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Distribution features of stable oxygen isotopes in the typical monsoon temperate-glacier region, Mountain Yulong in China

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Abstract During the summers of 1999 and 2000, sampling was carried out in Mt. Yulong, for the investigation of the spatial distribution of oxygen stable isotope in the atmospheric-glacial-hydro system and similar results obtained in the two years have confirmed our conclusion. There is an evident negative correlation between stable isotopic composition and air temperature-precipitation amount, suggesting that there exits a strong "precipitation amount effect" in this typical monsoon temperate-glacier region. There are marked differences between the $\delta^{18}O$ values in winter-accumulated snow, glacial meltwater, summer precipitation and glacier-feeding stream. Under the control of varied climatic conditions, spatial and temporal variations of above glacial-hydro mediums are apparent. Isotopic depletion or fractionation and ionic changes had occurred during the phase-change and transformation processes of snow-ice, ice-meltwater, flowing of runoff and contact with bedrock. The variation of stable isotope in a runoff can reflect not only its own flowing process but also its different feeding sources.

Key words stable isotopes, monsoon temperate-glacier, Mountain Yulong.

1 Introduction

Isotopic studies in the glacier's hydrological system have aroused much interest of us for a long time as it is an advanced and useful technical method in the research fields of glaciology and hydrology (Dansgaard 1964; Moser and Stichler 1980; Wagenbach 1989; He and Theakstone 1994, 1999; Raben and Theakstone 1995; Theakstone and Knudsen 1996; He *et al*. 1999). Initiating from 1990's, the Chinese scientists have studied distribution features of the stable isotopes in precipitation and in hydrological cycle on the Tibetan Plateau (Yao *et al*. 1991; Zhang and Yao 1995; Tian *et al*. 1997). They concluded that there is a marked positive correlation between $\delta^{18}O$ and temperature in northern part of the Tibetan Plateau but a negative correlation between $\delta^{18}O$ and temperature and precipitation amount in southern part of the plateau, especially in the monsoon climate region, known as "the precipitation amount effect". In the large glacier distributing areas of western China, there are 22% of temperate glaciers (or called as marine-type glaciers). Because of some reasons, there have been few reports dealing with the studies of stable isotopes in the monsoon-temperate glacier region in China made in the past. In order to fill up these gaps, in the summer of 1999, a research program dealing with ice core drilling (He *et al*. 2000, 2001) was firstly carried out in Mt. Yulong, the southmost temperate-glacier region of Eurasia, controlled by the climate of south-Asia monsoon. In the same time, a sampling program from different glacial-hydro mediums, such as accumulated snow, glacier meltwater, summer rain and glacier river water, was also undertaking at and around the glacier Baishui No. 1 in Mt. Yulong. The analytical results of oxygen isotope and chemical ions indicate that the $\delta^{18}O$ values of surface snow above the equilibrium line were much higher than those below the line and the isotopic composition in glacier river water at lower altitude is lower than that of glacial meltwater at higher altitude. The lowest values were measured from summer rain. This distribution pattern suggests that there is a varied atmosphere situation in the mountain and there exists a negative correlation between $\delta^{18}O$ value and the climatic condition. It is possible that a strong "precipitation amount effect" exists in this strong monsoon climate region. In order to confirm our conjecture, more detailed sampling and investigations were continued in the same glacier system in July 2000. Three snow pits were excavated at 5000 m, 4900 m and 4750 m respectively in the accumulation area of the glacier Baishui No. 1 and 77 samples were collected from the pits. In addition, 18 samples from surface snow, 17 samples from glacial meltwater in ablation area, 16 samples from summer rain and 18 samples from the glacier-fed river (River Baishui) at different elevation levels in Mt. Yulong, were collected. All samples were determined by a Delta Plus mass spectrometer in the laboratory of ice core and cold environment, Chinese Academy of Sciences. The results both in 1999 and 2000 are reported and discussed here.

2 General situation in the studied area

There are 19 glaciers in Mt. Yulong (27°10′ - 27°40′N, 100°9′ - 100°20′E), with total area of 11.61 km^2. The largest one, glacier Baishui No. 1, has an area of 1.52 km^2 with a length of 2.7 km (Fig. 1). Its equilibrium line is at around 4800 m. The broad and flat glacier's accumulation area between 4800 - 5000 m covers about 1.0 km^2 in area and there are dense crevasses distributing in the glacier's tongue, reflecting that it is very active in motion. The glacier terminated at about 4100 m. Glacial meltwater flows down to the Baishui River, which belongs to the Jinsha River Basin. Mt. Yulong, with the highest peak of 5596 m (Satseto), is located in the subtropical zone and the most precipitation in the region happened between May and September, originating from moisture-plenty and warm air masses of the southwestern summer monsoon. In winter it is relatively dry, controlled by the continent-originated winter monsoon. At Lijiang meteorological station (2393 m), the mean annual temperature is 12.6 ℃, with a positive mean temperature in every month. At 5400 m, the mean annual temperature is about - 7.5 ℃ and monthly mean temperature is below 0 ℃. The mean annual temperature around the equilibrium line (4800 - 5000 m) is - 3.3 - - 4.7 ℃ (Wang 1996). According to 772 mm of the multi-year mean precipitation at Lijiang station and a four-year average of 1646 mm at 3240 m of the mountain foot, a precipitation gradient was calculated to 103.3 mm/100 m. Accordingly, the precipitation above the equilibrium line ranges between 2383 mm and 2590 mm (Su and Pu 1996). The climate in high altitude area above 4100 m in Mt.

Yulong has provided the cold and moisture conditions for developing the glaciers and enabled the mountain area to become a southmost glacialized region in Eurasia. The glaciers in Mt. Yulong possess the characteristics of large accumulation and ablation, higher temperature, base-sliding and faster movement, which belongs to the typical sub-tropics temperate glaciers (Li and Su 1996).

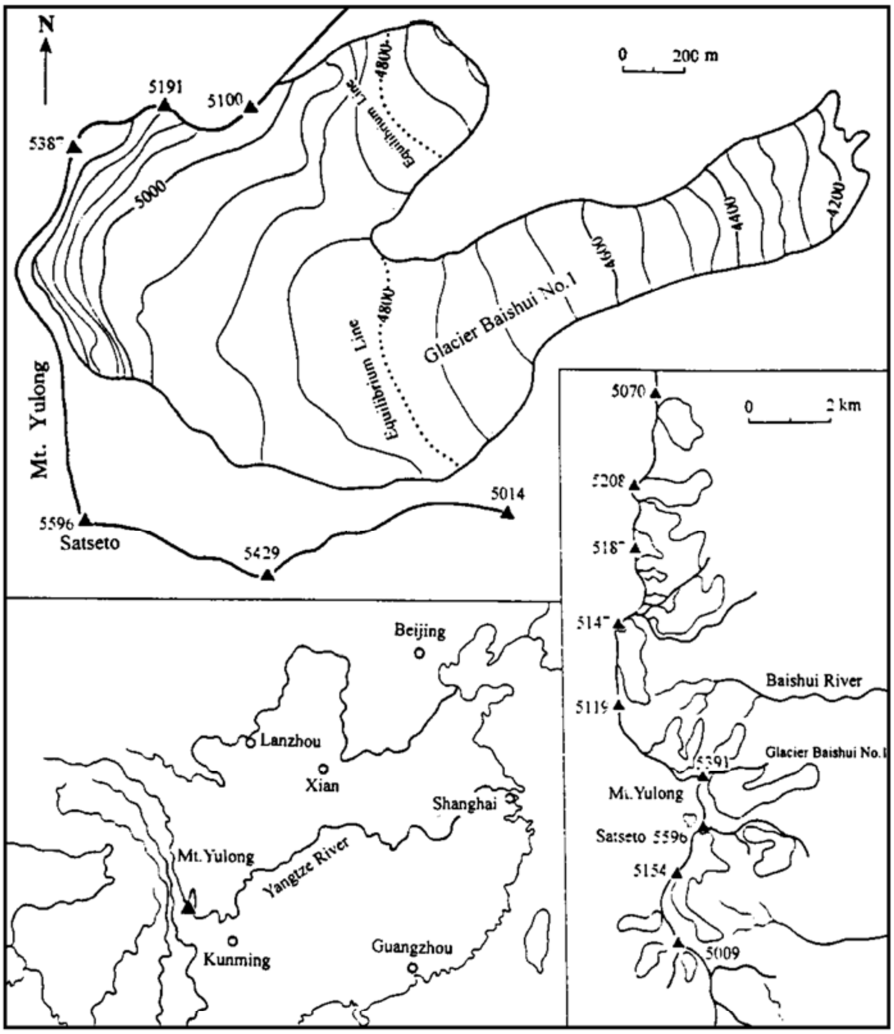

Fig. 1. The glacier distribution and the glacier Baishui No. 1 in Mt. Yulong.

3 Results obtained in 1999 with the discussion

$\delta^{18}O$, K^+, Na^+, Ca^{2+}, Mg^{2+}, NO_3^-, SO_4^{2-}, Cl^-, conductivity and pH values were determined from 23 samples collected from the new snow cover, supraglacial and subglacial meltwater, summer rain at the glacier Baishui No. 1 and the glacial fed stream Baishui in July 1999, by using a Finngan MAT-252 Spectrometer (precision 0.05 ‰), a Dinex-100 chromatography (precision 0.1%), 2380 Atomic Absorption Spectrophotometer (precision 0.2%), conductivity and pH meters. The results are shown in Table 1.

Looking over the total average, $\delta^{18}O$ values (mean − 8.87 ‰) in surface snow were highest. Those in summer rain and glacial meltwater (mean − 12.98 ‰ and − 12.43 ‰) were lower and the lowest values were measured in Baishui River (mean − 14.56 ‰). $\delta^{18}O$ values in the newly deposited snow of the accumulation area above the equilibrium line (4800 m), varied between − 4.87 ‰ and − 8.21 ‰, were much higher than those of − 12.67 ‰ and − 12.80 ‰ below the line. The variation amplitude of $\delta^{18}O$ (− 12.38 ‰ and − 12.73 ‰) was small in glacial meltwater in the ablation area and the values in newly precipitated rain reduced with the increasing elevation. Oppositely, the lowest values are measured in the glacial river water below the elevation of 3400 m due to the gradual feeding of low isotopic composition of summer rain. Differing from those in northern part of Tibetan plateau (Yao *et al*. 1991), this distributing feature indicates that there is a negative correlation between isotopic contents and air temperature-precipitation amount, and the overall distribution of $\delta^{18}O$ in different mediums of the glacier's surface hydro-system trends to increase with elevation, suggesting an obvious "precipitation amount effect" of the stable isotope in the strong monsoon region. The differences of isotopic composition in various glacial-hydro mediums probably were caused by different atmospheric circulation between summer and winter as well as varied precipitation sources.

Table 1. Chemical results of the samples from different glacial-hydro mediums at the glacier Baishui No. 1 in Mt. Yulong

Sample number	Elevation / m	$\delta^{18}O$ / ‰	K^+ / mg. L^{-1}	Na^+ / mg. L^{-1}	Ca^{2+} / mg. L^{-1}	Mg^{2+} / mg. L^{-1}	Cl^- / ng. L^{-1}	SO_4^{2-} / ng. L^{-1}	NO_3^- / ng. L^{-1}	Condu. μs/cm	pH
S1	5000	− 5.82	0.15	0.03	5.89	1.38	96.9	29.14	0	185	7.29
S2	4950	− 4.87	0.12	0.03	6.54	1.26	117.24	0	0	178	7.45
S3	4823	− 8.21	0.08	0.10	5.26	1.01	156.4	0	0	124	7.6
S4	4745	− 12.67	0.06	0.10	4.49	0.38	153.6	0	0	102	7.66
S5	4680	− 12.80	0.04	0.11	3.87	0.36	129.16	0	0	117	7.74
Mean		− 8.87	0.09	0.07	5.21	0.88	130.66			141	7.55
W1	4800	− 12.73	0.00	0.02	2.27	0.02	139.52	0	0	40.6	7.07
W2	4752	− 12.66	0.00	0.03	2.38	0.04	161.01	0	127.02	44.7	7.12
W3	4664	− 12.45	0.01	0.05	2.06	0.05	186.57	0	0	46.6	7.46
W4	4623	− 12.65	0.02	0.06	5.45	0.13	228.74	0	0	39	7.60
W5	4550	− 12.49	0.04	0.09	3.81	0.18	235.67	117.92	0	94.4	7.84
W6	4510	− 12.41	0.04	0.09	5.57	0.18	223.67	163.54	67.86	133	7.77
W7	4344	− 12.08	0.05	0.09	8.23	0.35	248.92	221.93	65.30	126	7.92
W8	4287	− 11.93	0.06	0.11	6.98	0.52	275.81	166.23	76.50	137	7.90
Mean		− 12.43	0.03	0.07	4.59	0.18	212.49	83.70	42.08	82.6	7.58
B1	3375	− 14.18	0.01	0.05	4.26	1.60	262.19	340.11	59.02	154	7.92
B2	3341	− 14.85	0.04	0.11	4.58	1.60	176.47	283.72	234.41	162	7.93
B3	3285	− 14.82	0.05	0.58	6.54	2.02	248.92	377.25	181.24	314	8.02
B4	3241	− 14.75	0.07	1.12	6.62	2.02	253.61	455.89	205.69	340	8.24
B5	3176	− 14.21	0.09	1.17	12.49	2.06	288.44	576.83	312.36	341	8.26
Mean		− 14.56	0.04	0.61	6.90	1.86	245.93	406.77	198.54	262	8.07
R1	4765	− 13.47	0.00	0.02	4.74	0.21	61.25	29.57	0	107	6.23
R2	4654	− 13.26	0.02	0.08	4.77	0.20	97.45	29.24	0	98	6.34
R3	4563	− 12.94	0.04	0.19	4.26	0.07	134.92	45.77	0	86	7.13
R4	4510	− 12.24	0.04	0.08	2.63	0.04	277.8	78.74	0	75	7.86
Mean		− 12.98	0.03	0.09	4.10	0.13	142.86	45.83	0	92	6.89

S, W, B and R represent the samples of the most recently deposited snow, the glacial meltwater, the Baishui River and summer rain, respectively.

Among the four cations, concentrations of Ca^{2+} and Mg^{2+} of all samples are much higher than Na^+ and K^+, with the highest values of Ca^{2+} and the lowest values of K^+. The cationic contents show a corresponding variation trend to those of conductivity and pH. The ionic composition of newer snow and rain reduced with decreasing elevation but a reverse pattern existed in glacial meltwater and glacier feeding stream. Variations of dissolved ions in different income and output parts of glacial-hydro system also reflect their different origins. Higher concentrations of the ions in the accumulation area may result from the stronger wind blow in higher elevation area. Most of them probably were deposited from four input routes in a relatively short distance: (1) strong mountainous wind-blew crust materials from the mountain slope to snow and glacial runoff; (2) the impurities to snow, ice and glacial streams were carried by the precipitation vapor uplifted along the mountainous slope; (3) contact with the glacier bed by ice flow and meltwater runoff; (4) avalanche occurred on the wall of the glacier valley. Because of an increased touch of glacial meltwater to the glacier's bed with decreasing altitude, the impurities in it, therefore, become more and more plenty.

Cl^- and Na^+ in the snow cover of the accumulation area show a corresponding correlation. Cl^- increases from the upperstream to the downstream both in the glacier's ablation area and the glacier feeding stream (Baishui River), as a result of gradual absorption of dissolved chloride from the bedrock and glacial tills. Ionic concentrations of rainwater at higher altitude are higher than that at lower elevation, which reflects that they probably origin from different sources. SO_4^{2-} and NO_3^- only appeared in the surface snow above the equilibrium line and the contents of the two anions in summer rain were lower. However their concentrations in glacial meltwater and river increase with decreasing altitude. This anionic and cationic pattern suggests that very few pollution occurred in the original precipitation, and more impurities in glacial meltwater and river enriched after deposition as they were contacted with other mediums.

4 Results obtained in 2000 with the discussion

In order to confirm the results in 1999, more detailed sampling and investigation for the analysis of stable oxygen isotope from different glacial-hydro mediums were continued in Mt. Yulong. The similar results with those in 1999 were obtained as shown in Table 2.

Table 2. Analytical results of $\delta^{18}O$ in different glacial-hydro mediums at and around the glacier Baishui No. 1 in Mt. Yulong

Snow pit 1 (5000 m a. s. l.)		Snow pit 2 (4900 m a. s. l.)		Snow pit 3 (4750 m a. s. l.)		Surface snow	
Depth /m	Mean value /‰	Depth /m	Mean value /‰	Depth /m	Mean value /‰	Elevation /m	Mean value /‰
0 - 1.0	-6.51	0 - 1.0	-6.57	0 - 1.0	-7.78	4700 - 5000	-7.58
1.0 - 2.0	-4.83	1.0 - 2.0	-6.24	1.0 - 2.0	-5.35	4600 - 4700	-10.23
2.0 - 2.6	-4.89	2.0 - 3.1	-9.81			4500 - 4600	-6.80
Total mean	-5.41		-7.54		-6.57		-8.08

Glacier meltwater		Summer rain		Baishui river	
Elevation /m a. s. l.	Mean value /‰	Elevation /m a. s. l.	Mean value /‰	Elevation /m a. s. l.	Mean value /‰
4600 - 4700	-16.79	4500 - 4700	-22.24	3250 - 3300 (south branch)	-16.59
4500 - 4600	-12.57	4506 (upper st.)	-17.74	3250 - 3280 (north branch)	-16.28
4400 - 4500	-11.84	3351 (lower st.)	-14.40	3250 (junction)	-16.09
3200 (Ganhaizi)	-13.54	3150 - 3250 (main stream)	-12.70		
Total mean	-13.62		-16.10		-14.69

4.1 Variation of $\delta^{18}O$ in precipitation

Table 2 indicates the spatial distributing features of isotopic composition in precipitation (surface snow and summer rain) around the glacier Baishui No. 1. $\delta^{18}O$ values of surface snow was the lowest between 4600 m and 4700 m (− 10.23 ‰), higher between 4700 m and 5000 m (− 7.85 ‰), and the highest between 4500 m and 4600 m (− 6.80 ‰). Similarly, those in summer rain are also lowest between 4600 m and 4700 m and rise with decreasing altitude below 4700 m. Among the three snow pits, $\delta^{18}O$ values in newer snowpack above the depth of 1.0 m are lower and those in older snowpack are higher. The total average of $\delta^{18}O$ are the highest for snow pits, higher for surface snow, and lowest for summer rain. The highest and higher values of snow pits and surface snow correspond to the winter-deposited snow formed under lower air temperature and lower precipitation amount in winter. In contrast, the lowest values of summer rain deal with higher air temperature (10 ℃ − 20 ℃ during sampling) and higher precipitation amount in summer. The pattern clearly indicates a negative correlation between stable isotopic composition and air temperature-precipitation amount, suggesting that Mt. Yulong is a strong monsoon-climate area, influenced by farther marine-originated wet airflows in summer and closer continent drier airmasses in winter. The "precipitation amount effect" in this region is apparent. According to this relation, it is inferred that there exists a highest precipitation zone between 4600 m and 4700 m.

4.2 Variation of $\delta^{18}O$ in snow pits and glacial meltwater

In the three snow pits of the accumulation area at the glacier Baishui No. 1, $\delta^{18}O$ values above the depth of 2.0 m were higher. Of which, the highest (− 2.65 ‰) and the lowest (− 9.71 ‰) values were observed at 1.4 m in Pit 1 and at 0.2 m in Pit 3, respectively. δ values below 2.0 m in Pit 2 obviously decreased from − 7.03 ‰ to − 15.97 ‰. Large amplitude of isotopic variation reflects a changeable climatic condition during the time of precipitation. Between 0 m and 2.0 m in three snow pits, those were deposited during a relatively low temperature and precipitation period, the mean value (− 5.67 ‰) was the highest in Snow Pit 1 at higher altitude and lower in Pit 2 (− 6.40 ‰) and Pit 3 (− 6.37 ‰) at lower altitude. The average isotopic composition of the surface snow, accumulated during a relatively high temperature and precipitation period, was − 7.58 ‰ above 4700 m and − 8.52 ‰ between 4500 m and 4700 m. This distributing pattern further confirms a strong negative correlation between the stable isotope and the climate.

The $\delta^{18}O$ values in glacial meltwater have gradually risen with decreasing elevation. However, their mean value (− 13.62 ‰) was much lower than those of snow pits (− 6.49 ‰) and surface snow (− 8.08 ‰), illustrating that a isotopic depletion occurred during the phase-change processes of snow-ice, ablation, evaporation, flowing of meltwater in glacier's interior and along the glacier's bed.

4.3 Variation of $\delta^{18}O$ in glacier feeding stream

From the head of glacier-feeding river (Baishui) at 3250 m to Yunshanping (the valley's end) at 3150 m, samples for $\delta^{18}O$ analysis were collected in different sections of the stream. The average values show that there is a little difference between the southern and northern branches of the Baishui River (Table 2) above their junction at 3200 m. From the main stream after the two branches joined, the isotopic compositions have gradually increased from the mean value of − 16.09 ‰ at the junction to − 12.25 ‰ at Yunshanping (the end of river valley), suggesting a refractionation of stable isotope has happened during the course of flowing, percolation, evaporation and contact with the river bed from uppersteam to downstream. Looking at the total average, the mean value of Baishui River (− 14.69 ‰) is just between the mean value of glacial meltwater (− 13.62 ‰) and the mean value of summer rain (− 16.10 ‰), illustrating that the river water was a mixture of glacial meltwater and summer precipitation. Of course, some ground water may also feed to the river, the proportion of the three feeding sources needs further sampling and analysis to calculate. Above results suggest that the variation of stable isotope in a runoff not only can reflect its own spatial and temporal changes but also can identify different feeding sources to it.

5 Conclusions

(1) There is an evident negative correlation between stable isotopic composition and air temperature and precipitation amount, showing a strong "precipitation amount effect", in the typical monsoon temperate-glacier region, Mt. Yulong. These particular relationship and effect have been confirmed by two-year's systematic sampling and isotopic analysis in different glacial-hydro mediums. According to this relation, it is inferred that there exists a highest precipitation zone between 4600 m and 4700 m.

(2) There are marked differences of the stable isotopic composition between winter accumulated snow, glacial meltwater, summer precipitation and glacier-feeding stream, and the stable isotope is one of best quantitative indexes to identify the different glacial-hydro mediums and precipitation sources.

(3) Under the control of varied climatic conditions, isotopic and ionic contents of snow, summer rain, meltwater and glacial runoff show obvious spatial and temporal variations. Isotopic depletion or fractionation and ionic variation had occurred during the phase-change and transformation processes of snow-ice, ice-meltwater, flowing of runoff and contact with bedrock.

(4) The variation of stable isotope in a runoff not only can reflect its own spatial and temporal changes but also can identify different feeding sources to it.

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