Recent Progress of the Studies on Environmental Information in the Glacial System, Mt. Yulong, China

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Abstract

Investigations in relation to environmental information in the glacial system in Mt. Yulong, Lijiang, China, where is controlled by the south-western monsoon climate, have been carried out since 1999, with following achievements. (1) The climatic records in a 10.10m long firn core indicate that the amplitude of isotopic variations in the profile decreased with increasing depth, and isotopic homogenization occurred below 7.8 m as a result of meltwater percolation. Variations of $\delta^{18}O$ above 7.8 m showed an approximate correlation with the winter climatic trend at Lijiang station, 25 km away. Concentrations of Ca^{2+} and Mg^{2+} were much higher than those of Na^{+} and K^{+}, indicating that the air masses for precipitation were mainly from a continental source, and that the core material accumulated during the winter period; (2) Investigations of the spatial variations of oxygen isotopes in the atmosphere-glacier-river system confirm that there is an apparent inverse relation between the oxygen isotopic composition of precipitation and air temperature/precipitation amount in this region, with lower $\delta^{18}O$ values when the amount of precipitation and air temperature in summer is higher, due to the influence of intense summer monsoon on the study area. There are marked differences of the $\delta^{18}O$ values of winter-accumulated snow, glacial meltwater, summer precipitation and the glacier-fed river water. Spatial and temporal variations of isotopic composition are controlled by varied weather conditions at different altitudes; (3) Glaciers have greatly retreated after the Little Ice Age because of warming of the climate. The recent 50-year climatic data at Lijiang, the closest meteorological station to Mt.Yulong, indicates that there are 2-3-year periodic changes for the local temperature and apparent 11-12-year periodic cycles for precipitation, showing a corresponding pattern with that in northeastern part of India. During the most recent half-century, glaciers in Mt. Yulong have alternately retreated and advanced, with smaller amplitudes. Those glaciers on Mt. Yulong with the lowest latitude and smallest area have reduced in size by 60% from the Little Ice Age to the present (He et al, 2003a). It is evident that there is a close relation between atmospheric temperature and glacier retreat on Mt. Yulong. Therefore we conclude that global warming is the major and most important reason for glacier retreat in the Lijiang-Mt. Yulong region.

Introduction

Mt. Yulong, located in the Hengduan Mountain Range (southeastern edge of the Tibetan Plateau), north of Lijiang, Yunnan Province, China (27° 10'-27° 40'N; 100° 07'E-100° 10'E), is the southernmost glacierized area in Eurasia (Fig.1). The climate of the high altitude area (above 4100 m) on Mt. Yulong, which is controlled by the South-Asia/Indian monsoon, has provided the cold, moist conditions necessary for glacier development. The 19 glaciers on Mt. Yulong cover 11.61 km^2. Their high accumulation and ablation, high temperatures, basal sliding and rapid movement are typical of sub-tropical temperate- glaciers (Li and Su, 1996). The largest glacier, Baishui No.1, has an area of 1.52 km^2 and is 2.7 km long (Fig.1). Its broad, flat accumulation area covers about 1.0 km^2 between 4800 m and 5000 m. The glacier terminates at about 4150 m. Its tongue is heavily crevassed, reflecting very active motion. Glacial meltwater flows to the Baishui River, within the upper Yangtse River basin.

Mt. Yulong, with a highest peak, Satseto, of 5596 m, is in the subtropical zone. 70% of the region's precipitation falls between June and September from the warm, moisture-rich air masses of the prevailing southwestern summer monsoon from Indian Ocean. In winter, the climate is relatively dry, controlled by the winter monsoon of closer continental origin. The multi-year mean annual precipitation at Lijiang meteorological station (2393 m) is 772 mm, and the four-year average at the mountain foot (3240 m) is 1646 mm (Su and Pu, 1996). An ice core acquired in 1999 at around 4950 m indicated a four-year mean annual net accumulation of 900 mm water equivalent (He et al., 2001a). Because the measured net accumulation is the only data obtained in relation to the atmospheric precipitation above 4800 m in Mt. Yulong, it is assumed to represent an "average" rate in the glacier's accumulation area although it might be different in other sites. Using the mean net accumulation rate recovered in the core, together with the ablation rates measured by Su and Wang (1996), the mean annual precipitation amount in the accumulation area (above 4800m) of the glacier is roughly estimated in a range of 2400-3100 mm (He et al., 2001). However, the precipitation in the glacier's ablation area between 4150m and 4800 m is still unknown. The mean annual temperature at Lijiang is 12.6°C, with a positive mean temperature in every month. At 5400 m, the mean annual temperature is about -7.5°C, and all monthly mean temperatures are below 0°C. The mean annual temperature above the equilibrium line (4800-5000 m) is -3.3 to -4.7°C (Wang, 1996). This suggests an adiabatic lapse rate of about 0.7°C /100 m, which is higher than that for a pure maritime area because Mt.Yulong is distant from India Ocean, under the monsoon climate of wetter summer but drier winter. Since 1999, studies in relation to the climatic records in a shallow ice core, environmental signals in the atmosphere-glacier-river system, and glacial variations in 20th century have carried out (He et al, 2000abc, 2001, 2002ab, 2003ab). The results of these scientific investigations are reviewed and summarized in this paper.

Climatic Records in a Shallow Ice Core

In July of 1999, a 10.10m long core was drilled at 4950 m in the accumulation area of the glacier Baishui No. 1, using a US-made PICO corer. 101 samples, each 0.1 m long, were collected for isotopic and ionic analysis. Five net accumulation layers could be identified from the periodic variations of the $\delta^{18}O$ values in the core, with their abrupt changes between higher and lower values. These were at depths of 0-2.0 m, 2.0-3.2 m, 3.2-5.0 m, 5.0-6.5 m and 6.5-7.8 m, corresponding to the balance years 1998/99, 1997/98, 1996/97, 1995/96 and 1994/95, respectively. The variations of $\delta^{18}O$ values within an annual layer represent air temperature trends during precipitation events. The decreasing amplitude between the surface and 7.8 m, and smoothed values below 7.8 m, reflect a gradual homogenization process caused by meltwater percolation. $\delta^{18}O$ values between the surface and 7.8 m are roughly correlated with the variations of temperature and precipitation at Lijiang station during the winter months between the balance years of 1998/99 and 1994/95 (Fig.2). Below 7.8 m, however, the climatic signals are smoothed as a result of a slowly occurring homogenization process because the glacier in Mt. Yulong belongs to a high-melting temperate glacier. The correspondence between cationic concentrations and the isotopic profile is pronounced. Peak values of cationic content appear at the depths of identified summer surfaces and the positions of thick dirty ice layers. There is a significant relationship between Cl^- and Na^+ and the correlation coefficient between the two ions for 101 samples is 0.53 (Fig.3), indicating their common source. The ratios of Na^+/Cl^- are also calculated and plotted. Gradually reduced variation amplitude of the ratios, corresponding to those of $\delta^{18}O$ and other ions, further indicates a progressive effect of meltwater percolation and the homogenization process in the core. Concentrations of Ca^{2+} and Mg^{2+} are much higher than that of Na^+; this reflects the fact that more of the impurities in the core came from a continental source than from a marine one. Because of the positive mean air temperature in the study area between July and September, most materials in the core are believed to be deposited during the winter season, between October and May. Winter air masses, forced upwards by the blocking mountain, carry more land-surface impurities, resulting in the higher concentrations of Ca^{2+} and Mg^{2+}.

Environmental Signals in the Atmosphere-Glacier-River System

Stable isotopes and ions are useful tracers in glaciological and hydrological research (Dansgaard, 1964; Moser and Stichler, 1980). In July 1999, samples of recently deposited snow, summer rain, supraglacial and subglacial meltwater were collected from the glacier Baishui No.1, and river water samples were collected from the glacier-fed Baishui River. The samples were collected at the field sampling sites (Fig.1). The analyzed results are shown in Figs. 4 and 5.

The high-altitude winter deposited snow samples were more enriched in the heavy isotope than any other samples, such as recently deposited (one month) snow and summer rain obtained during the 1999 study. The general increase of $\delta^{18}O$ values with altitude (Fig. 4) indicates an irregular and varied spatial pattern, in contrast with the situation in the northern part of the Tibetanplateau (Yao et al., 1991), in this monsoon-dominated region.

Four samples of summer rainfall were collected at the Baishui No. 1 glacier during a single precipitation event in July 1999. There was a trend of increasing $\delta^{18}O$ values with decreasing elevation (Fig. 4), but the range was low (1.23‰). $\delta^{18}O$ values of precipitation samples collected during a single event may differ, and their average value, which depends strongly on the meteorological situation at different altitudes of the air in which it is produced and through which it falls (Rozanski et al., 1993). Accordingly, the slight differences of $\delta^{18}O$ values in this single summer rain event are caused by the different climatic conditions at varied elevations. Decreasing of $\delta^{18}O$ values with altitude rising corresponds to increasing of precipitation amount and decreasing of temperature with increasing altitude, indicating a complicated isotopic variation during the course of the single precipitation.

Eight meltwater samples were collected in the glacier's ablation area. Their $\delta^{18}O$ values tended to increase with decreasing altitude , but the range was small (0.80‰). In general, the samples were less depleted of ^{18}O than were the rainfall samples (Fig.4). The $\delta^{18}O$ values of the samples from the Baishui River varied only slightly from a mean of -14.56‰, suggesting that glacial meltwater was mixed with water which was more depleted of the heavy isotope.

Variations of dissolved ions in the different sources of supply to, and output from, a glacio-hydrological system reflects their different origins. Most of the ions in the accumulation area of the Baishui No. 1 glacier probably came from nearby sources: (1) wind-blown crustal materials from the mountain slopes, (2) impurities carried by moist air moving up the slopes, (3) avalanches from the valley walls, and (4) contact with the glacier bed by flowing ice and meltwater. Ionic concentrations in rainwater were low, particularly at high altitude (Fig. 5), and it is apparent that the impurity content of the precipitation falling on the Baishui No. 1 glacier was small. Solutes are acquired by meltwater and glacier river water as a result of contact with other sources. The increasing contact area between meltwater and the glacier bed with decreasing altitude led to higher ionic concentrations in the meltwater and the Baishui River (Figs. 5). The increase of Cl^- indicates gradual absorption of dissolved chloride from bedrock and till.

In most of the samples collected in 1999, Ca^{2+} and Mg^{2+} concentrations were much higher than those of Na^+ and K^+ (Fig. 5). Ca^{2+} inputs to the Baishui No. 1 glacier catchment probably are dominantly from local (continental) sources. K^+ may originate from continental dust sources. Mg^{2+} has marine as well as continental sources. The data suggests that the impurities deposited in the glacier’s system were mainly of a continental origin. Concentrations of Mg^{2+}, Ca^{2+} and K^+ were higher in snow at high altitude than in that closer to the equilibrium line, but Na^+ and Cl^- concentrations were lower at higher altitude. In general, the elution of Ca^{2+} and Mg^{2+} from a snowpack is more rapid than is that of Na^+ and K^+ (Davies et al., 1987). Thus, the decrease of ionic concentrations with decreasing altitude in the surface snow at the Baishui No. 1 glacier might be the result of a longer period of melting at lower elevations. However, this cannot account for the pattern of Na^+ and Cl^- concentrations. SO_4^{2-} was detected in surface snow only at the highest site (5000 m). Most SO_4^{2-} in snow is removed relatively rapidly in the early part of the melt season, and concentrations decrease particularly quickly at lower altitudes, where melting starts earlier (Raben and Theakstone, 1994). Early-season ionic elution of snow results in meltwater with a high ionic content. This has readily observed effects on river water (Tranter et al, 1987). The supraglacial meltwater formed from the leached snow is depleted of SO_4^{2-} (Tranter and Raiswell, 1991). SO_4^{2-} was detected in meltwater at the glacier Baishui No.1 only at lower altitudes; the concentrations were higher than in the one sample of summer rain in which SO_4^{2-} was found (Fig. 5).

Differences of conductivity of the samples of surface snow, rainfall, and meltwater reflected the general trends apparent in the concentrations of individual ions (Fig. 5).

Sampling in the Mt. Yulong area in 2000 was more detailed than those carried out in 1999. $\delta^{18}O$ of all samples were analyzed with a new Delta Plus mass spectrometer in the Laboratory of Ice Core and Cold Environment, Chinese Academy of Sciences.

The $\delta^{18}O$ values of winter accumulated snow, collected at the surface above the elevation of 4800 m on 5 July, decreased with decreasing altitude (Fig. 4). However, the $\delta^{18}O$ values of a set of samples from about 30 mm of newly precipitated snow, which were collected on 10 July between 4400 m and 4750 m when the temperature was lower (-5~0?), decreased with increasing altitude. The samples of surface snow from above 4800 m represent a winter precipitation event, but those from new accumulated snow below 4800 m represent a summer precipitation event. The $\delta^{18}O$ values indicate that the patterns of variation of winter and summer snowfalls differ.

Samples of summer rain were collected during a single precipitation event with a higher amount of precipitation (50 mm on average). Air temperature during sampling between 4700 m and 3200 m ranged from 10 ° C to 20 ° C. Summer rain was much more depleted of ^{18}O than the winter and summer snow covers were (Fig. 4). Four rainfall samples were collected at each of four locations (Fig. 4) - Ganhaizi (3200-3270 m), the Lower Cableway Station (3330-3360 m), the Upper Cableway Station (4490-4520 m), and the glacier (4550-4700 m). The $\delta^{18}O$ values were highest at Ganhaizi where precipitation amount was lowest. The lowest values were for the samples collected between 4600 m and 4700m, where precipitation amount was highest.

It is apparent that, below 4800 m, the higher δ^{18}O values of summer snow correspond to a lower-temperature environment and the lower values of summer rain is associated with a higher-temperature condition. The lowest values of summer deposited snow between 4650 m and 4750 m and of summer rain between 4600 m and 4700 m (Fig. 4) suggest that there probably is a highest precipitation-amount zone between 4600 m and 4750m in the glacier area. This irregular and varied pattern is characterized by an obvious reverse relation between δ^{18}O values and temperature/precipitation amount in the prevailing summer monsoon period when samples were collected.

Ten samples of glacial meltwater were collected between 4530 m and 4750 m. δ^{18}O values displayed a general increase with decreasing elevation (Fig. 4). The mean value (-13.94‰) was much lower than the means of winter deposited snow (-9.46‰) and accumulated snow at the pit sites (-6.70‰), indicating that alternative isotopic depletion and fractionation occurred during the processes of snow-ice transformation, ablation, evaporation, and supraglacial meltwater flow.

Water samples were collected from various sections of the glacier-fed Baishui River at altitudes between 3300 m and 3150m. The mean of the five δ^{18}O values of samples from the river's southern branch was -16.59‰ and that of the three from the northern branch was -16.28‰ (Fig. 4). Below the junction at 3250 m (-16.09‰), values increased, suggesting that re-fractionation occurred during water flow, percolation, evaporation and contact with the river bed and groundwater. The highest δ^{18}O value (-11.75‰) was at the valley's end (Fig. 1). The mean value of the twenty Baishui River samples (-15.44‰) was between those of glacial meltwater (-13.94‰) and summer rain (-16.98‰), demonstrating that the river water was a mixture of glacial meltwater and sources more depleted of ^{18}O, including summer precipitation. Ground water may enter the river, and further sampling and analysis is needed to calculate the relative contributions of meltwater, groundwater and precipitation to river discharge. The spatial and temporal variations of stable isotopes in the river may be used to identify the different sources of supply.

Glacier Variations since the Little Ice Age

Glaciers have greatly retreated after the Little Ice Age because of warming of the climate. The recent 50-year climatic data at Lijiang, the closest meteorological station to Mt.Yulong, indicates that there are 2-3-year periodic changes for the local temperature and apparent 11-12-year periodic cycles for precipitation, showing a corresponding pattern with that in northeastern part of India (Fig. 6). During the most recent half-century, glaciers in Mt. Yulong have alternately retreated and advanced, with smaller amplitudes (Table 1). Since the 1950's, global climatic change has had a significant response in China's monsoonal temperate-glacier region. Observed data indicate that, in the Lijiang–Mt. Yulong region, the average annual temperature between 1982 and 2001 was 0.2ºC higher than that of 1962-1981 and, in particular, the average annual temperature between 1998 and 2001 was 0.6ºC higher than that of 1982-1997. In Zhongdian, close to Lijiang, the average annual temperature during the 20 years 1982-2001 increased by 0.7ºC in comparison with that of the previous 20 years, 1962-1981. The average annual temperature during the most recent 4 years (1998- 2001) was 0.8ºC higher than that between 1982 and 1997, demonstrating a rapid warming trend in the area (He et al, 2000a, 2003ab, Jones et al, 1999). Against this climatic background, a more rapid speed of glacial changes has occurred on Mt. Yulong (Table 1, indicated by increased ablation of the glaciers, retreat of the glacier margins, reduction of the glaciers' areas and a rise of the snow line.

Table 1. Variation of Baishui No. 1, Mt Yulong since the Little Ice Age

Time Period	Altitude of Glacier End, m	Advance (+) and Retreat (–), m
Biashui Number 1 Glacier, Mt. Yulong (*Area, 1.7 km²; Length, 2.5 km*)		
Little Ice Age (17-19 centruries)	3800	+
19th century to 1957	4353 (1957)	–1250
1957 – 1982	4100 (1982)	+800
1982 – 1997	4200 (1997)	– 150
1998 – 2002	4250 (2002)	– 100

The Baishui glacier No.1 on Mount Yulong (Fig.1), the southernmost glacier of Eurasia, with a small area, is most sensitive to climate, and its area has decreased by 60% from the Little Ice Age to the present. The data listed in Table was from local historic records and geomorphic evidences of newer moraine and snow line variations, indicating that the glacier retreated about 1250 m between the Little Ice Age and the middle of the 20th century, and it has retreated again since the 1980s (Table 1). As a distinct indicator of climate change, the end of glacier Baishui No.1, the largest glacier on Mt. Yulong, has retreated by 100 m during the most recent 4 years, from 1998 to 2002, and the glacier's size and thickness have been reduced at the same time (He et al, 2000a, 2003ab).

Acknowledgments

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Figure Captions

Fig 1. The sketch map indicating the location of Mt.Yulong in southeastern Asia (top), the glacier Baishui No. 1, with the of locations of snow pits used in 2000 (middle), and the area around Mt. Yulong, with precipitation and river water sampling sites (bottom).

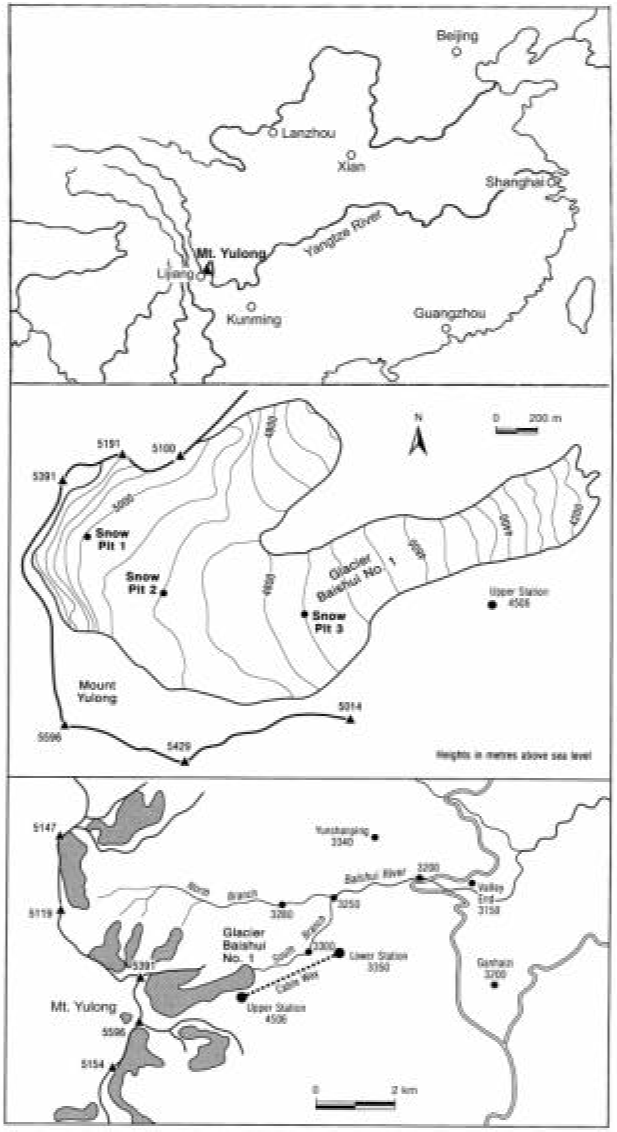
Fig.2. Isotopic variations above the depth of 7.8m in the core collected in 1999 (top) and the mean temperature and total precipitation at Lijiang meteorological station during winter months of the balance years 1994/95 to 1998/99 (bottom).

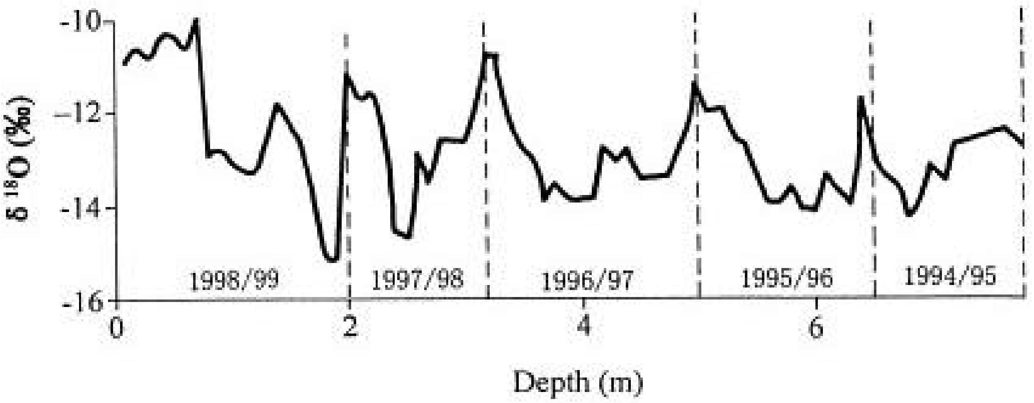
Fig.3. The relationship between Cl^- and Na^+ and variation of Na^+/Cl^- ratios in the core from the glacier Baishui No.1 indicates their common source.

Fig.4. Altitudinal variations of $\delta^{18}O$ values in accumulated snow, summer rainfall and glacial meltwater at the glacier Baishui No.1, and in glacier-fed river water, July 1999 and July 2000.

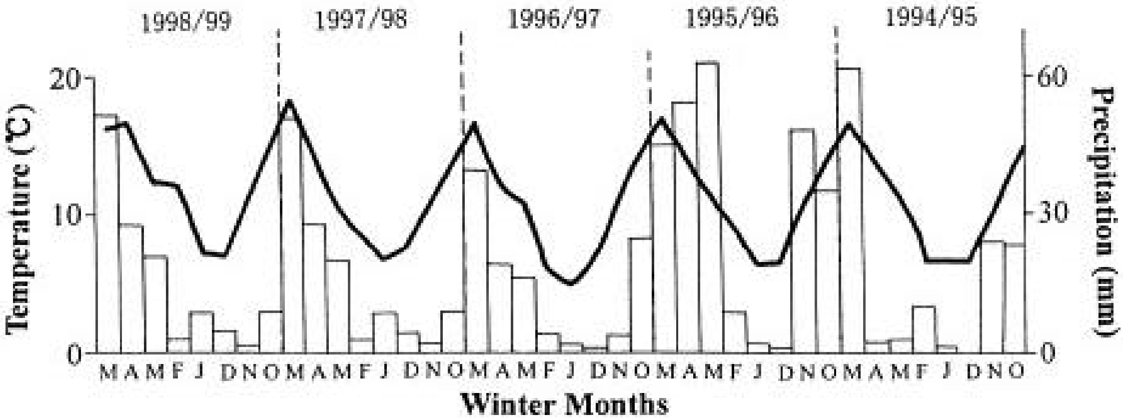
Fig.5. Altitudinal variations of Ca^{2+}, Cl^-, K^+, Na^+, Mg^{2+}, SO_4^{2-}, conductivity and pH values in accumulated snow, summer rainfall and glacial meltwater at the glacier Baishui No.1, Mt. Yulong, July 1999.

Fig.6 Variations of mean annual precipitation at Lijiang station (P), northwestern India(NWI), north central India (NCI) and northeastern India (NEI) from 1950 to 1996, indicating 11-12 year periodic cycles and 2-3 year sub-periodic cycles for southwestern monsoon. .

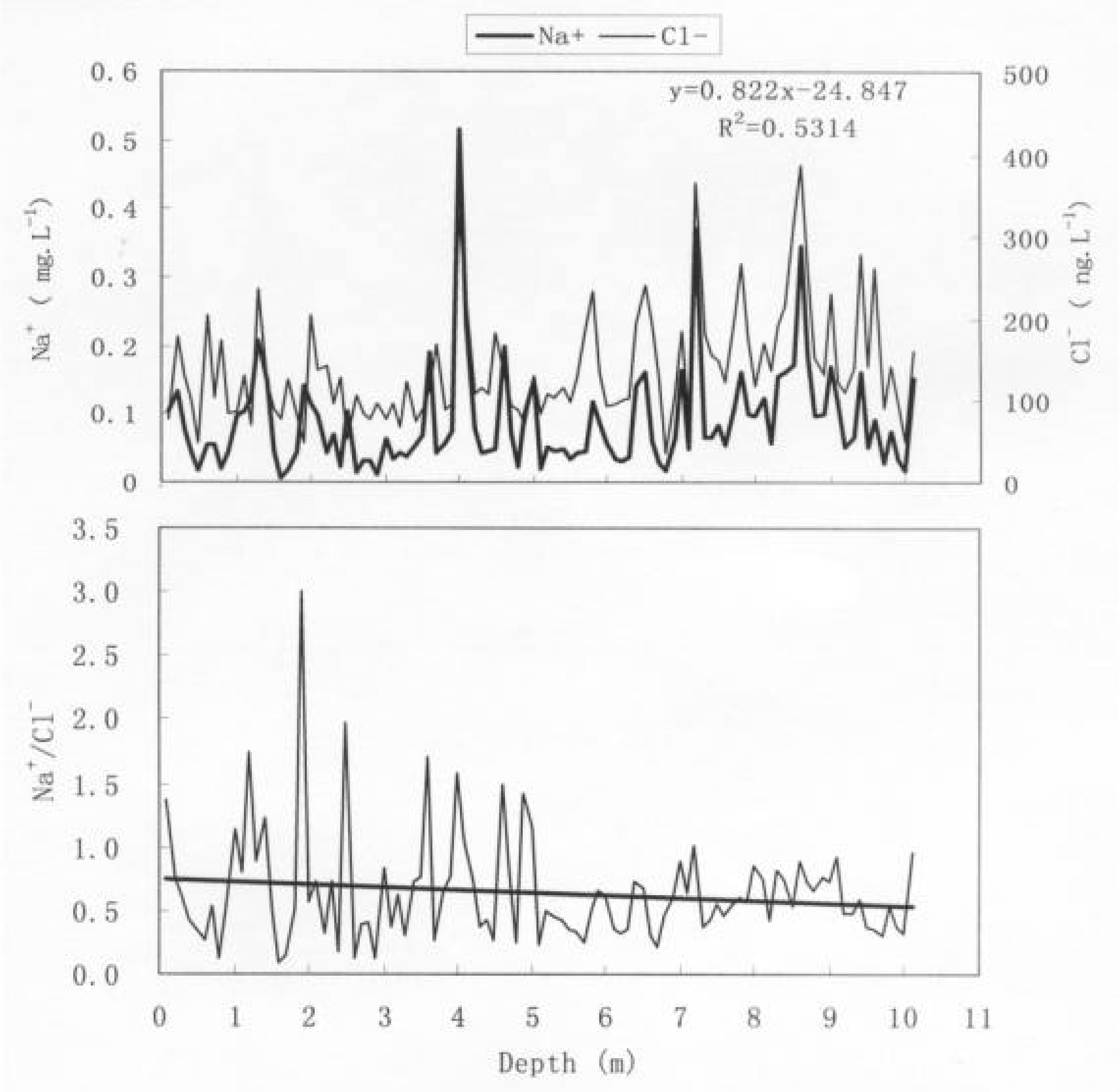

Beijing
Lanzhou
Xian
Shanghai
Yangtze River
Mt. Yulong
Lijiang
Kunming
Guangzhou
N
0 200 m
5191
5100
5391
4800
5000
Snow Pit 1
Snow Pit 2
4900
Glacier Baishui No. 1
4600
4400
4300
Snow Pit 3
Upper Station 4506
Mount Yulong
5014
5596
5429
Heights in metres above sea level
5147
Yunshanping 3340
North Branch
Baishui River
3200
Valley End 3150
5119
3280
3250
Glacier Baishui No. 1
South Branch
3300
Lower Station 3350
5391
Cable Way
Upper Station 4506
Ganhaizi 3200
Mt. Yulong
5596
5154
0 2 km



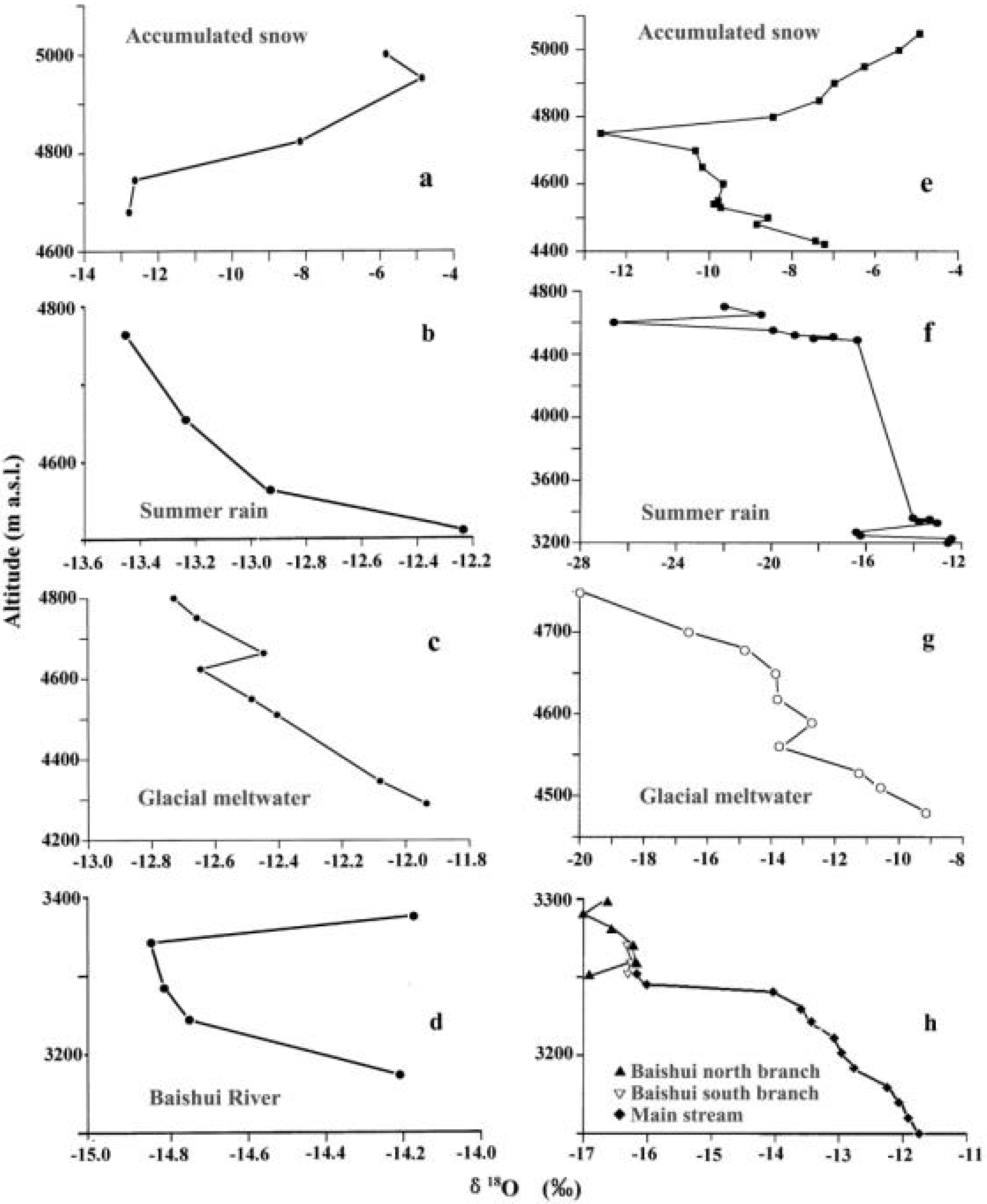
δ 18O (‰)
-10
-12
-14
-16
1998/99
1997/98
1996/97
1995/96
1994/95
0
2
4
6
Depth (m)

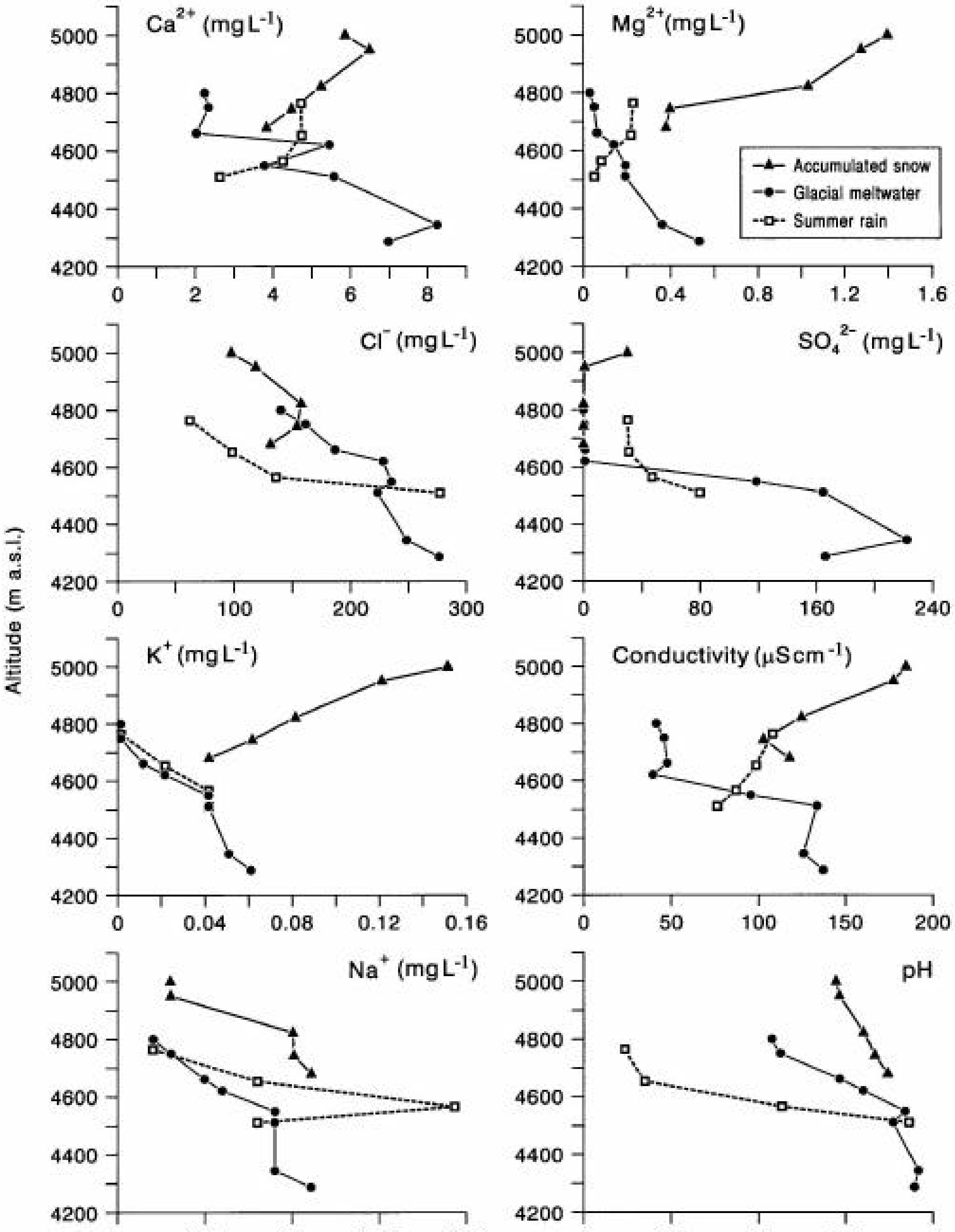


1998/99
1997/98
1996/97
1995/96
1994/95
Temperature (℃)
20
10
0
Precipitation (mm)
60
30
0
M A M F J D N O M A M F J D N O M A M F J D N O M A M F J D N O M A M F J D N O
Winter Months

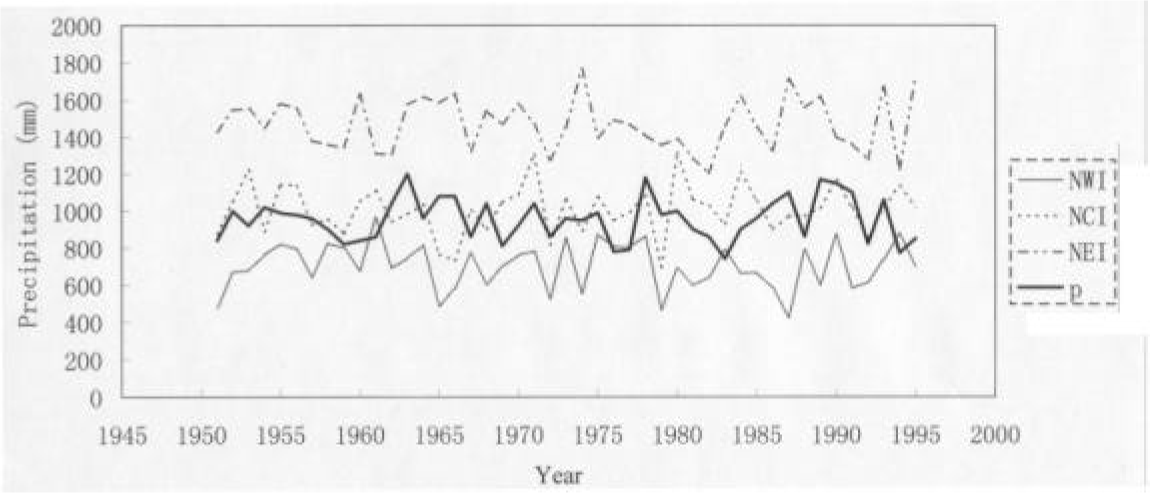


Na+
Cl-
y=0.822x-24.847
R²=0.5314
Na⁺ (mg.L⁻¹)
Cl⁻ (ng.L⁻¹)
0.6
0.5
0.4
0.3
0.2
0.1
0
500
400
300
200
100
0
Na⁺/Cl⁻
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
9
10
11
Depth (m)


Accumulated snow
a
5000
4800
4600
-14
-12
-10
-8
-6
-4
Accumulated snow
e
5000
4800
4600
4400
-12
-10
-8
-6
-4
Summer rain
b
4800
4600
-13.6
-13.4
-13.2
-13.0
-12.8
-12.6
-12.4
-12.2
Summer rain
f
4800
4400
4000
3600
3200
-28
-24
-20
-16
-12
Altitude (m a.s.l.)
Glacial meltwater
c
4800
4600
4400
4200
-13.0
-12.8
-12.6
-12.4
-12.2
-12.0
-11.8
Glacial meltwater
g
4700
4600
4500
-20
-18
-16
-14
-12
-10
-8
Baishui River
d
3400
3200
-15.0
-14.8
-14.6
-14.4
-14.2
-14.0
h
3300
3200
▲ Baishui north branch
▽ Baishui south branch
◆ Main stream
-17
-16
-15
-14
-13
-12
-11
δ ¹⁸O (‰)



Altitude (m a.s.l.)
Ca2+ (mg L-1)
Mg2+ (mg L-1)
Cl- (mg L-1)
SO4 2- (mg L-1)
K+ (mg L-1)
Conductivity (μS cm-1)
Na+ (mg L-1)
pH
Accumulated snow
Glacial meltwater
Summer rain
4200
4400
4600
4800
5000
0
2
4
6
8
0.4
0.8
1.2
1.6
100
200
300
80
160
240
0.04
0.08
0.12
0.16
50
150
0.05
0.1
0.15
0.2
6
6.5
7
7.5
8


Precipitation (mm)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
NWI
NCI
NEI
P