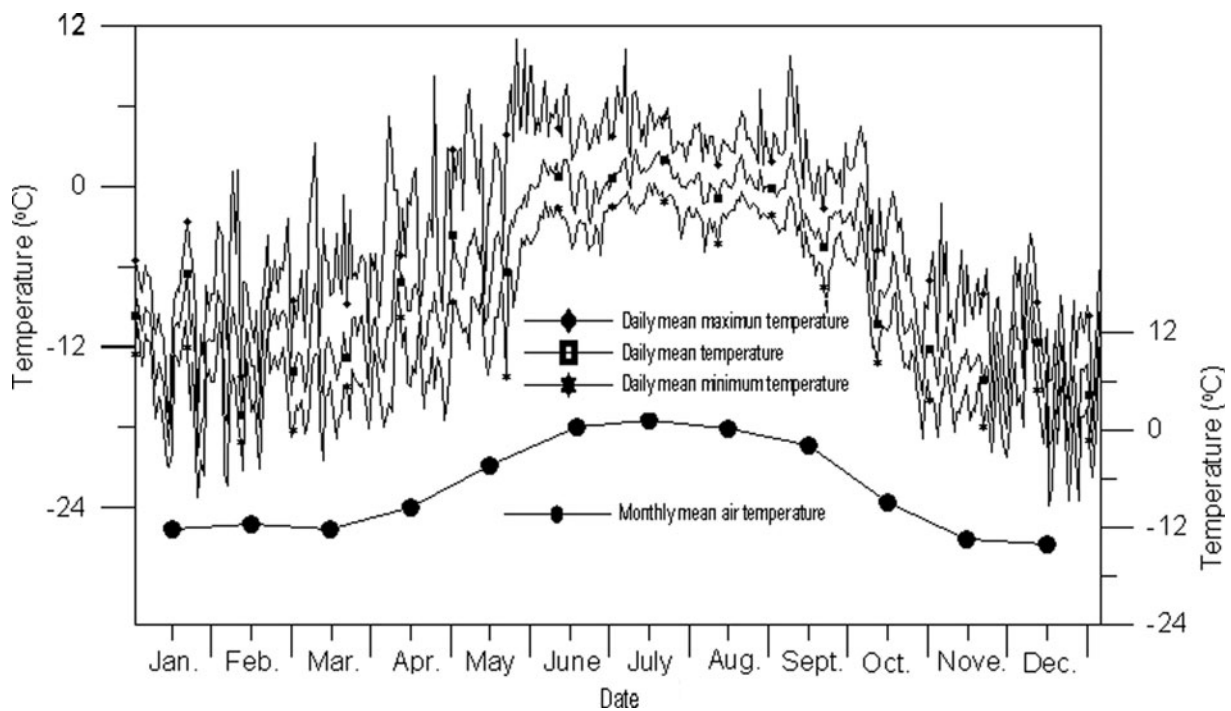


Fig. 2. Variation of air temperature on the pass of ZD glacier during 2006.

an IR-MS (Thermo Finnigan MAT-253; $\pm 0.2\%$ precision). All data are reported in standard delta (δ) notation vs Vienna Standard Mean Ocean Water (V-SMOW).

RESULTS AND DISCUSSION

Air temperature and snow stratigraphy at sampling site

Variability of daily and monthly air temperatures on the pass of ZD glacier is presented in Figure 2. The annual mean air temperature was -5.6°C and the monthly average temperature was 0.2°C in June, 1.2°C in July and 0.2°C in August. The daily maximum temperatures were above 0°C from May to September, indicating that snowmelt could occur in this high-elevation region during the summer. However, daily minimum temperatures were still below 0°C throughout the summer (Fig. 2), suggesting that meltwater might refreeze during the night.

Snow-pit stratigraphy of each snow pit is presented in Figure 3. As mentioned above, the bottom of each snow pit reached the glacier ice surface. The snow pits mainly consisted of firn, although SP8 (August) consisted of coarse-grained firn, indicating meltwater percolation that contributes to fast snow deformation (Paterson, 1994). The deepest snow pit occurred in May (SP5), prior to the summer ablation season.

Variability of $\delta^{18}\text{O}$ in snowpack

Comparisons of variations of $\delta^{18}\text{O}$ with depth in snow pits and precipitation at Nam Co station are presented in Figures 4 and 5. With the exception of SP7 (July) and SP8 (August), fluctuations of $\delta^{18}\text{O}$ are clearly visible. Average $\delta^{18}\text{O}$ values in spring (e.g. May) and autumn (e.g. September) were more negative than those in mid-summer (Table 1), and standard deviations of each snow pit (Table 1) also showed small values during July and August. This suggests that the most intensive elution was caused by percolating meltwater due to

high air temperatures as indicated by the automatic weather station (Fig. 2), resulting in reduced or smoothed isotopic value oscillations (Fig. 4). Previous research has reported that when air temperatures are high, the original $\delta^{18}\text{O}$ oscillations in snow pits may be rapidly altered in the presence of percolating meltwater (e.g. Árnason, 1969; Raben and others, 1998; Hou and others, 2002; Wang and others, 2006).

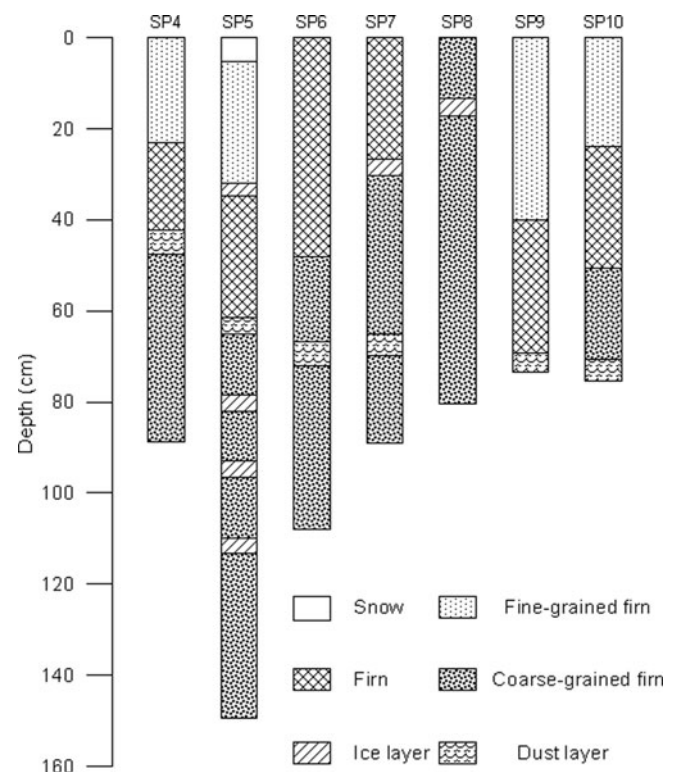


Fig. 3. Stratigraphies of snow pits on the pass of ZD glacier during April to October 2006 (for details of SP4 to SP10 see Table 1).

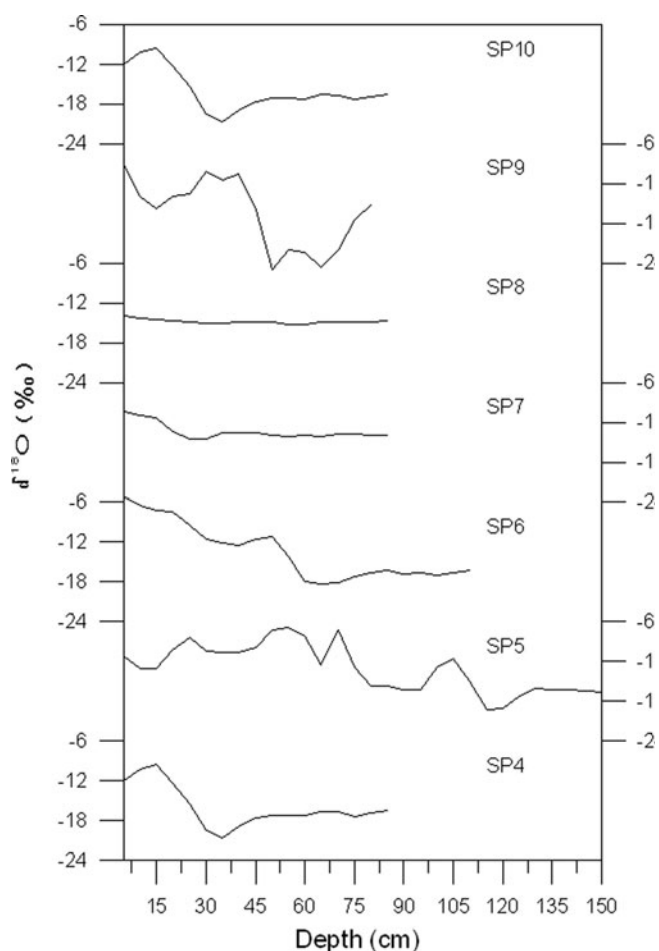


Fig. 4. Variation of $\delta^{18}\text{O}$ values with depth in snow pits on the pass of ZD glacier from April to October 2006 (for details of SP4 to SP10 see Table 1).

Therefore, the elution process of meltwater on the pass of ZD glacier clearly has affected the original $\delta^{18}\text{O}$ signals, at least during July and August.

Comparisons of $\delta^{18}\text{O}$ variations between snow pits and precipitation at Nam Co station were performed (Fig. 5). At the station, observed minimum $\delta^{18}\text{O}$ in precipitation occurred on 11 March, coinciding with the minimum $\delta^{18}\text{O}$ value at 35 cm depth in SP4. There were no observed precipitation events at the station from 11 March to 13 April, but snowfall occurred in the glacier region during this time (Fig. 5). In SP5, the minimum $\delta^{18}\text{O}$ value at 115 cm depth was preserved, consistent with the snowfall event on 11 March at the station. The position of the minimum $\delta^{18}\text{O}$ value moved downward in SP5, mainly as a result of the heavy snowfall in the glacier region in May and of snow compaction.

The variability of $\delta^{18}\text{O}$ was smoothed slightly, as shown in SP6 (Fig. 4); however, the seasonal trend of $\delta^{18}\text{O}$ in the snow pit was similar to that in precipitation at the station (Fig. 5). It is clear that less negative $\delta^{18}\text{O}$ occurred in May and early June, as observed from both the glacier region and station. Due to the meltwater percolation, variability of $\delta^{18}\text{O}$ in SP7 and SP8 was smoothed and no similarities with precipitation $\delta^{18}\text{O}$ from the station found. The effects of intensive elution during the day from above-freezing temperatures (Fig. 2) could cause the complete change of the original chemical signals recorded in snow pits (e.g.

Raben and others, 1998; Eichler and others, 2001; Hou and Qin, 2002; Li and others, 2006).

In SP9 and SP10, variations of $\delta^{18}\text{O}$ were consistent with those at the station. Notably, the most negative $\delta^{18}\text{O}$ values appeared at 50 cm and 64 cm depth in SP9 and SP10, respectively, consistent with the extreme $\delta^{18}\text{O}$ value of the precipitation event on 27 August at the station. Daily maximum air temperature decreased below 0°C from September and new precipitation in the snowpack was preserved due to minimal effects of meltwater percolation. In summary, $\delta^{18}\text{O}$ records in snow pits were strongly influenced by meltwater percolation only during July and August, at least in 2006. This suggests that the selection of future ice-coring sites in the region, and the interpretation of ice-core records from this region, should consider the percolation effects on glaciochemical records.

During the summer, the climate in the southern Tibetan Plateau is dominated by the Indian summer monsoon. The southern airflow extends to about 35°N , and brings warm-humid air masses from the Indian Ocean to the southern Tibetan Plateau (Murakami, 1987; Tang, 1998; Tian and others, 2001a). Variations of monthly mean $\delta^{18}\text{O}$ in precipitation are dominated by the amount effect in the southern plateau (e.g. Wake and Stievenard, 1995; Kang and others, 2000a; Tian and others, 2001b). In the northern plateau, moisture source and air temperature affect the spatial distribution and temporal fluctuations of $\delta^{18}\text{O}$, respectively (Yao and others, 1991, 1996). Therefore, seasonal variations of $\delta^{18}\text{O}$ in snow pits and precipitation show more negative $\delta^{18}\text{O}$ values during the summer monsoon season and less negative $\delta^{18}\text{O}$ values in spring (or the pre-monsoon season) in the southern regions of the plateau (Tian and others, 1997, 2001b; Kang and others, 2002b). Our results show that less negative $\delta^{18}\text{O}$ values appeared during April to early June (SP4, SP5 and SP6 in Fig. 5), consistent with previous research. Although very negative $\delta^{18}\text{O}$ values occurred in August at both the station and snow pits (SP9 and SP10), there were still some less negative $\delta^{18}\text{O}$ values in July and September when the climatic condition is considered to be the summer monsoon season (You and others, 2007). By analyzing air-mass backward trajectories, Xu and others (2007) found that moisture from both the Indian monsoon and local lake evaporation influenced the Nam Co region during summer. Furthermore, moisture transported by the monsoon had more negative $\delta^{18}\text{O}$ values, whereas precipitation from more local sources had less negative $\delta^{18}\text{O}$, as observed at Nam Co station (Xu and others, 2007) and other sites on the plateau (Yao and others, 1991; Kang and others, 2002b). This could account for the less negative $\delta^{18}\text{O}$ values during the summer.

Variabilities of major ions in snowpack

Average concentrations of major ions in the snow pits (Table 1) suggest that the highest major-ion concentrations occurred during spring (SP4, SP5 and SP6), with the highest values for most ions in SP5. As Figure 5 shows, most of the snow in SP5 accumulated during spring (March to May), reflecting the high ionic concentrations in spring snow. Previous research showed that major ions (e.g. Ca^{2+} , Mg^{2+} , SO_4^{2-}) in snow over the southern Tibetan Plateau and Himalaya had a clear seasonal difference: non-monsoon ionic concentrations are much higher than monsoon ionic concentrations (e.g. Wake and others, 1993; Kang and others, 2000b, 2004; Marinoni and others, 2001; Shrestha and

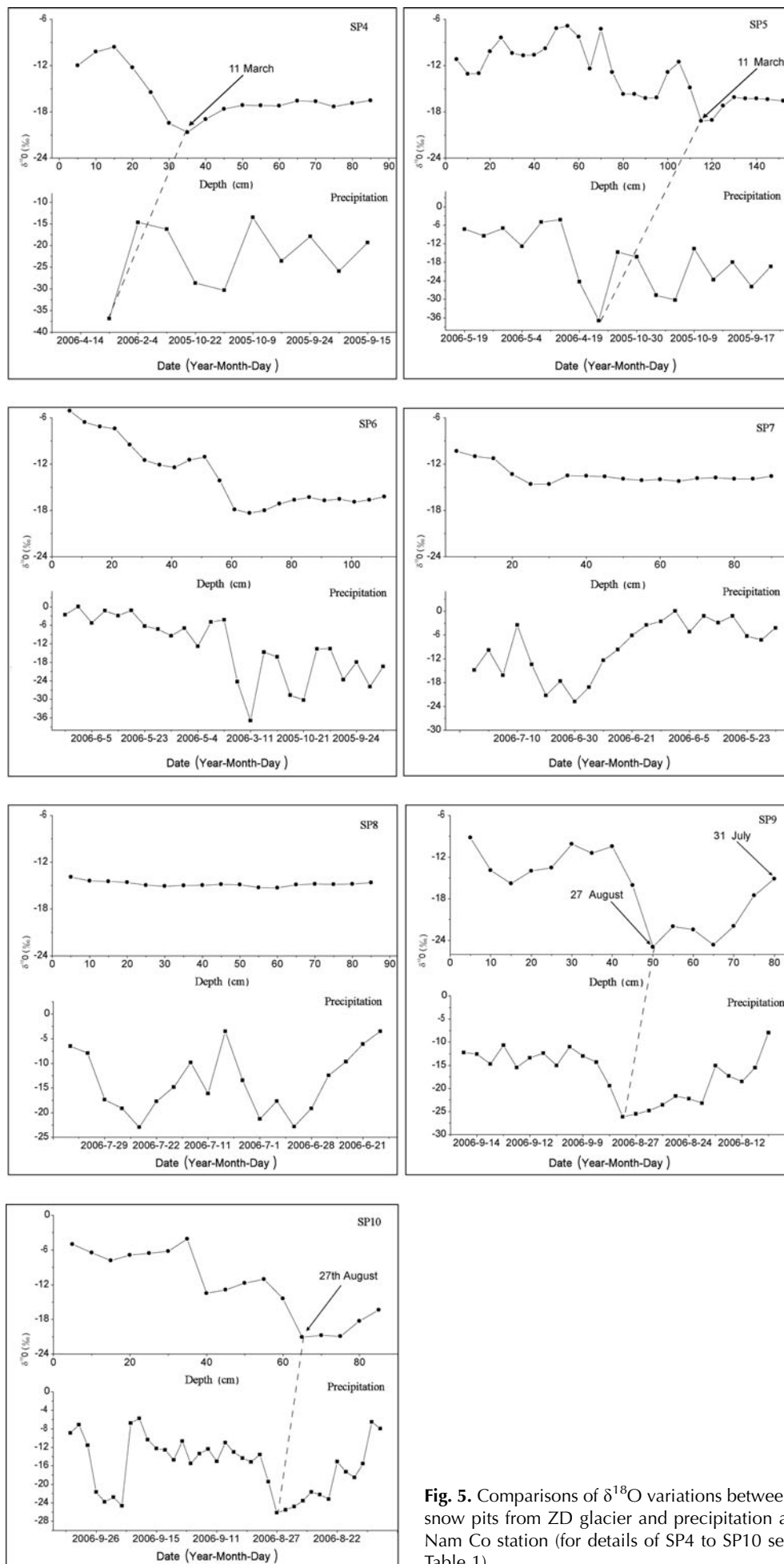


Fig. 5. Comparisons of $\delta^{18}\text{O}$ variations between snow pits from ZD glacier and precipitation at Nam Co station (for details of SP4 to SP10 see Table 1).

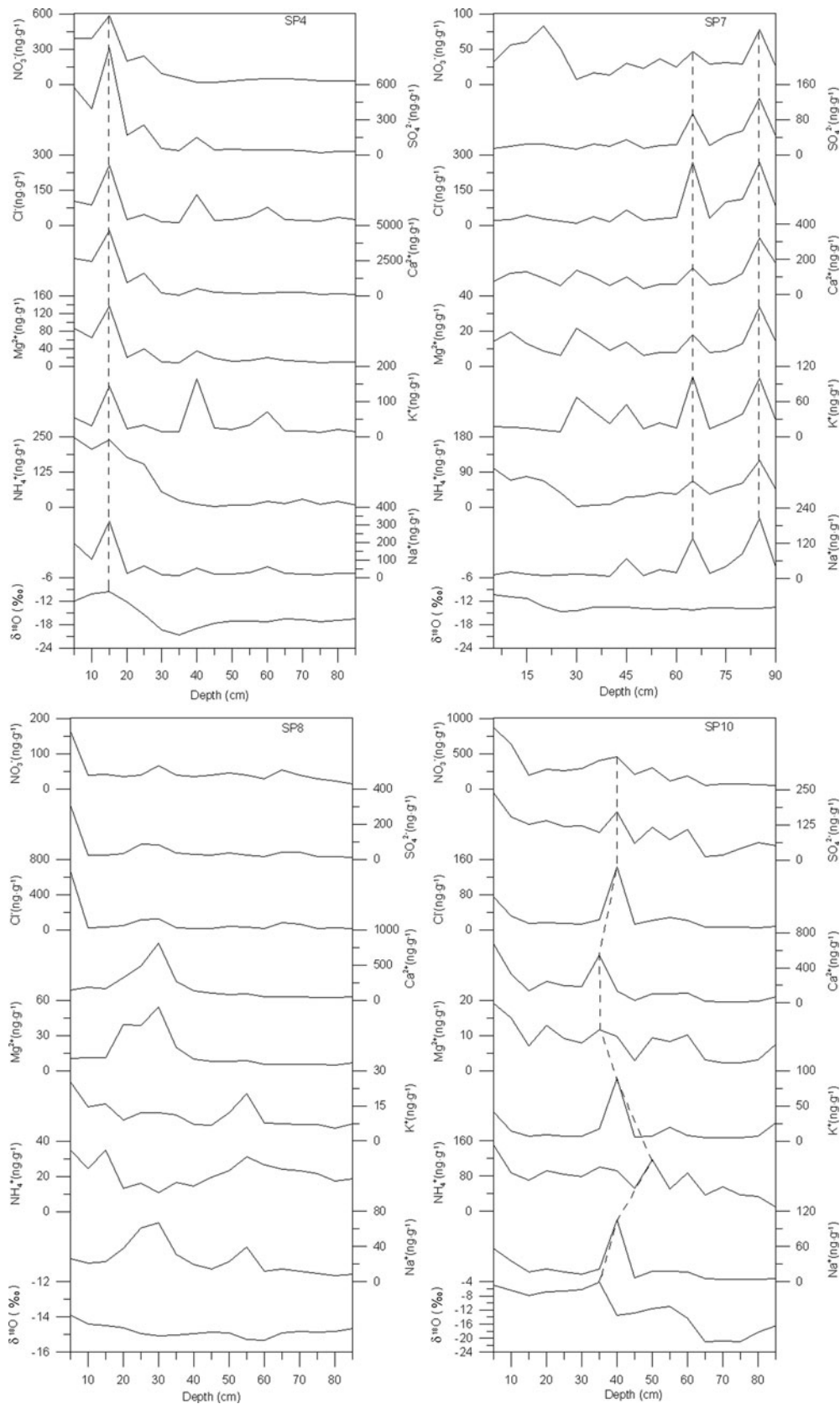


Fig. 6. Variation of $\delta^{18}\text{O}$ values and major-ion concentrations with depth in snow pits on the pass of ZD glacier from April to October 2006 (for details of SP4 to SP10 see Table 1; dashed lines represent corresponding peaks among species).

others, 2002). The snow chemistry is strongly influenced by crustal aerosols from local or arid (semi-arid) regions, especially during dust-storm periods in the non-monsoon seasons (e.g. winter and spring) (Qian and others, 1997; Song and

others, 2004). High ionic concentrations in spring snow at ZD Glacier are consistent with previous results, and probably reflect the high loading of dust aerosols during spring in the region (Song and others, 2004; Li and others, 2007).

Ionic concentrations in the snow pits decreased during the summer season (SP7 and SP8). Low ionic concentrations were also observed in Himalayan snow during the summer monsoon season (e.g. Kang and others, 2000b, 2004). Our results in ZD glacier snow pits could be caused by both low dust aerosols in the atmosphere (Li and others, 2007) and meltwater percolation during the summer, especially in July and August. The effect of meltwater percolation on ionic concentrations is shown in Figure 6. Peaks of $\delta^{18}\text{O}$, which corresponded with the high ionic concentrations, were clearly presented in SP4 and SP10. However, the spring $\delta^{18}\text{O}$ profile was destroyed by percolation and there is no counterpart of $\delta^{18}\text{O}$ peaks with ionic peaks in SP7 and SP8. It is noteworthy that different ion peaks corresponded to each other very well in the bottom of SP7, but that these peaks vanished in SP8. This phenomenon could be explained by elution processes, in which the percolation of meltwater resulted in the accumulation and washout of major ions (Fig. 6) (Hou and Qin, 1999). Additionally, a phase discrepancy existed among ionic peaks in SP8, which could be primarily interpreted as the original ionic peaks modified to various degrees due to their varied stability against meltwater percolation (Brimblecombe and others, 1987; Hou and Qin, 2002).

CONCLUSIONS

A monthly glaciochemical survey at the pass of ZD glacier was conducted by analyzing $\delta^{18}\text{O}$ and major ions in seven snow pits between April and October 2006. Our discussion has also incorporated results from the $\delta^{18}\text{O}$ in precipitation at Nam Co station. The annual mean air temperature was -5.6°C at the pass, and monthly air temperature was above 0°C from June to August, indicating that snowmelt might occur in this high-elevation region during the summer. The variability of $\delta^{18}\text{O}$ and major ions in snow pits was clearly influenced by the percolation of meltwater in mid-summer (July and August), and atmospheric concentrations during other seasons. Less negative $\delta^{18}\text{O}$ values and high concentrations of major ions occurred during the spring.

The trends of $\delta^{18}\text{O}$ variations in the ZD snow pits were consistent with those in precipitation at Nam Co station, with the exception of July and August. This suggests that climate signals were preserved well in the snow-pit $\delta^{18}\text{O}$ records during the non-summer months; however, during summer these climate signals were destroyed by strong percolation of meltwater. Although our observations were carried out for only 1 year, the phenomenon that glaciochemical records could be affected by meltwater percolation at high-elevation sites (e.g. 5800 m a.s.l.) should be considered when selecting ice-core sites and when interpreting ice-core records from such sites.

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