ORIGINAL ARTICLE

Changes in ionic and oxygen isotopic composition of the snow-firn pack at Baishui Glacier No. 1, southeastern Tibetan Plateau

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Abstract To properly interpret climatic and environmental information recorded in ice cores retrieved in the temperate-glacier region, the post-depositional processes, especially the meltwater percolation, need to be well understood. From late April to mid-July 2006, two successive snow pits, site P1 located at 4,750 m a.s.l. in the ablation zone and site P2 at 4,900 m a.s.l. in the accumulation area at Baishui Glacier No. 1, Mt. Yulong, southeastern Tibetan Plateau, were excavated. Changes in soluble ions (K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^- and SO_4^{2-}) and stable oxygen isotopes ($\delta^{18}O$) in the snow pits were investigated. Before the melting period, soluble ions and $\delta^{18}O$ exhibit pronounced seasonal variations, with high values in the upper snow-firn layer (accumulated in winter/spring season) and relatively low values in the lower firn layer (deposited in summer season), reflecting seasonal shift in the Indian summer monsoon and winter westerlies over the region. During the melting period, most ions in the upper snow-firn layer were leached with different efficiencies. Although no significant changes in ion concentrations in the lower firn layer were observed, the impurities in the upper snow-firn layer could be eluted down into the lower firn layer. However, the pre-melting isotopic stratigraphy remained relatively unchanged during the observation period, indicating that the influence of meltwater percolation on stable isotopes is less significant than that on soluble ions. This understanding is crucial for the interpretation of ice-core records in the monsoon temperate-glacier region.

Introduction

Wet/dry deposition plays an important role in the transfer of chemical constituents from atmosphere to snow. The chemical composition of snow is closely related to atmospheric aerosols (Boutron and Delmas 1980; Sun et al. 1998). Thus, analysis of snow and ice chemistry could provide valuable information on the sources of atmospheric aerosols (Wolff 1990; Wake and Mayewski 1993; Legrand and Mayewski 1997), atmosphere circulation (Xiao et al. 2002; Kang et al. 2002; Aizen et al. 2004) and past climatic and environmental changes (Barrie et al. 1985; Hou et al. 2003).

Snow and ice chemistry investigations have been conducted on the Tibetan Plateau (Wake and Mayewski 1993; Shrestha et al. 1997; Kang et al. 2004). Such studies in China's monsoonal temperate-glacier region in the southeastern part of Tibetan Plateau, including the Hengduan mountains, eastern part of the Himalayas and the central and eastern segments of the Nyainqentanglha range, accounting for 22 % of the total glaciers of China (Pu 1994), have been restricted to the Baishui Glacier No. 1, Mt. Yulong, Hengduan mountains (He et al. 2001, 2002a, b; Pang et al. 2007). These investigations have mainly dealt with glaciochemical records in shallow firn/ice cores retrieved during the summers. However, climatic and

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environmental information reconstructed from these cores is limited because the ice-core records are significantly modified by meltwater percolation processes (He et al. 2001, 2002b; Pang et al. 2007).

To translate ice-core records in the monsoonal temperate-glacier region, depositional and post-depositional data, for example, seasonal input of impurities into snowpack from atmosphere (the disturbance of meltwater percolation on ice-core records) has been compared and rated. Thus, two snow pits at Baishui Glacier No. 1 (i.e., sites P1 and P2) were excavated successively at the time interval of about 2 weeks from the pre-melting to melting season. Basic information (sampling date, depth, number of sample) of these pits is presented in Table 1. Li et al. (2009a, b) discussed the depositional information, including ion sources and spatial differences in ion concentrations, using the data of soluble ions of the two snow pits excavated on 7 May. In this paper, we focus on the post-depositional information considering the disturbance of meltwater percolation on glaciochemical records using the ionic and isotopic data for all snow pits retrieved from late April to mid-July 2006.

Study area, sample collection and analytical methods

Mt. Yulong, located in the Hengduan mountains (southeastern edge of the Tibetan Plateau), 25 km north of Lijiang, Yunnan Province, China, is the southernmost glacierized area in mainland Eurasia (Fig. 1a). Dominant atmospheric circulations in the Mt. Yulong region, responsible for the monsoonal temperate-glacier regime, are the Indian summer monsoon and the southern branch of winter westerlies (Fig. 1a). The prevailing Indian summer monsoon (June to September) not only brings plentiful precipitation (about 70 % of the annual precipitation) but also transports marine aerosols to this region (Pang et al. 2007). Although wintertime precipitation in the region is

Table 1 Basic information of the successive snow pits at sites P1 (4,750 m a.s.l.) and P2 (4,900 m a.s.l) excavated in 2006 from Baishui Glacier No. 1, Mt. Yulong

Site	Sample date	Depth (cm)	Number of sample
P1	25 April	400	40
	7 May	340	34
	20 May	350	35
	7 June	310	31
P2	7 May	400	40
	25 May	410	41
	16 June	400	40
	29 June	390	39
	13 July	320	32

relatively sparse, about 2.0-m-thick snow can be accumulated during winter. The continental crustal impurities associated with dust brought in winter from the central/west Asia, Africa or the Thar Desert area can be captured in the winter snowpack (Li et al. 2009a). Stable isotopes in precipitation (δ^{18}O or δD) over the region are closely related to the atmospheric circulation systems as mentioned above. In summer, the precipitation isotopic composition is controlled by the 'amount effect', which refers to the depletion of heavy water isotopes during summer monsoon rains (Aizen et al. 1996; Tian et al. 1996, 2001; Vuille et al. 2005; Pang et al. 2006). In winter, the precipitation isotopic ratio is controlled by the 'temperature effect', which indicates a positive correlation of precipitation isotopic ratio with temperature (Dansgaard 1964; Moser and Stichler 1980; Thompson et al. 1989). In general, vapor for winter precipitation over the region deriving from continental moisture sources and continental recycling could be significant, which would lead to the enrichment of heavy isotopes in precipitation (Tian et al. 2001; Henderson-Sellers et al. 2004; Froehlich et al. 2008).

Mt. Yulong has 19 modern temperate glaciers, covering 11.61 km^2 (27°10′–27°40′N, 100°07′–100°10′E) (Fig. 1b). The biggest one, Baishui Glacier No. 1, has an area of 1.52 km^2 and is 2.7 km long, with the present equilibrium line at about 4,800 m a.s.l. Annual mean temperature at equilibrium line is −3.0 °C (calculated based on the temperature data at Lijiang meteorological station from 1951 to 2000, using the lapse rate 0.65 °C/100 m). Stake observations at 4,700 m a.s.l. reveal that the winter accumulation (October 2008–May 2009) is 1,383 mm w.e. and the summer ablation (June–September 2009) is −3,268 mm w.e..

During late April to mid-July 2006, more than 300 snow/firn samples of successive snow pits were collected at sites P1 and P2 (Fig. 1c). Snow strata of the two pits, including snow type, dust layer, ice layer as well as their developments, have been investigated by Zhang et al. (2010). Snow pit P1, located in the ablation zone, when it was first excavated on 25 April, glacier ice was covered by 4.0-m snow-firn pack. According to recent work by Zhang et al. (2010), the snow layer, about 40 cm below the surface of the pit P1, is fine-grained firn (diameter: <1 mm), which should correspond to snow deposited in spring 2006. Below the fine-grained firn layer to a remarkable dust layer (corresponding to a thin ice layer with thickness less than 1 cm) located at 0.9 m above the base of the pit is medium-grained firn (diameter: 1–2 mm). The hardness of this layer is rather difficult to dig, which should be deposited during the winter 2005/2006. Below the medium-grained firn layer to the base of the pit is coarse-grained firn (diameter: >2 mm). However, the hardness of the layer is rather low because it is easy to dig, suggesting that the snow layer was

Fig. 1 Maps showing **a** the location of Mt. Yulong in the southeastern Tibetan Plateau, **b** the modern glacierized area in Mt. Yulong and **c** the Baishui Glacier No. 1 with the locations of successive snow pits at sites P1 and P2 excavated from late April to mid-July in 2006. The *arrows* in **a** indicate the dominating atmospheric circulation systems over the monsoonal temperate-glacier region, and the *rectangle* in **b** denotes the Baishui Glacier No. 1. The GNIP stations (Lhasa and Kunming) and the weather station Lijiang mentioned in the text are also *marked as solid circle* in **a**
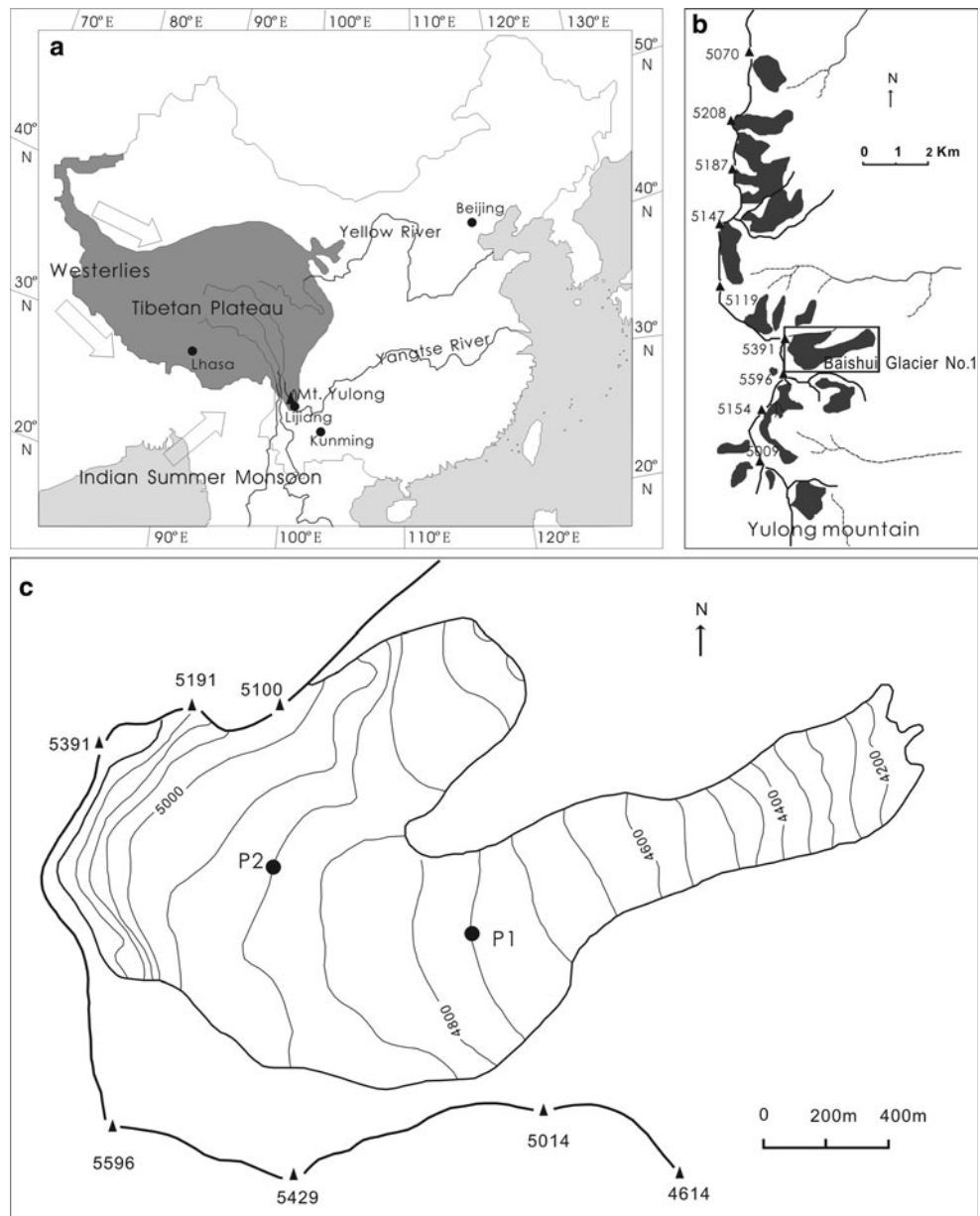
accumulated during the summer 2005. As a result, the visible dust layer at 0.9 m above the bottom of the pit is an annual mark, which is interpreted as the upper snow-firn layer when the 2005/2006 winter accumulation started. In early winter, more dust is accumulated on the glacier surface because less precipitation (or no precipitation) occurs. Meantime, one or more thin ice layers might be formed at a shallow depth or at the glacier surface due to surface melting/refreezing processes when snow melting is weak in early winter. Thus, impurities deposited in early winter could be accumulated above the thin ice layer due to meltwater percolation and form a dust layer. In addition, there is a clear dust layer at the base of the pit, which was likely formed in the summer 2005 when the glacier ice surface was exposed. The bare glacier ice surface is

accessible for receiving atmospheric dust or weathered materials from surrounding valleys.

Snow pit P2 is in the accumulation area, about 700 m glacier upward to site P1 (Fig. 1c). The pit was first excavated on 7 May down to an infiltration ice layer located at 4.0 m below the surface (formed in the late summer 2005 due to meltwater percolation). The stratigraphy of pit P2 is almost same to that of pit P1. At about 1.5 m above the infiltration ice layer, a clear dust layer (also corresponding to a thin ice layer with thickness less than 1 cm) was observed. Similar to site P1, the remarkable dust layer is the boundary between the upper snow-firn layer accumulated during the 2005/2006 winter season and the lower firn layer likely deposited in a mass balance year (from late summer 2004 to late summer 2005). The profiles

of oxygen isotopes and soluble ions of the pits P1 and P2 presented in the following section corroborate the dating.

Snowpack melt began in early May 2006, but a short cold period followed during May 14–23 (the daily mean air temperatures at both sites below 0 °C); then the temperatures increased above 0 °C (Fig. 2). High temperatures since 24 May resulted in near-continuous conditions for snowpack melting. On each visit to a site, the pit was extended sideway by 1 m and its stratigraphy was recorded before sampling. Totally, four and five successive snow pits were collected at sites P1 and P2, respectively (Table 1).

To avoid contamination, non-participating suit, polyethylene gloves and masks were used during sample collection. Samples were placed in pre-cleaned high-density polyethylene bottles that were washed by soaking and rinsing with 18.2 MΩ water. All samples were kept in frozen state during transportation and in the laboratory until analysis. All samples were analyzed at the State Key Laboratory of Cryospheric Science, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences. Stable oxygen isotope ratio ($\delta^{18}O$, expressed as relative to VSMOW) was analyzed by a Finnigan Delta-plus mass spectrometer (accuracy ±0.05 ‰). Cations (Na^+, K^+, Mg^{2+} and Ca^{2+}) were analyzed in the laboratory with a Dionex-600 ion chromatograph, and anions (Cl^-, NO_3^- and SO_4^{2-}) with a Dionex-300 ion chromatograph. The analytical precision for each ion is ±1 ppb. For further details on laboratory analysis, see Pang et al. (2007).
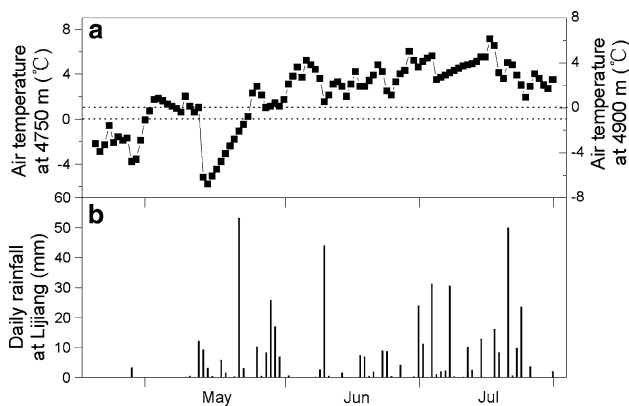
Fig. 2 Daily variations in **a** air temperatures at sites P1 (4,750 m a.s.l.) and P2 (4,900 m a.s.l.) and **b** rainfall at Lijiang from 20 April to 31 July in 2006. Daily temperatures at sites P1 and P2 are estimated by the temperature data from the automatic meteorological station at 4,506 m a.s.l. of Baishui Glacier No. 1, Mt. Yulong, with the lapse rate 0.65 °C per 100 m, and the temperature 0 °C at each site is indicated by a *dot line*. The daily rainfall data are from Lijiang weather station (2,393 m a.s.l.), about 25 km south of Mt. Yulong

Results

Development of oxygen isotopes

Variations in $\delta^{18}O$ in snow pits at sites P1 and P2 are presented in Fig. 3. As shown in Fig. 2, the daily mean temperature at site P1 (P2) is generally below 0 °C before 25 April (7 May), which indicates the pre-melting period. In the pre-melting period, vertical patterns of $\delta^{18}O$ at both sites are similar: with high $\delta^{18}O$ values in the upper snow-firn layer and low values in the lower firn layer (Table 2, Fig. 3). During the melting period, the pre-melting isotopic stratigraphy changed little (Fig. 3). Nevertheless, the isotopic profile shows weak homogenization, reflected by the gradual decrease in the coefficient of variation of $\delta^{18}O$ over time (Table 3).

Development of soluble ions

Development of ion concentrations (Cl^-, Na^+, K^+, SO_4^{2-}, NO_3^-, Mg^{2+} and Ca^{2+}) at sites P1 and P2 during the observation period is shown in Figs. 4 and 5, respectively.

At site P1 on 25 April, ion concentrations in the upper snow-firn layer are relatively high, especially in the upmost part of the layer, whereas the concentrations are relatively low in the lower firn layer (Fig. 4). There are two peaks of ion concentrations at the boundary between the upper snow-firn layer and the lower firn layer and at the base of the pit, respectively (Fig. 4). From 25 April to 7 May, all ions show a sharp decline in their concentrations both for the upper snow-firn layer and for the lower firn layer (Table 2, Fig. 4). During the following month (7 May–7 June), ion concentrations in the upper snow-firn layer exhibit an overall decreasing trend; nevertheless, the ions Na^+, K^+, Mg^{2+} and Ca^{2+} have a cognizable rise in their concentrations from 20 May to 7 June (Table 2, Fig. 4). On the other hand, the decline trend of ion concentrations in the lower firn layer is not evident from 7 May to 7 June; especially, most ion concentrations increased from 7 May to 20 May (Table 2, Fig. 4).

At site P2 on 7 May, the vertical pattern of ions almost coincides with that of site P1 on 25 April: high ion concentrations in the upper snow-firn layer and low values in the lower firn layer (Fig. 5). The peak of ion concentrations at the boundary between the upper snow-firn layer and the lower firn layer is also remarkable; however, there is no peak of ion concentrations at the base of the pit. From 7 May to 25 May, no significant changes in ion concentrations are observed both for the upper snow-firn layer and for lower firn layer (Table 2). For the upper snow-firn layer from 25 May to 13 July, all ions exhibit an overall decline trend in their concentrations (Table 2, Fig. 5); especially, the concentrations decreased sharply from 25 May to 16

Fig. 3 Evolution of oxygen isotopes (δ^{18}O) in successive snow pits excavated at sites P1 (*top*) and P2 (*bottom*) from late April to mid-July in 2006, Baishui Glacier No. 1, Mt. Yulong. The *grey horizontal line* at about 0.9 m (1.5 m) above the bottom of the pit P1 (P2) indicates the boundary between the upper snow-firn layer and the lower firn layer
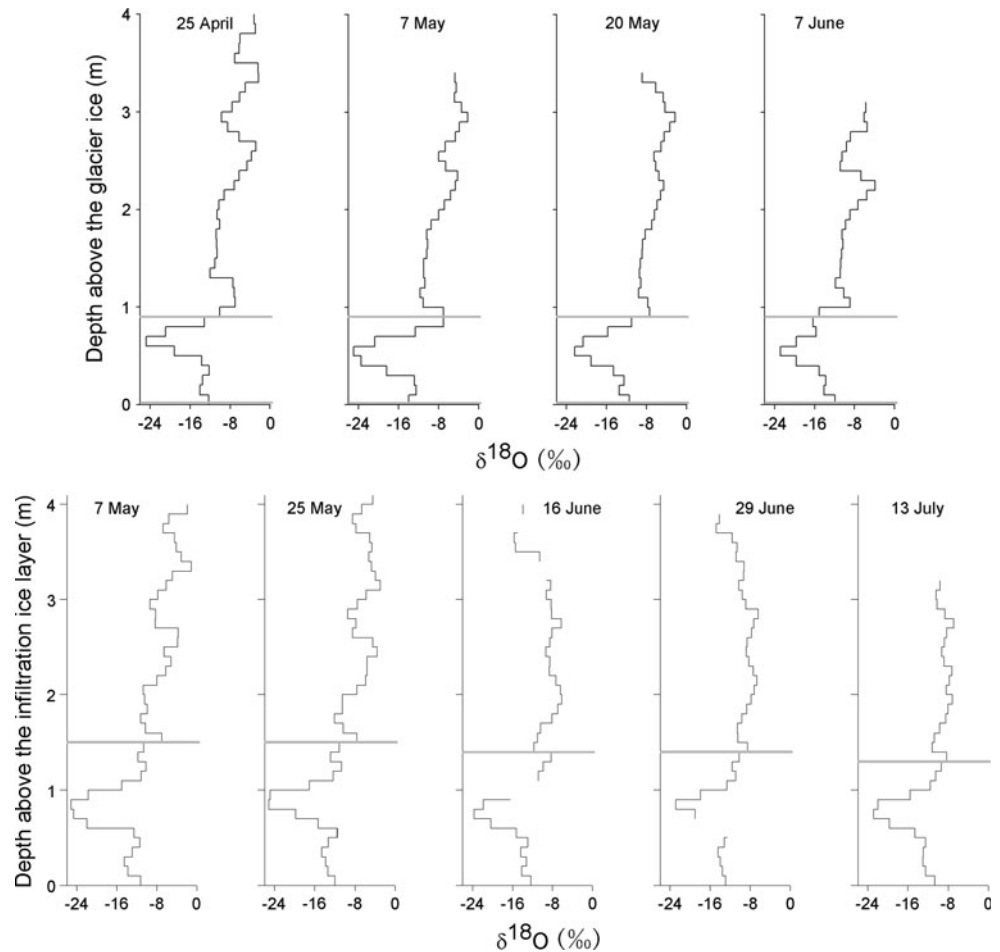
June. Nevertheless, most ions changed little in their concentrations during 16 June–29 June. From 29 June to 13 July, the ions Cl$^-$, NO$_3^-$ and SO$_4^{2-}$ started to decrease again, whereas the other ions show a recognizable rise in their concentrations, especially for Mg^{2+} and Ca^{2+}. On the other hand, for the lower firn layer during 25 May to 13 July, the overall decreasing trend of ion concentrations is not significant. But most ions decreased significantly from 16 June to 29 June. From 29 June to 13 July, the changes in ion concentrations in the lower firn layer are consistent with those in the upper snow-firn layer.

Ion elution sequence

It is well known that some ions in snowpack are removed more rapidly than others upon melt; this phenomenon is called "preferential elution" (Davies et al. 1982). In order to determine the elution sequence of ions in snowpack at Baishui Glacier No. 1, the mean values of ion concentrations of individual snow pit at sites P1 and P2 are normalized by the equation ($N_i = (X_i - \bar{X})/\bar{X}$). Here, N_i, X_i and $\bar{X}$ are the normalized value, the mean value of ion concentration in an individual snow pit and the mean value

of the successive snow pits, respectively. Temporal variations in the normalized values at sites P1 and P2 are shown in Fig. 6 with their linear trends. The slope of the linear regression denotes the decline rate of ion concentration with time. Thus, by comparing these slopes, the following elution sequence is obtained: NO$_3^-$ > SO$_4^{2-}$ > K$^+$ > Cl$^-$ > Mg^{2+} > Ca^{2+} > Na$^+$ at site P1 and K$^+$ > SO$_4^{2-}$ > NO$_3^-$ > Cl$^-$ > Ca^{2+} > Mg^{2+} > Na$^+$ at site P2.

Analysis of results

Oxygen isotopes

In the pre-melting period (on 25 April at site P1 and 7 May at site P2), the isotopic stratigraphies at pits P1 and P2 are almost same, suggesting the similar depositional conditions at both sites. The relatively depleted isotopic composition in the lower firn layer supports that the layer was deposited during summer. It is well known that the depletion of heavier isotopes (^{18}O) in summer precipitation over the Asian monsoon region is attributed to the so-called precipitation amount effect (Wake and Stievenard 1995;

Table 2 Mean values of $\delta^{18}O$ (‰, VSMOW) and ion concentrations (ppb) in the upper snow-firn layer, the lower firn layer and the whole column of successive snow pits excavated at sites P1 and P2 from Baishui Glacier No. 1, Mt. Yulong

	Date	$\delta^{18}O$	Cl^-	NO_3^-	SO_4^{2-}	Na^+	K^+	Mg^{2+}	Ca^{2+}
Snow pit P1									
The upper snow-firn layer	25 April	−7.15	261.20	1,830.70	2,797.81	50.86	167.99	121.89	3,671.74
	7 May	−7.23	157.06	897.32	1,629.64	32.47	74.22	83.99	2,308.53
	20 May	−6.59	104.95	654.96	671.27	16.18	43.71	61.18	1,781.85
	7 June	−9.01	68.33	463.04	645.39	34.92	57.62	66.82	2,630.73
The low firn layer	25 April	−15.38	141.07	3,770.95	1,462.46	67.95	160.97	337.12	11,584.88
	7 May	−16.26	58.33	292.17	720.39	8.98	27.37	86.74	5,958.53
	20 May	−15.65	70.83	376.39	359.99	46.66	77.84	99.89	5,288.63
	7 June	−16.55	93.04	323.21	532.96	15.79	17.96	86.59	2,882.11
The whole column	25 April	−9.21	231.17	2,315.76	2,463.97	55.13	166.23	175.70	5,650.03
	7 May	−9.62	130.92	737.13	1,388.96	26.25	61.82	84.72	3,274.71
	20 May	−8.99	95.92	581.22	588.87	24.02	52.49	71.13	2,683.60
	7 June	−11.20	75.74	421.09	611.66	29.18	45.72	72.75	2,706.15
Snow pit P2									
The upper snow-firn layer	7 May	−6.59	110.23	856.94	1,271.43	17.82	91.48	58.42	1,404.12
	25 May	−6.80	99.57	723.29	944.59	51.03	105.25	54.82	1,700.44
	16 June	−9.66	45.44	294.52	394.38	18.27	25.49	36.99	1,141.27
	29 June	−9.35	101.43	332.00	371.97	18.73	29.75	36.78	1,024.64
	13 July	−8.86	49.33	298.87	328.55	22.97	31.03	93.37	1,283.91
The low firn layer	7 May	−15.25	47.40	224.56	290.37	31.38	52.01	95.21	6,614.65
	25 May	−15.17	62.12	276.88	477.50	16.88	47.16	119.96	6,036.68
	16 June	−14.90	59.24	388.28	628.45	58.57	30.43	103.98	4,783.02
	29 June	−14.30	77.20	305.28	415.63	12.33	13.54	45.75	3,103.06
	13 July	−14.44	24.54	120.71	226.55	59.13	15.66	67.48	6,119.89
The whole column	7 May	−9.84	86.67	619.79	903.53	23.04	76.30	72.57	3,408.17
	25 May	−9.86	85.87	559.97	773.70	38.53	84.00	78.65	3,286.87
	16 June	−11.50	50.53	329.06	480.61	33.12	27.31	61.67	2,482.97
	29 June	−11.04	92.73	322.41	387.65	16.43	23.93	40.00	1,770.74
	13 July	−11.13	39.26	226.49	287.11	37.66	24.79	82.85	3,248.53

Araguás-Araguás et al. 1998; He et al. 2006; Pang et al. 2006), whereas the relatively enriched $\delta^{18}O$ values in the upper snow-firn layer demonstrate that the layer was accumulated during the winter/spring season. Tian et al. (2001) reported that the isotopic composition in winter precipitation is relatively heavy due to the continental recycling processes of water. The observed seasonal pattern of $\delta^{18}O$ in the snow pits is accordant with the seasonality of precipitation $\delta^{18}O$ (or δD) at GNIP (Global Network of Isotopes in Precipitation) stations (e.g., Lhasa and Kunming) located in the monsoon region. Additionally, the exceptionally low $\delta^{18}O$ values in the upper part of the lower firn layer of pit P1 (or P2) are likely related to the late summer monsoon precipitation in 2005. It was documented that the late Indian summer monsoon precipitation exhibits lowest $\delta^{18}O$ values (Pang et al. 2006; Breitenbach et al. 2010).

In general, we would expect a homogenization of $\delta^{18}O$ in snow pits during the melting period. Nevertheless, the homogenization of $\delta^{18}O$ can be seen only weakly in the upper snow-firn layer (Table 3). In contrast, the homogenization of $\delta^{18}O$ in the successive snow pits excavated at Austre Okstindbreen Glacier (Norway) is remarkable due to meltwater percolation (Raben and Theakstone 1998; Theakstone 2003). The difference in homogenization degree of $\delta^{18}O$ between Baishui Glacier No. 1 and Austre Okstindbreen Glacier is likely accounted for by the distinct percolation processes between the two sites. Relatively, little changes in snow pit thickness at Baishui Glacier No. 1 (Table 1) suggest that the snowpack had not experienced strong melting during the observation period. As a result, we assume that the percolating/refreezing process of meltwater is prevailing. Refreezing of meltwater during percolation could lead to isotopic redistribution (Taylor

Table 3 Coefficients of variation (σ/μ) in δ^{18}O and ion concentrations in the upper snow-firn layer, the lower firn layer and the whole column of successive snow pits excavated at sites P1 and P2 from Baishui Glacier No. 1, Mt. Yulong

	Date	δ^{18}O	Cl$^-$	NO$_3^-$	SO$_4^{2-}$	Na$^+$	K$^+$	Mg^{2+}	Ca^{2+}
Snow pit P1									
The upper snow-firn layer	25 April	−0.41	1.03	1.26	1.16	0.84	1.21	1.45	1.61
	7 May	−0.41	0.88	1.00	1.72	0.88	1.02	1.25	0.99
	20 May	−0.32	0.89	0.92	0.69	0.92	0.91	1.65	1.87
	7 June	−0.29	0.85	0.79	0.73	2.21	1.04	1.17	1.30
The low firn layer	25 April	−0.30	1.68	2.42	2.19	1.14	2.19	1.91	1.43
	7 May	−0.37	1.23	0.79	0.99	1.30	1.46	1.43	1.74
	20 May	−0.26	1.06	1.01	0.52	1.68	1.49	1.32	1.64
	7 June	−0.21	1.79	1.37	1.46	1.69	0.75	1.22	1.28
The whole column	25 April	−0.54	1.14	2.11	1.32	0.96	1.46	2.03	1.78
	7 May	−0.58	1.00	1.11	1.77	1.03	1.14	1.28	1.74
	20 May	−0.54	0.93	0.97	0.73	1.76	1.29	1.53	1.98
	7 June	−0.40	1.33	0.92	0.93	2.27	1.18	1.18	1.27
Snow pit P2									
The upper snow-firn layer	7 May	−0.43	1.11	1.22	1.26	0.89	1.00	1.55	1.18
	25 May	−0.36	0.86	1.18	1.02	2.05	0.81	1.30	1.58
	16 June	−0.29	1.08	1.35	1.71	1.39	0.89	1.58	2.06
	29 June	−0.22	1.10	0.74	1.05	1.62	1.13	1.60	1.55
	13 July	−0.14	1.02	1.18	0.89	2.00	0.84	3.20	1.24
The low firn layer	7 May	−0.35	0.74	1.22	1.06	1.52	1.54	1.50	1.38
	25 May	−0.31	0.72	1.13	1.11	1.20	1.63	1.13	1.48
	16 June	−0.31	1.26	1.28	1.55	2.19	1.14	1.36	1.55
	29 June	−0.25	2.31	0.74	0.74	2.08	1.44	1.10	1.40
	13 July	−0.30	0.78	0.61	0.86	1.80	1.16	1.38	1.54
The whole column	7 May	−0.59	1.19	1.44	1.50	1.40	1.16	1.56	1.83
	25 May	−0.54	0.87	1.31	1.10	2.21	1.03	1.31	1.85
	16 June	−0.38	1.17	1.32	1.65	2.44	1.00	1.64	2.05
	29 June	−0.32	1.48	0.73	0.93	1.73	1.26	1.39	1.70
	13 July	−0.36	1.07	1.27	0.90	2.04	0.97	2.84	1.99

Here, σ and μ are the mean values and standard deviations of δ^{18}O and ion concentrations, which are not presented in the Table

Homogenization is reflected in a reduction in the coefficient of variation

et al. 2001). This would give rise to relatively slow δ^{18}O homogenization because the percolation depth is limited. On the other hand, substantial thinning of snow pits at Austre Okstindbreen Glacier during the observation period demonstrates that they had undergone intense melting. Thus, here the meltwater percolation within the snowpack at Austre Okstindbreen Glacier is dominant. Feng et al. (2002) reported that isotopic exchange between the firn and the percolating water could occur during the meltwater percolation, which would cause more and more enriched in heavy isotopes in the firn. Therefore, the δ^{18}O homogenization at Austre Okstindbreen Glacier is likely rapid because the percolation depth is deeper and the interaction time between firn and meltwater is longer. It probably elucidates that stronger percolation leads to stronger isotope homogenization, whereas weaker percolation gives rise to weaker homogenization. It implies that the melting conditions in the past could be assessed by the homogenization degree of stable isotopes in ice cores.

Soluble ions

Previous studies of snow and ice chemistry in the monsoon region have revealed that major ions (Ca^{2+}, Mg^{2+}, Na$^+$, K$^+$, NH$_4^+$, SO$_4^{2-}$, NO$_3^-$ and Cl$^-$) show significant seasonal variations, with high concentrations during the non-monsoon season and relatively low concentrations during the monsoon season (Shrestha et al. 2000; Hou et al. 2003; Kang et al. 2004; Liu et al. 2010). In the pre-melting period, the high concentrations of ions in the upper snow-firn layer should be related to dust deposition during the 2005/2006 winter/spring season and the low concentrations in the lower firn layer may indicate the levels of ion concentrations after being eluted by meltwater percolation or the initial ion concentrations when being deposited during the summer 2005.

During the melting period, ion concentrations in the upper snow-firn layer decreased significantly due to ion elution processes, reflected by most impurities being

Fig. 4 Evolution of ion concentrations (Cl$^-$, Na$^+$, K$^+$, SO$_4^{2-}$, NO$_3^-$, Mg^{2+} and Ca^{2+}) in successive snow pits at site P1 from 25 April to 7 June 2006, Baishui Glacier No. 1, Mt. Yulong. The location of dust layer is indicated by a *grey horizontal line*. The boundary between the upper snow-firn layer and the lower firn layer, indicated by a remarkable dust layer, is about 0.9 m above the bottom of the snow pit
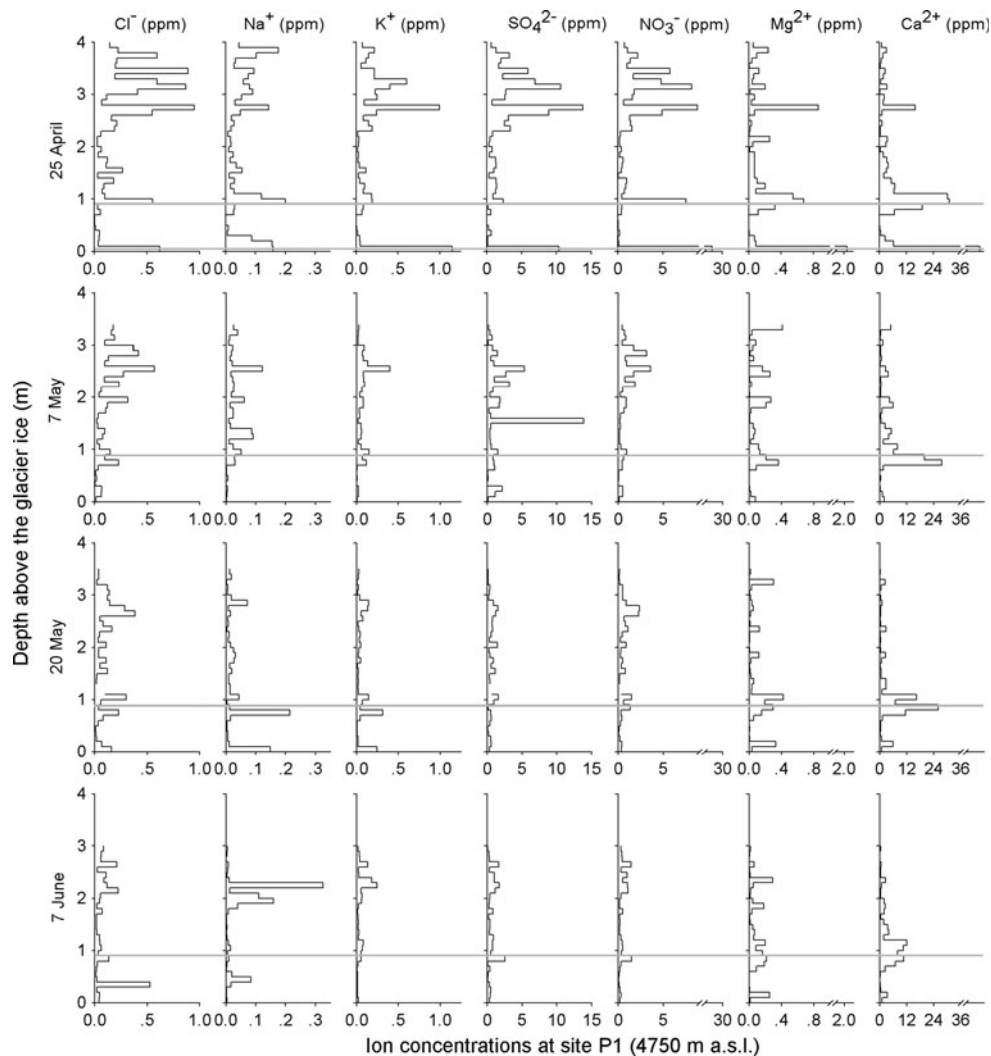

removed from the snowpack. The sharp decrease in the concentrations from 25 April to 7 May at site P1 and from 25 May to 16 June at site P2 may be associated with the first stage of snowpack melting, which is accordant with the result of Johannessen and Henriksen (1978). They pointed out that 50–80 % of the pollutant load is released with the first 30 % of the meltwater. Nevertheless, the overall decline trend of ion concentrations in the upper snow-firn layer is more or less disturbed by the gradual increasing summer precipitation events since late May (Fig. 2b). The recognizable rise in the concentrations of ions Na$^+$, K$^+$, Mg^{2+} and Ca^{2+} in the upper snow-firn layer at site P1 from 20 May to 7 June and at site P2 from 29 June to 13 July probably suggests additional considerable amount of impurities enriched in these cations being input into the upper snow-firn layer. According to the meteorological data at Lijiang weather station, both the monsoonal precipitation frequency and rainfall during these two periods are relatively high (Fig. 2b). The abundant input of

marine aerosols associated with the Indian summer monsoon rich in Na$^+$ and K$^+$ would result in increase in ions Na$^+$ and K$^+$. The increase in Mg^{2+} and Ca^{2+} is probably due to more intense weathering of limestone (CaCO$_3$ + H$_2$O = Ca^{2+} + CO$_2$ + 2OH$^-$) under the conditions of plentiful precipitation, for the limestone is widely distributed in the Mt. Yulong region (Li and Su 1996).

During the melting period, the decline trend of ion concentrations in the lower firn layer is not evident at both sites. The clear increase in ion concentrations (excepting for SO$_4^{2-}$ and Ca^{2+}) from 7 May to 20 May at site P1 is likely a result of the impurities in the upper snow-firn layer being eluted down into the lower firn layer. Also, the recognizable increase in Na$^+$, K$^+$, Mg^{2+} and Ca^{2+} in the lower firn layer at site P2 from 29 June to 13 July is accounted for by the ion elution processes in the upper snow-firn layer. Evidently, ion concentrations in the lower firn layer could be modified significantly by the ion elution processes in the upper snow-firn layer; namely, the eluted

Fig. 5 Evolution of ion concentrations (Cl⁻, Na⁺, K⁺, SO₄²⁻, NO₃⁻, Mg²⁺ and Ca²⁺) in successive snow pits at site P2 from 7 May to 13 July 2006, Baishui Glacier No. 1, Mt. Yulong. The boundary between the upper snow-firn layer and the lower firn layer, indicated by a remarkable dust layer (the *grey horizontal line*), is about 1.5 m above the bottom of the snow pit
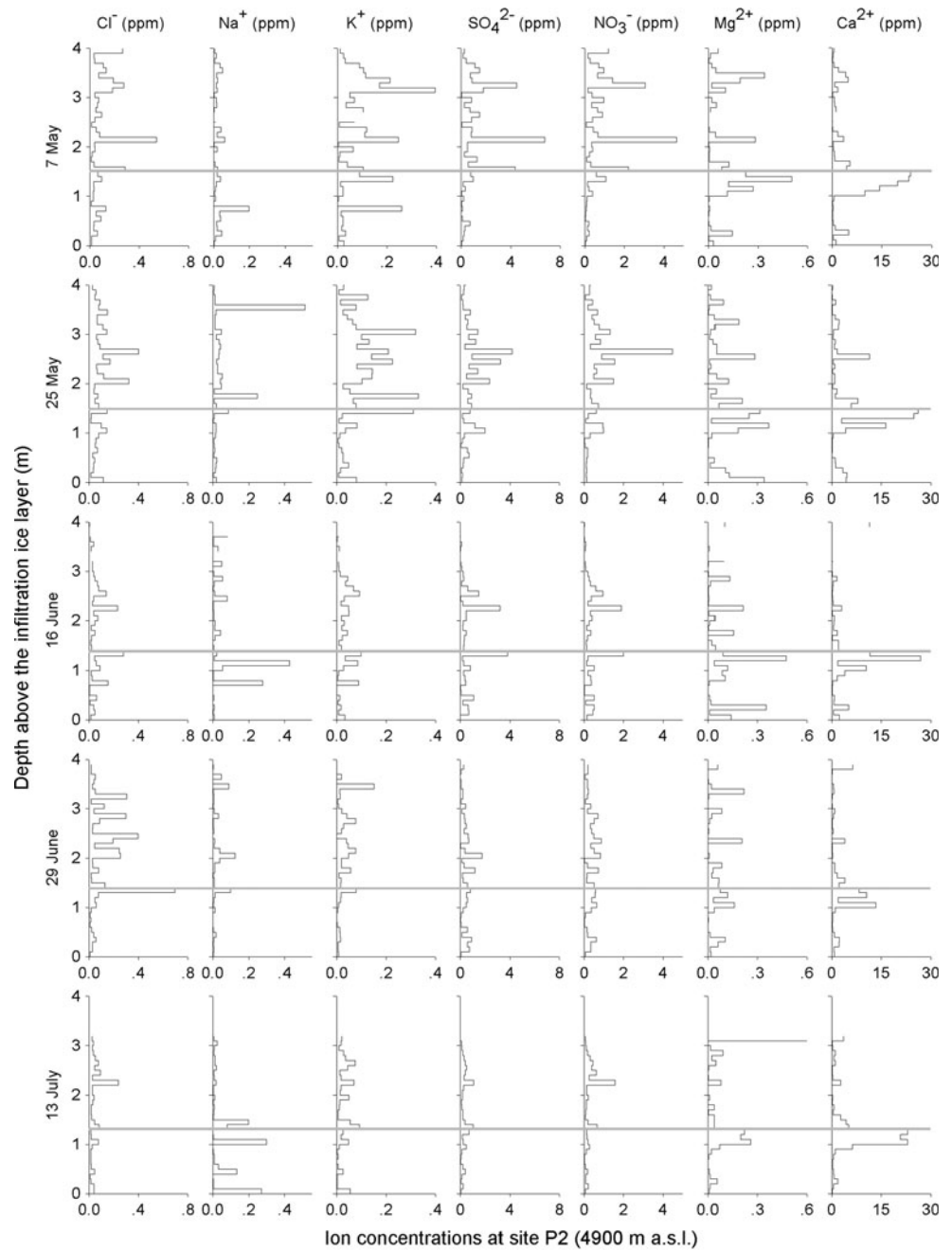

impurities from the upper snow-firn layer could be transported into the lower firn layer.

Ion elution sequence

Many studies demonstrated that soluble ions are leached from snow and firn with different efficiencies (Brimble-combe et al. 1985; Hewitt et al. 1989; Tranter et al. 1992; Eichler et al. 2001; Li et al. 2006). The rapid leaching of solute during the first phase of snow melting is the main cause of sharply decreasing ion concentrations in snowpack

(Johannessen and Henriksen 1978), and this process may be important in the chemical dynamics of ecosystems in many alpine regions (Leivestad and Muniz 1976). In addition, it is advantageous for explaining glaciochemical records in ice cores where the knowledge of elution sequence is known (Yoshinori et al. 2002). As a result, the ion elution sequence has been investigated in various field and laboratory studies. For instance, the sequences $SO_4^{2-} > Mg^{2+} \sim Ca^{2+} > K^+ > Na^+ > NO_3^- > Cl^-$ (Hewitt et al. 1989), $SO_4^{2-} > Mg^{2+} > Na^+ \sim NO_3^- > Cl^-$ (Tranter et al. 1992) and $SO_4^{2-} > NO_3^- > K^+ > Ca^{2+} > Mg^{2+} > Na^+ > Cl^-$

Fig. 6 Temporal variations in the ions Cl⁻, Na⁺, K⁺, SO_4^{2-}, NO_3^-, Mg^{2+} and Ca^{2+} are shown along with their linear trends (*left* site P1; *right* site P2)
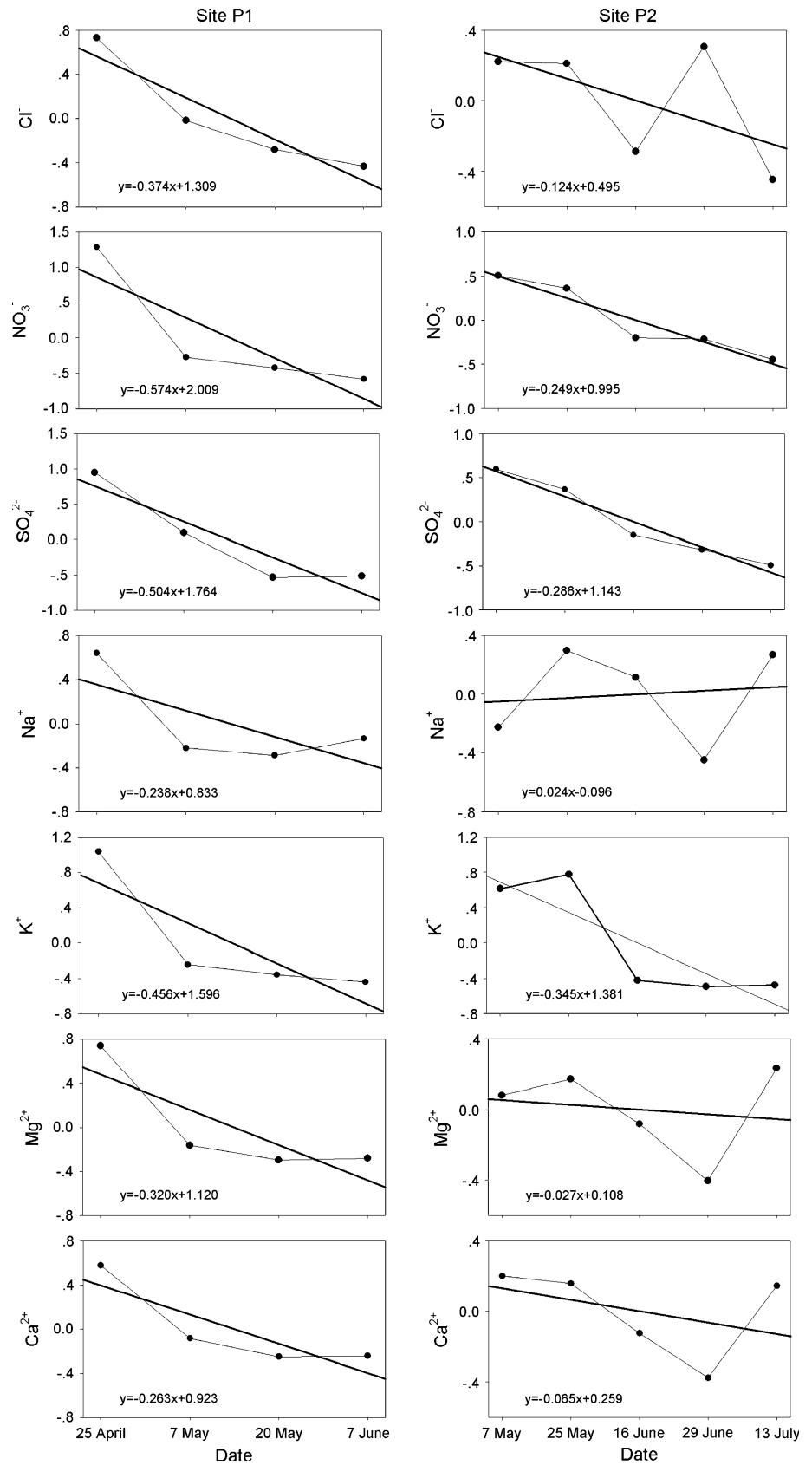
(Brimblecombe et al. 1985) were measured by laboratory experiments, and the sequences $SO_4^{2-} > Ca^{2+} \sim Mg^{2+} > K^+ \sim Na^+ > NO_3^- > Cl^-$ (Eichler et al. 2001) and $SO_4^{2-} > Ca^{2+} > Na^+ > NO_3^- > Cl^- > K^+ > Mg^{2+}$ (Li et al. 2006) were determined by field surveys. However, there are few studies of elution sequence in the monsoonal temperate-glacier region.

In this paper, the ion elution sequences $NO_3^- > SO_4^{2-} > K^+ > Cl^- > Mg^{2+} > Ca^{2+} > Na^+$ at site P1 and $K^+ > SO_4^{2-} > NO_3^- > Cl^- > Ca^{2+} > Mg^{2+} > Na^+$ at site P2 were determined. Evidently, the sequences are different at the two sites, although the distance between them is only about 700 m. Many factors could influence the ion elution sequence, for example, the initial ion concentrations in snow, the melting intensity, the additional impurities (or rainfall) input into the snowpack and eventually the snow-firn texture (Goto-Azuma et al. 1994; Li et al. 2006). The combined result of these factors is likely responsible for the difference between sites P1 and P2. Additionally, it is worth noting that the slight difference in slope between ions (for instance, Na^+, Mg^{2+} and Ca^{2+}) might not indicate the real difference in ion elution rate, for the used data are not enough. Nevertheless, the slopes of sites P1 and P2 exhibit a common characteristic: the relatively steep slopes for ions SO_4^{2-}, NO_3^- and K^+ (slope < -0.450 at site P1 and slope < -0.245 at site P2), the middle slope for ion Cl^- (slope $= -0.374$ at P1 and slope $= -0.124$ at P2) and the relatively flat slopes for ions Ca^{2+}, Mg^{2+} and Na^+ (slope > -0.320 at P1 and slope > -0.065 at P2) (Fig. 6). This may reflect the strong, moderate and weak elution of these ions, respectively.

The strong elution of SO_4^{2-} is in agreement with the previous results from the laboratory experiments and field surveys. But the intense elution of NO_3^- is different with the previous results, which may be related to a re-emission of HNO_3 after deposition by evaporation or photochemical decomposition (Ehhalt and Drummond 1982; Neubauer and Heumann 1988) on the condition of relatively strong solar radiation in the Mt. Yulong region. However, the fast elution of K^+ was not found in previous studies. The mechanism for intense elution efficiency of K^+ deserves further study. Finally, the elution rates of Mg^{2+} and Ca^{2+} are slower than those from the laboratory experiments and field surveys, resulted from the abundant weathering material from limestone (enriched in Mg^{2+} and Ca^{2+}) input into the snowpack because of the widely distributed limestone in the region (Li and Su 1996).

Discussion

Successive observations of glaciochemistry in snow pits excavated in ablation area (pit P1) and accumulation area (pit P2) from the pre-melting to melting period are useful to understand snow and ice chemistry in the monsoonal temperate-glacier region. The significant difference between ablation area and accumulation area signifies distinct geographical (e.g., altitude), meteorological (e.g., temperature) and hydrological (e.g., accumulation and ablation) conditions, which would lead to discrepant regular deposition and post-depositional modification in snow chemistry.

Based on the dating of the pits P1 and P2, the upper snow-firn layer of pit P1 is thicker than that of pit P2. It infers that more snow is accumulated at site P1 in winter/spring season, given that the density of upper snow-firn layer at P1 and P2 is the same. Meteorological observations in the central Himalayas reveal that winter snowfall increases as altitude increases (Lang and Barros 2004). As a result, we assume that the thicker winter snow-firn layer at P1 is likely due to snow drifting (snow redistributed by wind). The isotopic composition in winter snow decreases as altitude increases because of the "temperature effect". The mean value of $\delta^{18}O$ in the upper snow-firn layer at site P2 in the pre-melting period is about 0.5 ‰ higher than that at site P1 (Table 2), which supports the effect of snow drifting at site P1. For most small temperate glaciers, for instance, Baishui Glacier No. 1, the effect of snow drifting may be important because their firn basins are not so large. Consequently, the snow drifting factor needs to be considered when interpreting ice-core records in the region. On the other hand, the accumulated snow in the low firn layer at site P1 is less than that at site P2, which is mainly due to intense snow ablation at site P1 where the ablation zone is. There is no doubt that the low firn layer at site P1 was deposited during the summer 2005. Nevertheless, the low firn layer at site P2 may be deposited during an annual balance year (from the end of summer 2004 to the end of summer 2005). However, the shape of $\delta^{18}O$ profile in the low firn layer at site P2 is similar to that at site P1 (Fig. 3). Additionally, there is a peak in marine ions (e.g., Na^+ and K^+) in the middle part of the low firn layer at site P2 (Fig. 5), which vindicates the marine aerosols' input associated with the summer monsoon precipitation. Therefore, it is assumed that snow accumulation in the Mt. Yulong region mainly occurs in summer season. The upper snow-firn layer deposited in the winter/spring season may be ablated completely during the summer, implying that the winter snow layer could not be preserved in the annual snow layer. It verifies that accumulation and ablation in the monsoonal temperate-glacier region take place in the same season (summer). It suggests that ice-core records retrieved in the monsoonal region where the melt is high are mainly related to the summer monsoon activities and the post-depositional processes (especially the meltwater percolation).

There are many post-depositional factors that could modify snowpack chemistry, such as snow drifting,

sublimation/evaporation, melting/refreezing processes, meltwater percolation, surglacial runoff and liquid precipitation input. In winter, snow drifting and sublimation/evaporation might play a role in snow chemistry because winter westerlies prevail with a relatively high wind speed and the climate is dry with many sunny days. The observation period is from late spring to mid-summer 2006, which means a lot of overcast and rainy days with a relatively weak wind speed. Thus, the effect of snow drifting and sublimation/evaporation is limited during the observation period. For the period with weak melting (e.g., from 7 May to 25 May at site P2), little changes in mean values of ion concentrations and ion peaks in the upper snow-firn layer moving down (Table 2, Fig. 5) manifest that the melting/refreezing processes have a significant impact on snow chemistry. For the period with little changes in snow pit thickness (e.g., from 25 May to 29 June at site P2), the continuous decrease in ion concentrations is mainly due to meltwater percolation. However, additional snow accumulation is significant during this period, which counteracts the snowpack thinning due to the snow melting and metamorphism. The notable decrease in $\delta^{18}O$ in snow pits at sites P1 and P2 in the late May or early June (Table 2) denotes additional summer monsoonal snowfall input. For the period with rapid thinning of snowpack (e.g., from 29 June to 13 July at site P2), snow ablation and infiltration of liquid rainfall mainly account for the changes in ion concentrations in snowpack. After 7 June at site P1 and 13 July at site P2, the sampling was stopped because the snow pits were destructed by intense ablation of snow. It could be speculated that the upper snow-firn layer would be disappeared by the subsequent more intense ablation, which has been discussed as before.

The difference between ablation area and accumulation area means distinct melting conditions between sites P1 and P2. The sharp decrease in ion concentrations at site P1 occurred in late April or early May, and it happened in late May or early June at site P2. Additionally, the rapid snow ablation (indicating rapid thinning of snowpack) occurred in early June at site P1, and it happened in early July at site P2. The results demonstrate that snowpack melting at site P2 lags about one month compared to that at site P1. On the other hand, the absolute values of the linear regression slopes for soluble ions (Fig. 6) at site P1 are generally larger than those at site P2, suggesting the slower percolation of soluble ions in accumulation area than that in ablation area. The knowledge of snow melting and ions' percolation within snowpack is important for understanding water chemistry in the downstream glacial-river and interpreting ice-core records retrieved in the monsoonal temperate-glacier region.

Impurities in the upper snow-firn layer are gradually eluted by meltwater percolation during early summer, and

snow layer accumulated in the winter is likely ablated completely during mid-summer. Consequently, any climatic and environmental information associated with impurities deposited in winter snow layer cannot be preserved in ice cores drilled in the monsoon region where the melt is high. On the other hand, little changes in ion concentrations in the low firn layer during the observation period seem to imply that some information associated with the snow layer accumulated in summer could be preserved. However, the ion concentrations in summer snow layer could be disturbed by ion elution from its above upper snow-firn layer. As a result, reconstructing reliable climatic information through soluble ions in ice cores drilled in the area with high melt is unlikely, especially the ice cores drilled close to the equilibrium line where melt is intense (Koerner 1997; Hou et al. 2006). On the other hand, the pre-melting isotopic stratigraphy changed little during the observation period, implying that modification of the isotopic signal in snowpack by meltwater percolation is limited. On Severnaya Zemlya ice cap, Fritzsche et al. (2005) reported that meltwater percolation strongly smoothes the isotopic composition but not the deuterium excess, which also suggests that the isotopic signal could be preserved in ice cores where the melting is significant. Pang et al. (2007) found that the annual mean $\delta^{18}O$ record retrieved from a shallow firn/ice core at Baishui Glacier No. 1 is significantly correlated with the Indian summer monsoon index. The result suggests that isotopic record in ice cores drilled in areas with high melt still has the potential to reconstruct paleoclimate.

Conclusions

The heterogeneity of the pre-melting isotopic stratigraphy is considered to reflect seasonal variation in isotopic composition in precipitation, controlled by the Indian summer monsoon and winter westerlies. During the melting period, the pre-melting isotopic stratigraphy could still be identified clearly, although the homogenization process of $\delta^{18}O$ occurs. It suggests that isotopic record from ice cores drilled in the monsoonal temperate-glacier region with high melt still has the potential to retrieve valuable paleoclimatic information.

In the pre-melting period, the ion concentrations in the upper snow-firn layer reflect winter continental aerosols' input, which are associated with winter westerlies. During the melting period, ion elution within the snowpack is significant. The order of elution preference is $NO_3^- > SO_4^{2-} > K^+ > Cl^- > Mg^{2+} > Ca^{2+} > Na^+$ at P1 and $K^+ > SO_4^{2-} > NO_3^- > Cl^- > Ca^{2+} > Mg^{2+} > Na^+$ at P2. During the first melting phase, most impurities were released from the snowpack rapidly, indicated by sharp

decrease in the ion concentrations, which coincides with the result of Johannessen and Henriksen (1978). As the melting progressed, the impurities in the upper snow-firn layer could penetrate the annual layer boundary and enter into the lower firn layer. The results imply that the glaciochemical records in ice cores drilled in the monsoonal temperate-glacier region with high melt could be altered significantly by the elution effect. As a result, reconstructing reliable climatic and environmental records by ion records in ice cores drilled in the areas of high melt is unlikely. Nevertheless, the observed ion elution processes in this paper are meaningful for ice-core studies in the temperate-glacier region where the melt is relatively low.

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