

# Glacier meltwater runoff process analysis using $\delta D$ and $\delta^{18}O$ isotope and chemistry at the remote Laohugou glacier basin in western Qilian Mountains, China

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**Abstract:** Stable hydrogen and oxygen isotope has important implication on water and moisture transportation tracing research. Based on stable hydrogen ( $\delta D$ ) and oxygen ( $\delta^{18}O$ ) isotope using a Picarro L1102-i and water chemistry (e.g. major ions, pH, EC and TDS) measurement, this study discussed the temporal variation and characteristics of stable hydrogen and oxygen isotope, chemistry (e.g. TDS, pH, EC,  $Ca^{2+}$ ,  $Mg^{2+}$ ,  $Na^+$  and  $Cl^-$ ) in various water bodies including glacier meltwater runoff, ice and snow, and precipitation at the Laohugou glacier basin during June 2012 to September 2013. Results showed that  $\delta D$  and  $\delta^{18}O$  in the meltwater runoff varied obviously with the temporal change from June to September, showing firstly increasing trend and then decreasing trend, with the highest values in July with high air temperature and strong glacier melting, which could indicate the temporal change of glacier melting process and extent. Variations of  $\delta D$  and  $\delta^{18}O$  in the runoff were similar with that of snow and ice on the glacier, and the values were also above the GMWL, which probably implied that the glacier runoff was mainly originated from glacier melting and precipitation supply. The glacier meltwater chemical type at the Laohugou glacier basin were mainly composed by  $Ca-Na-HCO_3-SO_4$  and  $Ca-Mg-HCO_3-SO_4$ , which also varied evidently with the glacier melting process in summer. By analyzing the temporal change of stable hydrogen and oxygen isotope and chemistry in the melting period, we find it is easy to separate the components of the snow and ice, atmospheric precipitation and melt-runoff in the river, which could reflect the change process of glacier melting during the melting period, and thus this work can contribute to the glacier runoff change study of large-scale region by stable isotope and geochemical method in future.

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**Keywords:** meltwater runoff; stable hydrogen and oxygen isotope; chemistry; runoff process

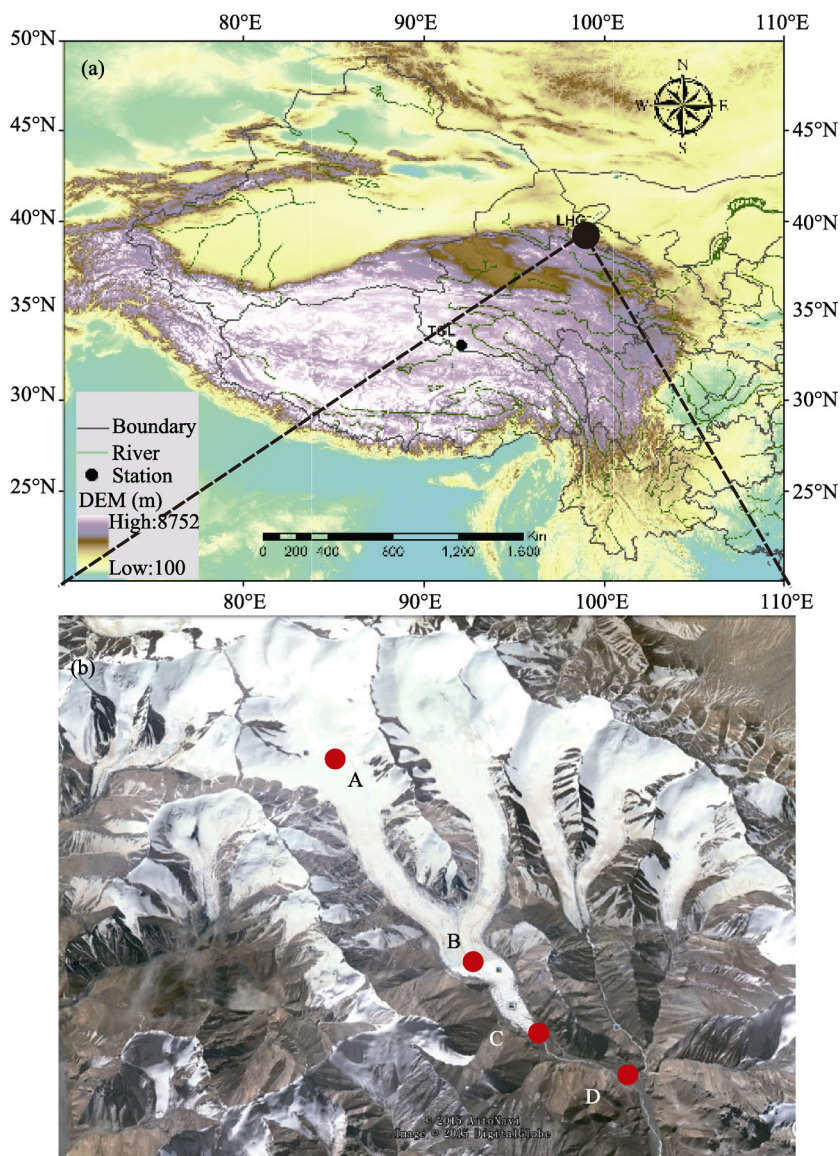
## 1 Introduction

Isotope hydrograph separation is often used for analyzing possible source area contributions to the meltwater stream runoff (Hooper *et al.*, 1990; Hooper, 2003). The method involves graphical analysis in which chemical and isotopic parameters are used to represent the designated end members. The isotopic ratios of oxygen and hydrogen ( $\delta^{18}\text{O}$  and  $\delta\text{D}$ , respectively) are powerful tools in studying climatic processes and environmental evolution because of their wide variations in different time and space scales (Aggarwal *et al.*, 2012; Hughes and Crawford, 2013; Chen *et al.*, 2006; Tian *et al.*, 2005). Their variabilities in natural archives of rainfall/snowfall are also valuable in hydrological studies (Kong and Pang, 2012). Much research has been carried out at alpine regions using stable isotopes as indicators of the processes involved in precipitation, the transformation of snow to ice, and runoff from glaciers and snow (Li *et al.*, 2015; Dansgaard, 1964; Theakstone, 2003; Chen *et al.*, 2015; Wu *et al.*, 2015). Hydrograph separation employing stable isotopes has been one of the effective methods used in small-scale catchment studies (Kong and Pang, 2012; Pu *et al.*, 2013; Michael *et al.*, 2009), particularly during rainfall or snowmelt events, to identify the contributions of different components to runoff and evaluate stream flow generation mechanisms.

Much study on stable isotopes of glaciers system has been carried out in alpine area around the world. However, little work has been done in the western Qilian Mountains, as the difficulties of continuous samples collection in the remote alpine glacier basin in northern Tibetan Plateau. The Laohugou (LHG) glacier basin ( $39^{\circ}20'\text{N}$ ,  $96^{\circ}34'\text{E}$ , with an altitude of 4200–5200 m a.s.l.) is located on the northeastern slope of the western Qilian Mountains. In order to explore the environmental significance of stable isotopes at the Laohugou glacier basin, a total of 149 samples were collected during June 2012 to September 2013, including atmospheric precipitation, glacier-snow meltwater, and meltwater runoff to explore the stable isotopes and chemical compositions of different water bodies during the glacier melting period, and the variation and characteristics of stable hydrogen and oxygen isotope, chemistry in the glacier meltwater, ice and snow, and precipitation at the Laohugou glacier basin were discussed, thus to find out the chemical composition change of various water bodies, and to reveal the relation between  $\delta^{18}\text{O}$  and  $\delta\text{D}$  variation and the glacier meltwater runoff change process during the melting period.

## 2 Sampling and laboratory analysis

The LHG Glacier basin (LHG,  $39^{\circ}25.09'\text{--}39^{\circ}32.25'\text{N}$ ,  $96^{\circ}25.37'\text{--}96^{\circ}36.44'\text{E}$ , with altitude of 4260–5010 m a.s.l.) is located in the northeast Tibetan Plateau, on the northern slope of the western Qilian Mountains with typical continental climatic conditions (Dong *et al.*, 2014a, 2014b). The Laohugou Glacier No.12 is the most typical glacier at the basin, with a length of 10 km and an area of  $20\text{ km}^2$ , and was divided into two branches at an altitude of 4560 m, providing a large amount of glacier meltwater runoff to the glacier basin in summer. During June and September in 2012 and 2013, in the glacier ablation period, we collected meltwater samples at the terminus (4260 m) of the LHG Glacier No. 12 (Figure 1), with a



**Figure 1** Map showing the location of sampling sites in the Laohugou glacier basin (a), and the sites of snow-pits (A), glacier ice (B), runoff at the terminus (C) and runoff 500 m away from the terminus (D) are shown on (b)

two-day frequency for each sample. Thus a total of 124 samples of meltwater runoff were acquired. In addition, we dugged one snow pit in the accumulation area (5040 m) of the Laohugou Glacier No. 12 in June, 2013, with a depth of 0.95 m, and totally 20 snow ice samples and 5 atmospheric precipitation samples were finally collected. Samples were kept frozen and transported in the condition of  $-18^{\circ}\text{C}$  until the laboratory measurement at the State Key Laboratory of Cryospheric Science, the Chinese Academy of Sciences (CAS).

$\delta\text{D}$  and  $\delta^{18}\text{O}$  were measured using Picarro L1102-i. Results are reported as relative to Vienna Standard Mean Ocean Water (VSMOW). Measurement precisions for  $\delta\text{D}$  and  $\delta^{18}\text{O}$  were better than 0.5 and 0.1‰, respectively. Cations are analyzed by a Dionex-600 Ion Chromatograph and anions with a Dionex-2500 Ion Chromatograph in the Cold and Arid

Region Environment and Engineering Research Institute, CAS. The analytical precision reaches  $10^{-9} \text{ g mL}^{-1}$  and the standard deviation is less than 5%. Moreover, the TDS, pH, and EC were also measured with the PHJS-4A and DDSJ-308A.

### 3 Results and discussion

#### 3.1 Characteristics and composition of stable isotope and chemistry in various water bodies

During the glacier ablation period of June to September in the years 2012 and 2013, we collected continuously the glacier meltwater runoff, snow and ice, and precipitation samples in the LHG basin, and stable isotope and chemistry were measured to find out the composition and difference of various water bodies at the remote alpine sites. The mean values and comparison of  $\delta^{18}\text{O}$  and  $\delta\text{D}$ , and various chemical species (e.g.  $\text{Mg}^{2+}$ ,  $\text{SO}_4^{2-}$ , and  $\text{Ca}^{2+}$ ) in the glacier meltwater runoff, snow and ice were shown in Table 1. We also analyzed the spatial variation of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in meltwater runoff at the terminus and another site of 500 m down the terminus of the glacier No.12 (see Table 1). The main objective for this work is to find out the stable isotope and chemical constituents change in the glacier meltwater runoff during the ablation period, and the samples in other water bodies (e.g. snow and ice in the glacier surface and snowpits, and precipitation in the glacier terminus at 4260 m) were used to provide comparison with that of the meltwater runoff (see Figure 1b). Result showed that, the highest value for  $\delta^{18}\text{O}$  was  $-8.87\text{‰}$ , and the lowest value of  $\delta^{18}\text{O}$  was  $-14.46\text{‰}$ , with a mean of  $-12.73\text{‰}$ ; while the highest value for  $\delta\text{D}$  was  $-65.96\text{‰}$ , and the lowest value of  $\delta\text{D}$  was  $-97.92\text{‰}$ , with a mean of  $-87.61\text{‰}$  (Table 1). Meanwhile, the water chemistry of the glacier meltwater runoff showing Ca-Na- $\text{HCO}_3$ - $\text{SO}_4$  type (at the glacier terminus) and Ca-Mg- $\text{HCO}_3$ - $\text{SO}_4$  type (500 m down the terminus) reflected a typical chemical type of water body in the dust source region of Central Asia (Dong *et al.*, 2014a, 2014b). In this work, the chemical composition of various water bodies showed large difference, as the snow pack and ice, and glacier meltwater runoff showed different chemical water types, which probably caused by the physical and chemical weathering and impacts during the glacier meltwater runoff formation and transport process. Large amount of local and regional chemical constituents may have been input to the meltwater, e.g. crustal dust, which may the

**Table 1** Comparison of chemistry of hydrogen and oxygen isotope ratio in the snow and ice, precipitation and runoff in the Laohuguo glacier basin

Sample sites	Elevation (m)	$\text{SO}_4^{2-}$ ( $\mu\text{g L}^{-1}$ )	$\text{Mg}^{2+}$ ( $\mu\text{g L}^{-1}$ )	$\text{Ca}^{2+}$ ( $\mu\text{g L}^{-1}$ )	$\text{HCO}_3^-$ ( $\mu\text{g L}^{-1}$ )	$\text{Na}^+$ ( $\mu\text{g L}^{-1}$ )	EC ( $\mu\text{S cm}^{-1}$ )	pH	TDS (mg $\text{L}^{-1}$ )	$\delta^{18}\text{O}$ (‰)	$\delta\text{D}$ (‰)	Chemical type
Snow and ice	4500–5010	2086.6	115.3	2580	2245.6	1044.1	12.2	5.6	21.3	-15.62	-93.7	Ca-Na- $\text{HCO}_3$ - $\text{SO}_4$
Terminus meltwater	4260	5023	2819.1	7313	4703	6910	135	7.39	61.4	-12.7	-87.61	Ca-Na- $\text{HCO}_3$ - $\text{SO}_4$
500 m down terminus	4200	12018	2832	6243.2	5011.5	1326	186.5	7.21	124.3	-13.5	-83.9	Ca-Mg- $\text{HCO}_3$ - $\text{SO}_4$

have affected the variation of chemical components and their concentrations. For example,  $\text{Mg}^{2+}$  concentration in snow and ice was much lower than that of glacier meltwater runoff at the terminus (4260 m), which reflected great influence of local crustal input to the meltwater runoff. Moreover, the pH, EC and TDS in various water bodies also presented obvious difference, which showed an increasing trend from high sites to lower sites in the water body, implying significant influence of various chemical species on the meltwater during the meltwater runoff formation process at the glacier basin, and this influence is closely related to the glacier melting extent.

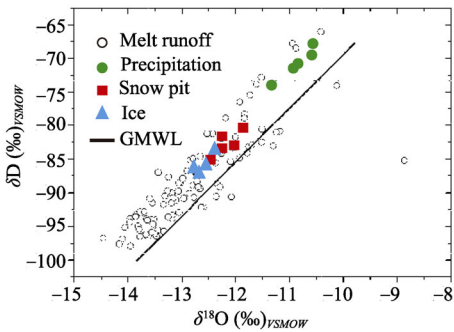
In the global atmospheric precipitation, the mean stable isotope of  $\delta\text{D}$  and  $\delta^{18}\text{O}$  was generally linear correlated, as the Global Meteorological Water Line (GMWL):  $\delta\text{D}=8\delta^{18}\text{O}+10\text{‰}$ . Because of the different climatic and geographic conditions in different regions, the GMWL showed different values for the slope and intercept parameters. The correlation between  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in various water bodies of the LHG glacier meltwater showed obvious difference with that of GMWL, and the meltwater runoff at 4260 m showed similar stable isotope result with that of snow and ice on the glacier (Figure 2). The  $\delta\text{D}$  and  $\delta^{18}\text{O}$  values in the meltwater runoff were distributed above the GMWL in Figure 2, thus we can infer that the supply of water in the LHG meltwater runoff was mainly originated from snow and ice ablation, and also from atmospheric precipitation. The precipitation stable isotope also distributed above the right side of the GMWL, which implied that the local environment influences  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in precipitation (Figure 2). Research of Clark and Fritz has indicated that, in summer of the arid and warmer region, the precipitation effect could cause a decreased slope and intercept of the local meteorological water line (LMWL) because of the evaporation process during raindrop fall in the atmosphere. Compared with the LMWL in the LHG basin, the slope and intercept of  $\delta\text{D}$  and  $\delta^{18}\text{O}$  correlation analysis line in the meltwater runoff showed decreased value, which may reflect: (i) obvious regional difference of LMWL, and the terminus meltwater runoff influenced by snow and ice input to the meltwater, and (ii) with the similar value of  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in meltwater and snow-ice, the meltwater runoff was largely originated from the snow and ice ablation contribution in the LHG glacier basin. However, in some samples the  $\delta\text{D}$  and  $\delta^{18}\text{O}$  values still showed lower than GMWL, which may be caused by the evaporation dynamics effect during meltwater runoff formation process. Heavy isotopes ( $\delta^{18}\text{O}$  and  $^2\text{H}$ ) in water vapor are depleted more easily than lighter isotopes ( $^{16}\text{O}$  and  $^1\text{H}$ ) as a result of rainfall from a mass of moist air during its long-distance transport. Therefore,  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in precipitation become more negative with increasing distance along the transportation path at the same time, parallel fractionation is destroyed owing to kinetic fractionation processes during water evaporation, resulting in differences in the relationship between  $\delta\text{D}$  and  $\delta^{18}\text{O}$  (Siegenthaler *et al.*, 1980). As shown in Figure 2, the relationship between  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in the meltwater runoff was as below:

$$\delta\text{D}=6.878\delta^{18}\text{O}-4.2\text{‰} \quad (R^2=0.7106, P<0.001) \quad (1)$$

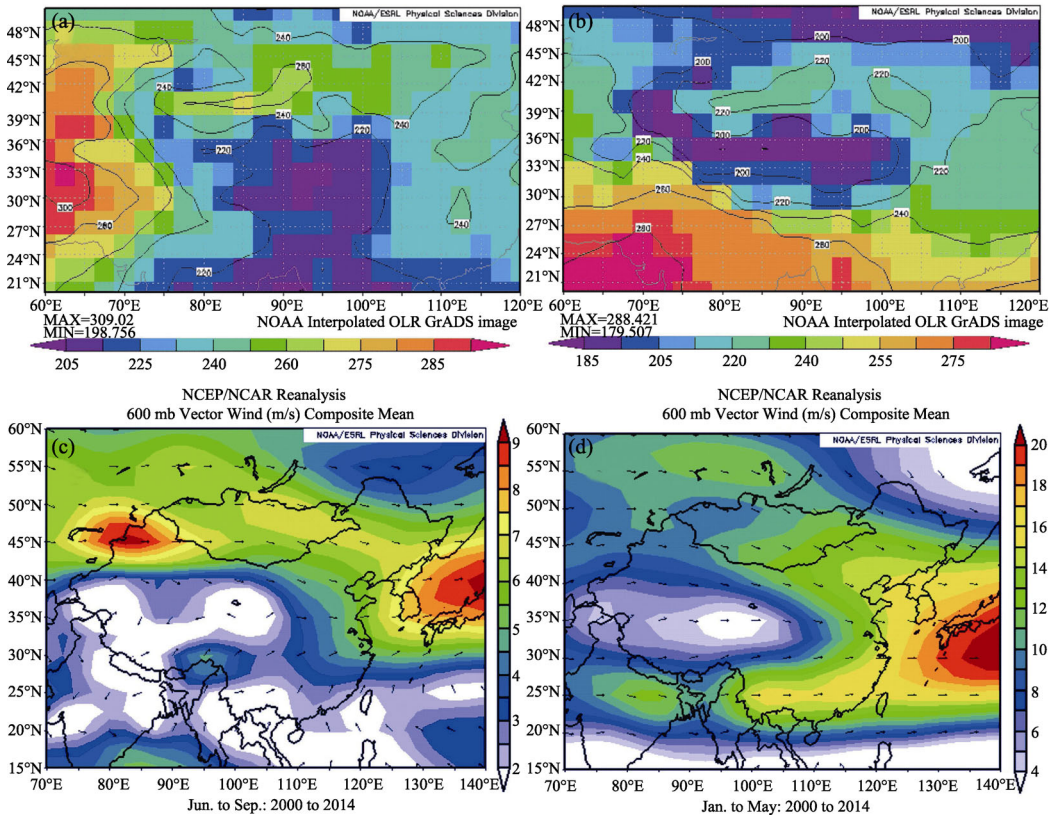
The change of  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in the water body at remote glacier basin was usually caused by the moisture source change and evaporation effect (Zhao *et al.*, 2011). In the study site of western Qilian Mountains, the temporal change of stable isotope in the meltwater runoff was probably also affected by those factors. Figure 3 showed the averaged Outgoing Long Wave radiation (ORL) and winds distribution (during 2000-2014) in the LHG basin and surrounding regions. Figure 3a and 3b respectively indicated ORL in summer (May-September) and



in winter-spring (October to April of the next year) in 2012–2013, based on the data from NOAA ([http://www.esrl.noaa.gov/psd/data/gridded/data.interp\\_OLR.html](http://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html)), reflecting the atmospheric vertical convection near the land surface caused by cold cloud at the high layers of the atmosphere in the study area (Gao *et al.*, 2013), thus it can be used to analyze the atmospheric vertical convection influence on water stable isotope in the LHG glacier basin of the western Qilian Mountains. Figure 3c showed the mean wind distribution at 600 hPa in the summer of 2000–2014, while Figure 3d showed that in winter-spring 2000–2014 based on the NCEP/NCAR reanalysis data (data from <http://www.esrl.noaa.gov/psd/data/>), which could reflect the atmospheric horizontal convection influence on the water stable isotope at the glacier basin. We find that, the LHG basin was significantly affected by stronger ORL in summer compared to the inland areas of the Tibetan Plateau regions (Figures 3a and 3b), which could influence the stable isotope change in the meltwater and other water body of the basin. Similarly, the ORL was also showing high value in



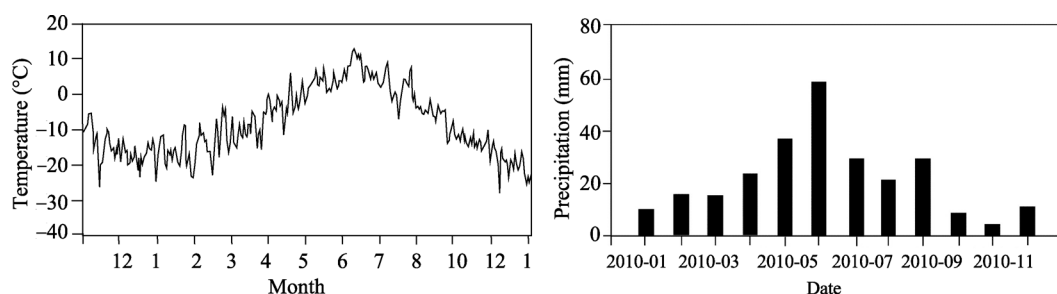
**Figure 2** Correlation analysis of hydrogen and oxygen isotope in the Laohugou basin, among which GMWL is  $\delta D = 8\delta^{18}O + 10\text{‰}$



**Figure 3** Averaged Outgoing Long Wave radiation (ORL) and winds distribution in the Laohugou and surrounding regions. (a) summer ORL; (b) winter and spring ORL; (c) wind distribution in summer 2000–2014; (d) wind distribution in winter and spring of 2000–2014

winter at the LHG basin. Such LHG atmospheric conditions may have caused the increased water isotopic fractionation, leading to the  $\delta D$  and  $\delta^{18}O$  change to large extent in the water body at the LHG glacier basin. However, as the meltwater was largely from the glacier ablation during the summer period, and samples were collected immediately at the terminus after the melting, the water isotopic fractionation effect of the meltwater may be weaker than that of the precipitation. The meltwater  $\delta D$  and  $\delta^{18}O$  value change could mainly reflect the condition of snow and ice, and the precipitation, and also their relative composition. The strong wind speed (Figure 3a and 3d) in the Tibetan Plateau and Qilian Mountains may have also caused the increased water isotopic fractionation effect at the LHG glacier basin in both summer (for various water bodies) and winter (just for snow accumulation).

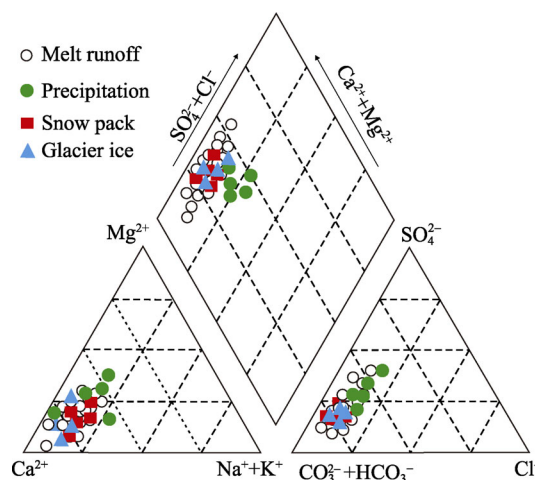
Precipitation and air temperature are also important meteorological conditions and parameters for stable isotope research. Air temperature and precipitation change in 2010–2011 at 4200 m sites measured by AWS in the LHG basin were shown in Figure 4. Reference has showed that (Cui *et al.*, 2011), the yearly mean air temperature at the LHG basin was above  $0^{\circ}C$ , with long winter and extreme low air temperature, and local atmospheric precipitation often occurred during May to September. Moreover, the moisture in this area was mainly originated from the westerly circulation. In summer, as there existed strong atmospheric vertical convection and large amount of precipitation, also with strong glacier ablation, and large amount of snowfall was deposited on the glacier accumulation zone. We can infer that the meltwater stable isotope composition in the glacier runoff was influenced by temporal change of air temperature and precipitation. Precipitation was also an important factor besides air temperature affecting the meltwater  $\delta D$  and  $\delta^{18}O$  during melting period. Precipitation showed firstly increasing trend and then decreasing trend during May to September (Figure 4), which was highly coincident with the change of air temperature during the ablation period. Moreover, the increased precipitation in July 2012–2013 also caused the increased supply to the meltwater runoff, contributing to the  $\delta D$  and  $\delta^{18}O$  value change and also to the runoff evolution process change at remote LHG site.



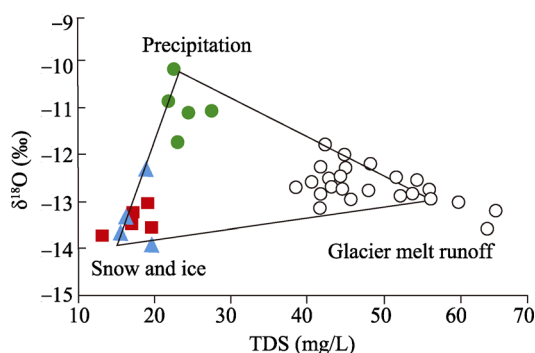
**Figure 4** Air temperature and precipitation change in the year 2010–2011 at 4200 m sites in the Laohugou basin

Stable hydrogen and oxygen isotope is important method for water and moisture transportation tracing research. The difference of meltwater runoff transport will lead to the different meltwater chemistry, and the chemical species concentration is affected by the erosion of meltwater runoff and crustal materials, e.g. moraine, cryoconite, and bedrock of the meltwater stream. Moreover, crustal dust from the glacier surface contributes both soluble and insoluble mineral particles to snowpack and meltwater, leading to differences in the fate

and transport of associated elements during snowmelt runoff (Bacardit and Camarero, 2010; Gaspari *et al.*, 2006). Figure 5 showed the relative composition of various chemical species in the LHG meltwater runoff, which is similar with the result of Table 1, reflecting the high coincidence of chemical characteristics between the meltwater and other water bodies such as precipitation, snow and ice. The water chemical composition showed a totally Ca-Mg-Na-HCO<sub>3</sub> style, in which Ca<sup>2+</sup> is the dominant cations in most of the samples, whereas SO<sub>4</sub><sup>2-</sup> is also dominant in some samples. Such a chemical composition of various water bodies well reflected the chemical characteristics of a remote glacier basin in the Qilian Mountains of the Central Asian region, where the atmospheric environment is significantly influenced by Asian dust source, often bringing plenty of dust particles to the glacier basin in alpine regions. This chemical composition may have influenced the  $\delta D$  and  $\delta^{18}O$  variability in various water bodies at the LHG glacier basin, as this change also affected by glacier melting process and extent change.



**Figure 5** Chemical compositions in the various kinds of water at the Laohugou glacier basin



**Figure 6** Stable hydrogen and oxygen isotope and TDS correlation analysis in various water sampling sites of the Laohugou basin

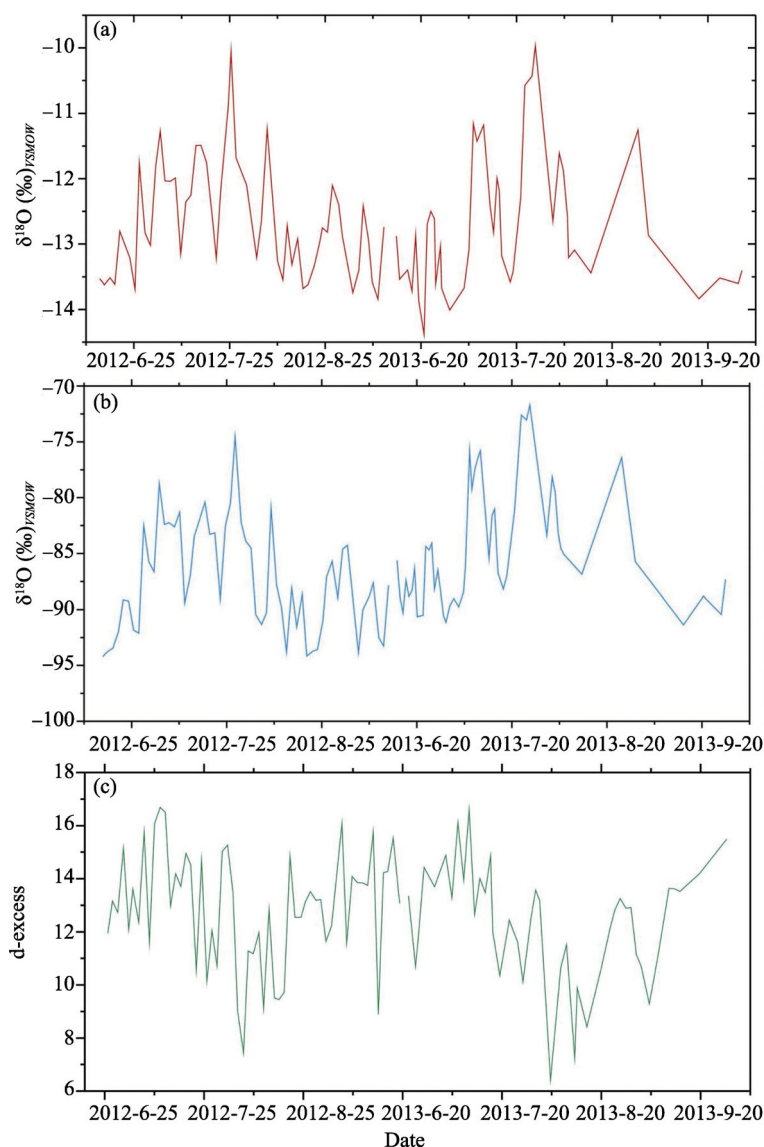
relatively stable  $\delta^{18}O$  variability. Such change of chemical composition also reflected the different phases of the meltwater runoff formation process, from snow and ice, precipitation, to the glacier meltwater runoff, with the sites elevations decreasing at the LHG glacier basin. Thus the stable  $\delta^{18}O$  and physio-chemistry of the water body could together reflect the glacier runoff change process in remote basin.

### 3.2 Temporal change of $\delta D$ and $\delta^{18}O$ in various water bodies during ablation period

We find obvious temporal (monthly) change of  $\delta D$  and  $\delta^{18}O$  in the glacier meltwater runoff at LHG basin in 2012–2013 (Figure 7). With the air temperature rise in June–July, the stable isotope value also showed obvious increasing trend, and the highest air temperature in July.

Figure 6 showed the correlation between  $\delta^{18}O$  and total dissolved solid (TDS) in various water bodies at the LHG glacier basin. Apparently, we can find out the difference of various water bodies by comparing their correlation. The TDS was larger in the meltwater runoff when compared with similar  $\delta^{18}O$  value in various water bodies, and the TDS value was lower in the snow and ice at the same period. Such difference was probably caused by the increase of TDS in the meltwater runoff during the meltwater runoff formation process with relatively





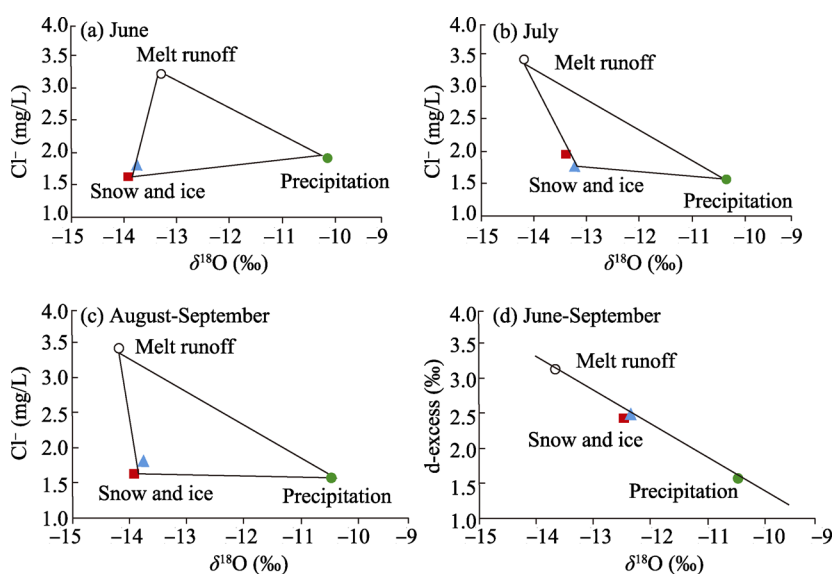
**Figure 7** Stable hydrogen and oxygen isotope variation with glacier melting in the summer 2012–2013

As the air temperature began to decrease in the mid-August, the  $\delta\text{D}$  and  $\delta^{18}\text{O}$  values also showed significant decreasing trend. Such an obvious monthly change of water stable isotope value indicated the dominant influence of summer air temperature to the meltwater stable isotope in the LHG glacier basin. Previous study has reported such phenomena in the glacier basin. For example, the  $\delta^{18}\text{O}$  record in the precipitation and ice cores of the northern Tibetan Plateau showed the dominant influence of air temperature on the  $\delta^{18}\text{O}$  value in temporal (annual and seasonal) and spatial variation, and the significantly high correlation between  $\delta^{18}\text{O}$  value and air temperature. Observed air temperature by a AWS at the LHG snowpack (with an elevation of 5040 m) also showed good correlation with  $\delta^{18}\text{O}$  record in the snow pit, implying that the  $\delta^{18}\text{O}$  in snow and ice of this area could also reflect “temperature effect”. However, the evident monthly change of  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in the glacier melt-

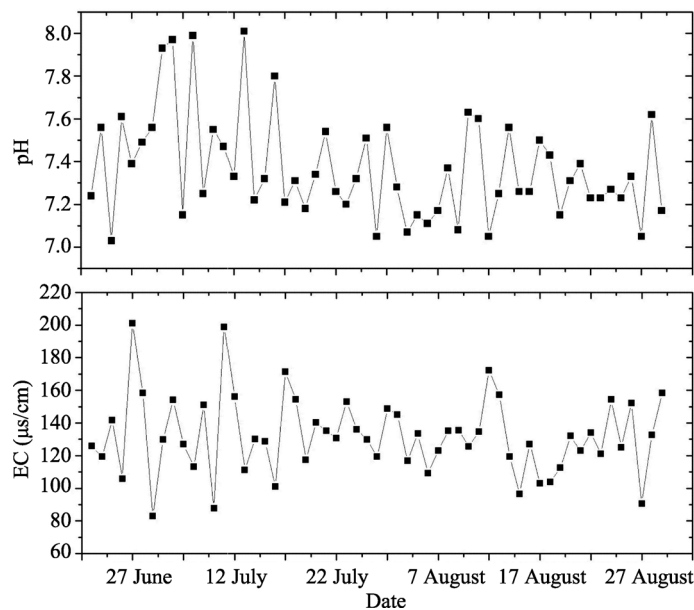
water runoff at remote LHG basin indicated stronger signals of climate influence on stable isotope in the western Qilian Mountains. Moreover, such temporal variability was also consistent with snow and ice melting extent during the ablation period, thus could reflect the glacier melting process during June to September.

The d-excess value in various water bodies (including precipitation and river water) is often correlated to the isotopic dynamic fractionation process of moisture during the evaporation occurred, which was mainly controlled by the relative humidity and air temperature of moisture source regions. The d-excess value in meltwater of the LHG glacier basin showed evidently reverse change trend with that of  $\delta D$  and  $\delta^{18}O$  during 2012–2013, showing decreasing trend in June–July but a sharp increasing trend in August–September. Such variability of d-excess was very consistent in the investigated two years, although with slight difference in values. We think the d-excess change was influenced by snow and ice melting, meltwater runoff, precipitation change, and the relative moisture in the glacier basin. The meltwater runoff process change could directly influence the d-excess,  $\delta D$  and  $\delta^{18}O$  change, thus reflecting the glacial, meteorological and hydrological change process at remote alpine basin (Figure 7).

Figure 8 showed the temporal variation of the correlation between stable oxygen isotope and  $Cl^-$  in the melt runoff of the Laohugou Glacier No.12, in which Figures 8a–8d respectively indicated the composition change of such correlation from June to September. The physical characteristics of meltwater (such as pH, EC, and TDS) also indicated higher value in July with the strongest glacier melting (see Figure 9 and Table 2). Moreover, the temporal change of SPM (suspended particulate matter) had well coincident with TDS in the LHG glacier basin (Dong *et al.*, 2014a). We find that, the temporal change of various chemical species, especially crustal species, e.g.  $Ca^{2+}$ ,  $Na^+$ ,  $Mg^{2+}$ ,  $K^+$  and  $Cl^-$  showed good correlation with that of dust particles in meltwater runoff during June to September in 2012–2013 (Table 2), which was probably caused by the glacier melting process. From the above analysis, we



**Figure 8** Temporal variation of the correlation between stable oxygen isotope and  $Cl^-$  in the runoff of the Laohugou Glacier No.12



**Figure 9** pH and EC variations in the glacier meltwater of the Laohugou glacier basin in summer 2012

**Table 2** Chemistry variation with month change in the glacier meltwater runoff in 2013

Sample	Time	Sample number (n)	$\text{SO}_4^{2-}$ ( $\mu\text{g L}^{-1}$ )	$\text{Mg}^{2+}$ ( $\mu\text{g L}^{-1}$ )	$\text{Ca}^{2+}$ ( $\mu\text{g L}^{-1}$ )	$\text{Cl}^-$ ( $\mu\text{g L}^{-1}$ )	$\text{Na}$ ( $\mu\text{g L}^{-1}$ )	$\text{EC}$ ( $\mu\text{s cm}^{-1}$ )	pH	TDS ( $\text{mg L}^{-1}$ )
Melt runoff	June	11	2015.3	982	3214	291	1215	79	7.21	32.1
	July	23	5579	2321	4329	113	2145	146	7.32	86.2
	August	28	3298.6	3176	3876	342	1137	133	7.43	65.4
	September	12	1126.8	874	2569	98	673	65	7.10	43.9

can infer that the  $\delta\text{D}$ ,  $\delta^{18}\text{O}$  and chemical species relative composition (e.g. TDS, pH, EC,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ , and  $\text{Cl}^-$ ) in various water bodies of the LHG glacier basin could reflect the different characteristics of the snow and ice, meltwater stream, and precipitation, and could also reflect the glacier meltwater runoff change process (Figures 8 and 9).

**4 Conclusions**

Stable hydrogen and oxygen isotope has important implication on water and moisture transportation tracing research, and much work has been done on isotope hydrograph separation for glacier regions around the world. However, little study on stable isotope of glaciers system has been carried out in the western Qilian Mountains of the northeast Tibetan Plateau. Based on hydrogen and oxygen isotope and water chemistry (e.g. major ions, pH, EC, and TDS) measurement during the ablation period, this study discussed the variation and characteristics of stable hydrogen and oxygen isotope, chemistry (e.g. TDS, pH, EC,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ , and  $\text{Cl}^-$ ) in the glacier meltwater, ice and snow, and precipitation at the Laohugou glacier basin. Results showed that,  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in the glacier meltwater varied obviously with

the temporal change from June to September, with firstly increasing trend and then decreasing trend, showing the highest value in July with the highest air temperature and strong glacier melting, which could indicate the temporal change of glacier melting process and extent.  $\delta\text{D}$  and  $\delta^{18}\text{O}$  value in the meltwater were similar with that of snow and ice on the glacier, and were also above the LMWL, which probably implied that the glacier runoff was mainly originated from glacier melting and precipitation supply. The glacier meltwater type of the Laohugou glacier basin were mainly composed by  $\text{Ca-Na-HCO}_3\text{-SO}_4$  and  $\text{Ca-Mg-HCO}_3\text{-SO}_4$ , which also varied with the glacier melting process in summer.

Through analyzing temporal and spatial change of stable hydrogen and oxygen isotope and chemistry in the melting period, we find it is easy to separate each component of water body, e.g. the snow and ice and melt-runoff in the river, which could reflect the change process of glacier melting during the melting period. The  $\delta\text{D}$ ,  $\delta^{18}\text{O}$  and chemical composition in various water bodies of the LHG glacier basin could reflect the different characteristics of the snow and ice, meltwater stream, and precipitation, and could also reflect the glacier meltwater runoff change process. Thus this work can contribute to the glacier runoff change study of large-scale region by stable isotope and geochemical method in future.

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## References

- Aravena R, Suzuki O, Pena H *et al.*, 1999. Isotopic composition and origin of the precipitation in Northern Chile. *Appl. Geochem.*, 14: 411–422.
- Bacardit M, Camarero L, 2010. Atmospherically deposited major and trace elements in the winter snowpack along a gradient of altitude in the Central Pyrenees: The seasonal record of long-range fluxes over SW Europe. *Atmos. Environ.*, 44: 582–595.
- Burns D, 2002. Storm flow-hydrograph separation based on isotopes: The thrill is gone-what's next? *Hydrological Process*, 16: 1515–1517.
- Chen H, Li Z Q, Wang P Y *et al.*, 2015. Five decades of glacier changes in the Hulugou Basin of central Qilian Mountains, Northwest China. *Journal of Arid Land*, 7(2): 159–165.
- Chen Z Y, Nie Z L, Zhang G H *et al.*, 2006. Environmental isotopic study on the recharge and residence time of groundwater in the Heihe River Basin, northwestern China. *Hydrogeol J.*, 14: 1635–1651.
- Dong Zhiwen, Qin Dahe, Chen Jizu *et al.*, 2014a. Physicochemical impacts of dust particles on alpine glacier melt water at the Laohugou glacier basin in western Qilian Mountains, China. *Sci. Total Environ.*, 493: 930–942.
- Dong Zhiwen, Qin Dahe, Kang Shichang *et al.*, 2014b. Physicochemical characteristics and sources of atmospheric dust deposition in snow packs on the glaciers of western Qilian Mountains, China. *Tellus B*, 66: 20956. <http://dx.doi.org/10.3402/tellusb.v66.20956>.
- Dansgaard W. Stable isotopes in precipitation. *Tellus*, 1964, 14: 436–468.
- Gammons C H, Poulson S R, Pellicori D A *et al.*, 2006. The hydrogen and oxygen isotopic composition of precipitation, evaporated mine water, and river water in Montana, USA. *Journal of Hydrology*, 328: 319–330.
- Gao Jing, Valerie Masson-Delmotte, Yao Tandong *et al.*, 2013. What controls precipitation  $\delta^{18}\text{O}$  in the southern Tibetan Plateau at seasonal and intra-seasonal scales? A case study at Lhasa and Nyalam. *Tellus B*, 65: 21043. <http://dx.doi.org/10.3402/tellusb.v65i0.21043>.

- Gaspari V, Barbante C, Cozzi G *et al.*, 2006. Atmospheric iron fluxes over the last deglaciation: Climatic implications. *Geophys. Res. Lett.*, 33: L03704.
- Hou Dianjiong, Qin Xiang, Wu Jingkui *et al.*, 2012. Isotopic, chemical characteristics and transforming relationship between surface water and ground water in the Xiaochangma River basin. *Journal of Glaciology and Geocryology*, 34(3): 698–705. (in Chinese)
- Jouzel J, Merlivat L, 1984. Deuterium and oxygen-18 in precipitation: Modeling of the isotope effects during snow formation. *Journal Geophysical Research*, 89: 11749–11757.
- Kong Yanlong, Pang Zhonghe, 2012. Evaluating the sensitivity of glacier rivers to climate change based on hydrograph separation of discharge. *Journal of Hydrology*, 434: 121–129.
- Merlivat L, Jouzel J, 1979. Global climate interpretation of the deuterium-oxygen 18 relationship for precipitation. *Journal Geophysical Research*, 84: 5029–5033.
- Michael T Hren, Bodo Bookhagen, Peter M Blisniuk *et al.*, 2009.  $\delta^{18}\text{O}$  and  $\delta\text{D}$  of streamwaters across the Himalaya and Tibetan Plateau: Implications for moisture sources and paleoelevation reconstructions. *Earth and Planetary Science Letters*, 288: 20–32.
- Qin Xiang, Cui Xiaoqing, Du Wentao *et al.*, 2015. Variations of the alpine precipitation from an ice core record of the Laohugou glacier basin during 1960–2006 in western Qilian Mountains, China. *Journal of Geographical Sciences*, 25(2): 165–176.
- Rozanski K, Araguas-Araguas L, Gonfiantini R, 1993. Isotopic Pattern in Modern Global Precipitation. Washington: American Geophysical Union, 1–37.
- Siegenthaler U, Oeschger H, 1980. Correlation of  $\delta^{18}\text{O}$  in precipitation with temperature and altitudes. *Nature*, 285: 314–318.
- Tian L D, Yao T D, White J W C *et al.*, 2005. Westerly moisture transport to the middle of Himalayas revealed from the high deuterium excess. *Chinese Science Bulletin*, 50: 1026–1030.
- Tian Lide, Yao Tandong, Macclune K *et al.*, 2007. Stable isotopic variations in west China: A consideration of moisture sources. *Journal of Geophysical Research*, 112: D10112. doi: 10.1029/2006JD007718.
- Cui Xiaoqing, Ren Jiawen, Qin Xiang *et al.*, 2011. Oxalate, floride record and their environmental significance in Laohugou Glacier No. 12, Qilian Mountains. *Environmental Chemistry*, 30: 1919e1925. (in Chinese)
- Wang N L, Zhang S B, He J Q *et al.*, 2009. Tracing the major source area of the mountainous runoff generation of the Heihe River in northwest China using stable isotope technique. *Chinese Science Bulletin*, 54: 2751–2757.
- Wu H W, Li X Y, Li J *et al.*, 2015. Evaporative enrichment of stable isotopes ( $\delta^{18}\text{O}$  and  $\delta\text{D}$ ) in lake water and the relation to lake-level change of Lake Qinghai, Northeast Tibetan Plateau of China. *Journal of Arid Land*, 7(5): 623–635.
- Zhao Liangju, Yin Li, Xiao Honglang *et al.*, 2011. Isotopic evidence for the moisture origin and composition of surface runoff in the headwaters of the Heihe River basin. *Chinese Sciences Bulletin*, 56(4/5): 406–416. (in Chinese)
- Zhou S, Nakawo M, Hashimoto S *et al.*, 2007. The effect of refreezing on the isotopic fractionation of melting snowpack. *Hydrological Process*, 22(6): 873–882. doi: 10.1002/hyp.6662.