

# An overview of precipitation isotopes over the Extensive Hexi Region in NW China

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**Abstract** Until now, most studies of the isotopic composition of precipitation in the Extensive Hexi Region have described individual sites. A systematic study considering the regional atmospheric circulation, the complex topography, and the re-evaporation process is lacking. This paper compares and summarizes previous studies in the Extensive Hexi Region, to provide a regional picture of the characteristics of isotopic composition of precipitation and moisture sources.  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values exhibit significant seasonal variability, with higher values in summer and lower values in winter due to the seasonality of temperature and moisture sources. The temperature effect is more pronounced in the Extensive Hexi Region than in northwest China. The altitude effects are also evident with a gradient of  $-0.23\text{‰}/100\text{ m}$  for  $\delta^{18}\text{O}$  and  $-1.67\text{‰}/100\text{ m}$  for  $\delta\text{D}$ . But, the d-excess increases gradually with altitude, and the higher d-excess values occur at mountain sampling sites which are attributed to the difference of the secondary evaporation between mountains and plain. Finally, the moisture source in the study area was investigated, and the results show relatively complex patterns: the westerly and polar air masses dominate in winter; however, there are inconsistent results in summer. Whether or not the westerly air mass is the

dominant supply of moisture in summer is yet to be determined. Additionally, in the course of reviewing and integrating, some new research questions are identified for future work.

**Keywords** Extensive Hexi Corridor · Precipitation · Stable isotope · d-excess · Moisture sources

## Introduction

The Extensive Hexi Region refers to the Qilian Mountains, the Hexi Corridor, the Badain Jaran, and Tengger Deserts in NW China, which is one of the driest areas in the world. Due to its complex topography (corridor plain surrounded by mountains), the main water resource is precipitation and glacier snow melt water from the Qilian Mountains (Wang et al. 2008), where several major inland rivers originate. Oases in the middle and lower reaches and the regional irrigated agriculture rely on this water. Therefore, research on the characteristics of precipitation in this region is of great importance.

The isotopic composition of precipitation has become an effective tracer for exploring complex hydrologic systems (Dutton et al. 2005; Hren et al. 2009; Jeelani et al. 2013). It can improve our understanding of the processes associated with the sources of water and system dynamics and provide quantitative estimates related to flow dynamics and transport parameters (Naoki et al. 2007) and their potential impacts on eco-hydrologic systems (Zhang et al. 2007a, b; Ma et al. 2012). Recently, great efforts have been devoted to exploring the dynamics of precipitation in the Extensive Hexi Region based on stable isotope methods (Zhang and Wu 2007a, b, 2009; Wu et al. 2010; Zhao et al. 2011; Ma et al. 2012). These studies have supplied much useful information for understanding the characteristics of precipitation, such as the local meteoric water line (LMWL), the temperature effect,

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precipitation amount effect, the variability of stable isotope, and d-excess values. However, most studies were based on monthly mean isotope values in a hydrological year at individual sites, and a systematic study considering the regional atmospheric circulation, the complex topography, and the re-evaporation process is lacking. Therefore, a detailed investigation of the stable isotopes of precipitation in the Extensive Hexi Region is necessary.

Here, we review the published stable isotope data of precipitation in the Extensive Hexi Region, to provide an overview of the spatial and temporal variability of stable isotope composition, the temperature effect, and the characteristics of d-excess. The potential reasons for the temporal and spatial variations of isotopes are also discussed. We aim to establish a quantitative relationship between  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in precipitation and altitude effect based on annual mean stable isotope values in different sampling sites and to explore the origin of moisture for precipitation, which will provide some useful suggestions for future studies.

## Study areas

The Extensive Hexi Region covers the Qilian Mountains, the Hexi Corridor, the Badain Jaran, and the Tengger Desert to the northeast of Tibetan Plateau (Fig. 1). The Hexi Corridor (37° 17' N to 42° 18' N and 92° 23' E to 104° 12' E) belongs to the transition zone between the summer monsoon and westerly air masses (Wang et al. 2003) and is one of the sensitive regions to climate change. It is a long shallow valley which spans approximately  $2.15 \times 10^7 \text{ km}^2$  between the South Mountains (including Qilian and Aertjin Mountains) and the North Mountains (including Mazong, Heli, and Longshou Mountains). The study area is dominated by an arid continental climate, with an annual mean air temperature of 5–9 °C. The annual mean precipitation decreases from southeast to northwest, with 162 mm in Wuwei, 125 mm in Zhangye, and 86 mm in Jiuquan. Precipitation in the Qilian Mountains above 4,000 m a.s.l. is over 500 mm per year, which mostly falls between June and September each year (Li et al. 1999). The precipitation is dominantly in the form of snow in winter and rain in the rest of the seasons.

There are 2,859 glaciers in the Qilian Mountains with a total area of 1,972  $\text{km}^2$ , and the total water reserves are approximately to  $954 \times 10^8 \text{ m}^3$  (Wang 1981). Rainfall and melt water from high altitude provide major water resources for the Extensive Hexi Region. Based on topography, physiography, and hydrometeorological condition, the area can be divided into two main runoff zones, i.e., the Qilian Mountains runoff-forming zone and the Hexi Corridor runoff-consuming zone (Cheng and Qu 1992). The Shiyang, Heihe, and Shule Rivers flow from the Qilian Mountains to the desert in the north (Fig. 1) and are the three main water sources to the Hexi oases.

## Data sources and methods

The data for stable isotopes in precipitation (deuterium, oxygen-18) used for this paper are mainly derived from local sampling sites (Fig. 1) that have been published and the Global Network for Isotopes in Precipitation (GNIP) database (<http://isohis.iaea.org>). To investigate the spatial and temporal variability of the stable isotope composition, temperature effect, and d-excess of precipitation in the Extensive Hexi Region, we compiled the monthly mean data from the ten sites available and the annual mean data for oxygen isotopes from 31 sites and for hydrogen isotopes from 23 sites (Table 1). Most studies of stable isotopes in precipitation of the Hexi Corridor relied on data of samples from the Qilian Mountains. The relationships between  $\delta^{18}\text{O}$  and temperature at different sites are listed in Table 2. Moreover, the ArcGIS™ version 10.1 was employed to investigate the spatial distribution of  $\delta\text{D}$ ,  $\delta^{18}\text{O}$ , and d-excess values with the Kriging interpolation method. The SPSS version 19.0 software was used to conduct regression analysis.

The measured ratios of the stable oxygen and hydrogen isotopes in water are usually expressed in delta values, defined as the per mil deviation from the standard Vienna Standard Mean Ocean Water (VSMOW):

$$\delta = \left[ \frac{(R_{\text{sample}} - R_{\text{standard}})}{R_{\text{standard}}} \right] \times 1000$$

where  $R_{\text{sample}}$  and  $R_{\text{standard}}$  stand for the isotope ratios ( $^2\text{H}/^1\text{H}$  or  $^{18}\text{O}/^{16}\text{O}$ ) of the sample and the standard, respectively.

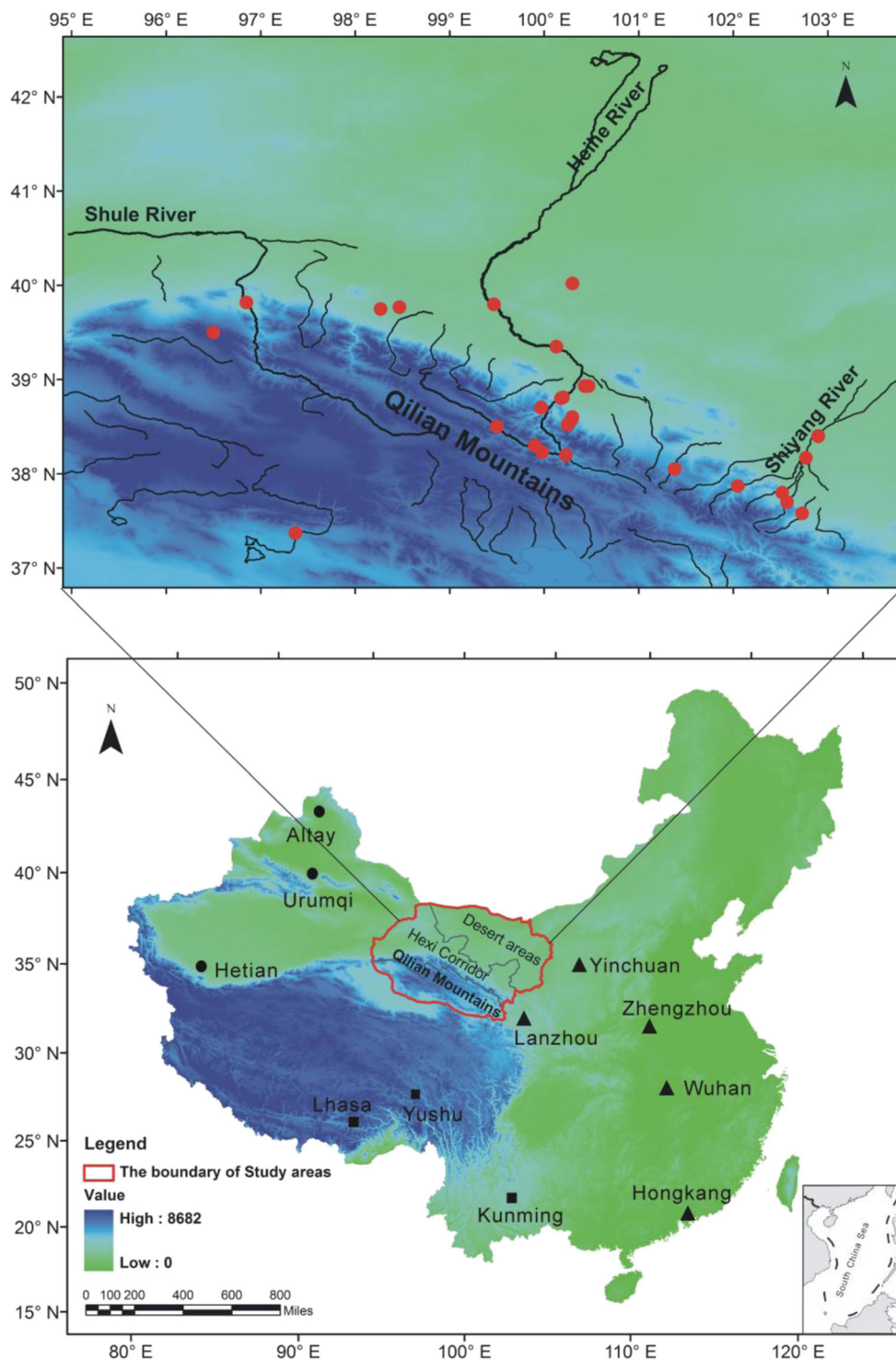
## Results and discussion

### Variation of $\delta^{18}\text{O}$ and $\delta\text{D}$ in precipitation

#### *Temporal variation of $\delta^{18}\text{O}$ and $\delta\text{D}$ in precipitation*

Variations in monthly average  $\delta^{18}\text{O}$  observed in all sites in the Extensive Hexi Region are shown in Fig. 2. They show a distinct seasonal variation with higher values in summer and lower values in winter (Fig. 2) at each site. The  $\delta^{18}\text{O}$  of precipitation in the mountain (Fig. 2a) and plain (Fig. 2b) stations showed similar seasonal variations. Integrated monthly average  $\delta^{18}\text{O}$  in the plain sites is slightly positive compared with the mountain region in the summer (Fig. 2c). Greater precipitation amount and lower temperature in the Qilian Mountains (more than 400 mm/yr, –25 to 22 °C) than the plain (200 mm/yr, –20 to 32 °C) may have caused such a difference. The local arid climate regime influences the stable isotope change in precipitation in both the mountains and the plain region. The elevated  $\delta^{18}\text{O}$  values in summer may result

**Fig. 1** Map showing the location of the study area (*lower panel*) and the topography of the study area (*upper panel*) with sites that have isotopic data (the *filled red circles*). The *filled black circles* refer to the sites in the westerly region, the *filled black squares* refer to the sites in the southwest monsoon region, and the *filled black deltas* refer to the sites in the southeast monsoon region



from significant re-evaporation of water in the local water cycle leading to isotope enrichment in summer rainfall.

Larger seasonal variation is observed in the Extensive Hexi Region than in the monthly average  $\delta^{18}\text{O}$  in the monsoonal region (Fig. 2d, e). In addition, the seasonality is opposite to both the eastern Asian monsoon region and the Indian monsoon region (called southwest monsoon in

China), where negative  $\delta^{18}\text{O}$  values are observed in the summer. During winter months (from October to April), the  $\delta^{18}\text{O}$  was depleted from southeast (Hong Kong) to northwest (Extensive Hexi Region), and higher values in summer months (from May to September) are seen in the northwestern region. The significantly depleted  $\delta^{18}\text{O}$  values in precipitation in winter are caused by the

**Table 1** The values of annual mean  $\delta^{18}\text{O}$ ,  $\delta\text{D}$ , and d-excess in precipitation and basic geographic information of each site over the Extensive Hexi Region (The numbers after some stations indicate different sampling sites in a common region by different researchers)

Station	Latitude ( $^{\circ}\text{N}$ )	Longitude ( $^{\circ}\text{E}$ )	Altitude (m)	$\delta^{18}\text{O}$ (‰)	$\delta\text{D}$ (‰)	d-excess (‰)	Observation period	Reference
Huangyang	37.58	102.73	2070	-7.29	-45.49	12.83	2008.1–2009.12	He 2011
Zamashi1	37.70	102.57	2010	-9.20	-57.59	16.01	2008.1–2009.12	He 2011
Jiutiaoling	37.87	102.05	2269	-8.01	-53.24	10.84	2008.1–2008.11	He 2011
Xidahe	38.05	101.38	2870	-10.78	-69.57	16.67	2008.1–2009.12	He 2011
Hongshuihe	38.17	102.77	1453	-8.74	-56.34	13.58	2008.1–2009.12	He 2011
Jiayuguan	39.75	98.27	1697	-3.17	-22.73	2.61	2007.12–2009.11	He 2011
Qilian1	38.2	100.23	2787	-6.65	-35.42	17.81	2009.5–2010.6	He 2011
Yingluoxia1	38.80	100.18	1674	-6.00	-38.40	9.59	2007.7–2009.10	He 2011
Langxinshan	40.02	100.3	1061	-5.82	-36.27	10.27	2008	He 2011
Dayekou	38.52	100.25	2600	-6.86	-37.81	17.04	2008.8–2009.9	He 2011
Changma	39.82	96.85	2112	-6.63	-41.86	11.14	2007.11–2009.10	He 2011
Nanying	37.80	102.52	1841	-7.42	-53.67	5.69	2008.11–2009.9	Ma et al. 2012
Hongya	38.40	102.90	1424	-6.78	–	–	2008.11–2009.9	Ma et al. 2012
Yingluoxia2	38.80	100.18	1674	-4.90	–	–	2006.5–2007.5	Wang et al. 2008
Qilian2	38.20	100.23	2590	-5.00	–	–	2006.5–2007.5	Wang et al. 2008
Zamashi2	38.23	99.98	2635	-5.84	–	–	2006.5–2007.5	Wang et al. 2008
Yeniugou	38.70	99.97	3320	-6.20	-35.02	14.58	2006.5–2007.5	Wang et al. 2008
Up basin of Heihe River 1	38.50	99.50	3320	-6.80	-39.30	15.10	2008/6~2009/9	Zhao et al. 2011
Up basin of Heihe River 2	38.60	100.30	2335	-11.60	-78.10	14.70	2008/8~2009/7	Zhao et al. 2011
Up basin of Heihe River 3	38.30	99.90	3040	-6.50	-36.00	16.00	2009/7~9	Zhao et al. 2011
Xishui	38.57	100.29	2569	-9.20	-58.70	14.90	2002.10–2003.9	Wu et al. 2010
Yingluoxia3	38.81	100.20	1698	-6.50	-42.80	9.20	2002.10–2003.9	Wu et al. 2010
Ganzhou	38.93	100.47	1526	-5.70	-34.80	10.80	2002.10–2003.9	Wu et al. 2010
Pingchuan	39.35	100.13	1382	-4.40	-27.40	7.80	2002.10–2003.9	Wu et al. 2010
Zhengyixia	39.8	99.47	1276	-2.20	–	–	2002.10–2003.9	Wu et al. 2010
Jiuquan	39.77	98.47	1480	-11.30	-82.00	8.40	2002.10–2003.9	Wu et al. 2010
Laohugou	39.50	96.50	4200	-21.60	-156.07	16.73	2009.1–2010.12	Hou 2011
Zhangye	38.93	100.43	1483	-5.97	-41.71	6.05	1986–2001	GNIP
Tuotuohe	34.22	96.43	4533	-11.85	–	–	1992–2005	Yao et al. 2009
Delingha	37.37	97.37	2982	-7.67	–	–	1992–2005	Yao et al. 2009
Xining	36.62	101.77	2261	-5.56	–	–	1991–1992	Zhang et al. 1995

GNIP Global Network for Isotopes in Precipitation

temperature variation from southern to northern China. Studies from Yamanaka et al. (2007) have recognized that  $\delta^{18}\text{O}$  in precipitation of southeast China in summer is lowered by the amount effect due to the strong monsoon activity. Positive  $\delta^{18}\text{O}$  values from the Extensive Hexi Region in the summer may be attributed to the inland local recycled moisture that forms the regional precipitation (Liu et al. 2008a, b, c). Additionally, the relative humidity is low in arid regions like the Extensive Hexi Region, and the rain experiences strong evaporation before reaching the ground, enriching the  $\delta^{18}\text{O}$  in precipitation. In contrast to the monsoonal region, the seasonal trend of  $\delta^{18}\text{O}$  in precipitation in the westerly

region exhibits almost the same variation as the Extensive Hexi Region. Although the  $\delta^{18}\text{O}$  in the Extensive Hexi Region is higher than Urumqi and Altay and lower than Hetian in summer months, almost no difference in the  $\delta^{18}\text{O}$  in winter is observed, indicating that the moisture of the Urumqi, Altay, Hetian, and Extensive Hexi Region may come from the same source in winter months. However, the  $\delta^{18}\text{O}$  in Hetian and Extensive Hexi Region is different from Urumqi and Altay in summer months, suggesting that the moisture source of precipitation in northwest China is not completely consistent. Because the Extensive Hexi Region belongs to a transitional area between the

**Table 2** The relationship of  $\delta^{18}\text{O}$ –T in the Extensive Hexi Region

Study areas	The $\delta^{18}\text{O}$ –T equation(‰)	Correlation coefficient	Study periods	Data sources
Northwest China	$\delta^{18}\text{O}=0.31\text{T}(\text{°C})-12.69$	$R^2=0.45$	2005.1–2005.12	Liu et al. 2008a, b, c
UP basin of Heihe River	$\delta^{18}\text{O}=0.44\text{T}(\text{°C})-10.7640$	$R^2=0.53$	2000.8–2001.8	Zhang et al. 2007a
Qilian	$\delta^{18}\text{O}=0.55\text{T}(\text{°C})-9.7102$	$R^2=0.50$	2006.6–2007.5	Wang et al. 2008
Zamashi	$\delta^{18}\text{O}=0.57\text{T}(\text{°C})-12.331$	$R^2=0.53$	2006.6–2007.5	Wang et al. 2008
Xishui	$\delta^{18}\text{O}=0.91\text{T}(\text{°C})-16.64$	$R^2=0.93$	2002.10–2003.9	Wu et al. 2010
Yingluoxia	$\delta^{18}\text{O}=0.76\text{T}(\text{°C})-18.87$	$R^2=0.91$	2002.10–2003.9	Wu et al. 2010
Zhengyixia	$\delta^{18}\text{O}=0.58\text{T}(\text{°C})-16.97$	$R^2=0.89$	2002.10–2003.9	Wu et al. 2010
Zhangye	$\delta^{18}\text{O}=0.51\text{T}(\text{°C})-16.97$	$R^2=0.89$	1986–2001	GNIP
Jiutiaoling	$\delta^{18}\text{O}=0.59\text{T}(\text{°C})-11.88$	$R^2=0.63$	2008.11–2009.9	Ma et al. 2012
Nanying	$\delta^{18}\text{O}=0.58\text{T}(\text{°C})-13.79$	$R^2=0.67$	2008.11–2009.9	Ma et al. 2012
Hongya	$\delta^{18}\text{O}=0.65\text{T}(\text{°C})-11.77$	$R^2=0.67$	2008.11–2009.9	Ma et al. 2012
Shiyang River Basin	$\delta^{18}\text{O}=0.59\text{T}(\text{°C})-12.6$	$R^2=0.67$	2008.11–2009.9	Ma et al. 2012
Tuotuohe	$\delta^{18}\text{O}=0.57\text{T}(\text{°C})-14.27$	$R^2=0.57$	1991–1999	Tian et al. 2003
Delingha	$\delta^{18}\text{O}=0.66\text{T}(\text{°C})-13.45$	$R^2=0.78$	1991–1999	Tian et al. 2003
Xining	$\delta^{18}\text{O}=0.29\text{T}(\text{°C})-8.52$	$R^2=0.14$	1991.9–1992.12	Zhang et al. 1995

GNIP Global Network for Isotopes in Precipitation

summer monsoon and the westerly air mass, the summer monsoon can produce precipitation there, but Urumqi and Altay are completely controlled by the westerly air masses in summer.

Hydrogen isotopes in precipitation have received little attention. Only Zhao et al. (2011) noted that the seasonal trend of  $\delta\text{D}$  in precipitation is almost consistent with trends on  $\delta^{18}\text{O}$  in the upper reaches of the Heihe River which is an important place in the Extensive Hexi Region. The  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in Zhangye (located in the Heihe Basin) have been monitored by GNIP since 1986, and the  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in precipitation displayed similar seasonal variations. Simultaneously, the  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in precipitation show a positive linear correlation (Fig. 5). Therefore, the  $\delta\text{D}$  and  $\delta^{18}\text{O}$  display a synergistic variation, with higher values in summer and lower values in winter.

#### Spatial distribution of $\delta^{18}\text{O}$ and $\delta\text{D}$ in precipitation

The values of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in precipitation in the Extensive Hexi Region are more positive than in other regions in China due to the influence of the inland water vapor cycle (Araguás-Araguás et al. 1998; Liu et al. 2008a). The spatial distribution of the annual mean  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values is shown in Table 1 and Fig. 3. The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  exhibit differences among various locations. The  $\delta^{18}\text{O}$  values in the Extensive Hexi Region varied from  $-21.6$  ‰ (Laohugou) to  $-2.2$  ‰ (Zhengyixia), and the  $\delta\text{D}$  values varied from  $-156.07$  ‰ to  $-22.03$  ‰, with the mean values of  $-7.49$  ‰ and  $-51.32$  ‰, respectively. The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in precipitation, shown in Fig. 3, reflect significant spatial variability. Higher values appear in the Heihe River Basin compared with other regions

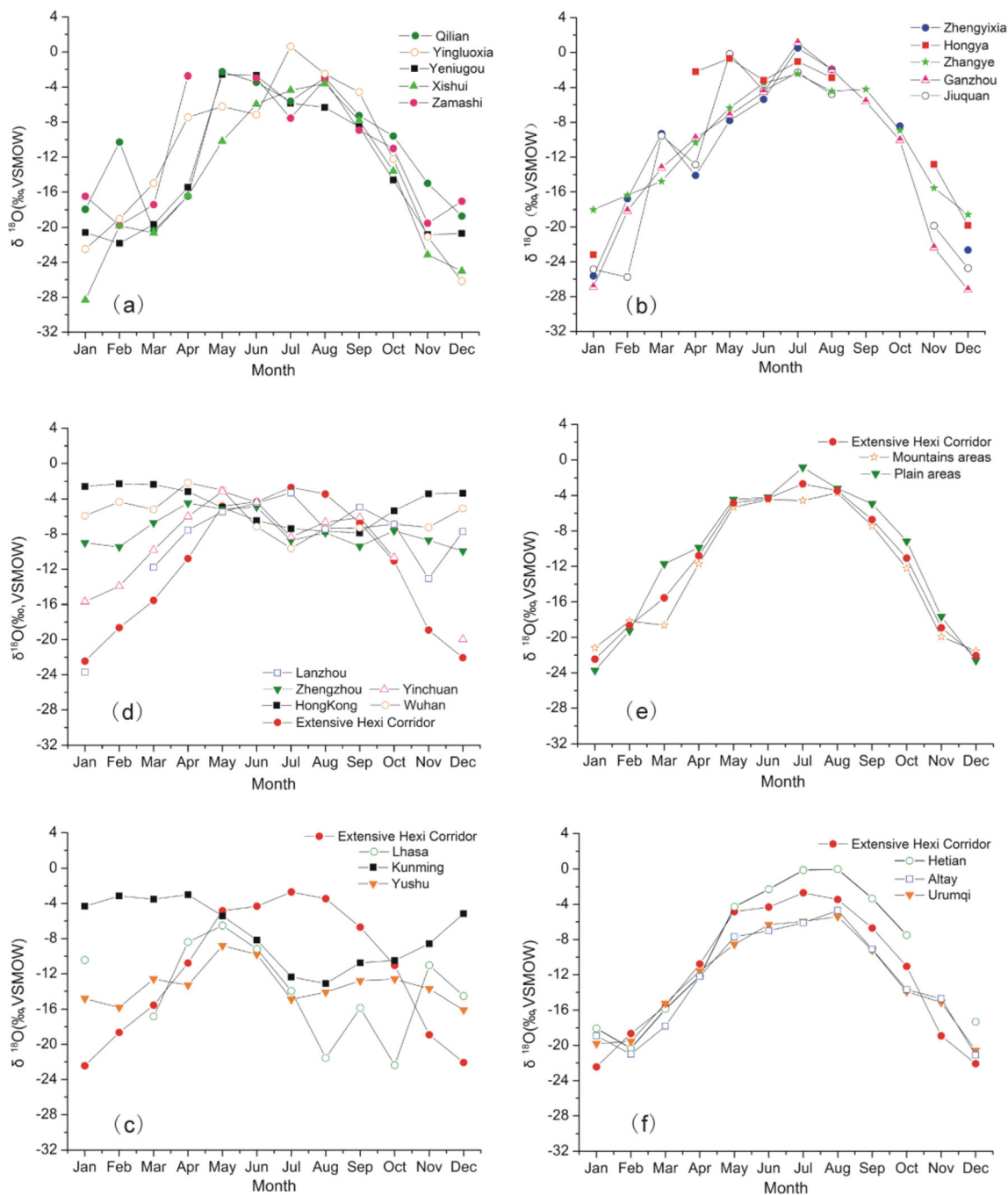
in the study area. Moreover, the values of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in the plain (the middle or lower reaches of rivers) were higher than in the Qilian Mountains. Tian et al. (2007) suggested that the recycled moisture is strong influence on seasonal isotope patterns in the extensive arid area of northwest China.

The change of isotope composition in precipitation with elevation, widely known as and hereby referred to as the altitude effect (Dansgaard 1964; Clark and Fritz 1997), was also determined in the Extensive Hexi Region based on the annual mean  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values from previous work. The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  are more positive in low altitude regions and gradually decrease with increasing altitude. The relationship can be described by the equations:

$$\delta^{18}\text{O} = -0.0023 * \text{Alt} - 2.2354 \quad ,n = 31 \quad (\text{Fig. 4a})$$

$$\delta^{18}\text{O} = -0.0167 * \text{Alt} - 14.345 \quad ,n = 23 \quad (\text{Fig. 4b})$$

The  $\delta^{18}\text{O}$ –altitude gradient is  $-0.23$  ‰/100 m, the  $\delta\text{D}$  depletion with altitude is  $-1.67$  ‰/100 m (Fig. 4b). The results show significant altitude control on the  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in precipitation across the study area. The altitude effect in precipitation is basically a temperature-dependent phenomenon and is explained on the basis of adiabatic cooling-related rainout processes. The obtained vertical isotope gradients among the other investigations vary between  $-0.15$  ‰/100 m and  $-0.5$  ‰/100 m for  $\delta^{18}\text{O}$  and vary from  $-1.0$  ‰/100 m to  $-4.0$  ‰/100 m for  $\delta\text{D}$  (Holdsworth et al. 1991; Clark and Fritz 1997). The  $\delta^{18}\text{O}$ –altitude gradient in the Extensive Hexi Region is similar to the results of  $-0.20$  ‰/100 m from Zhang and Wu (2007a) and  $-0.18$  ‰/100 m from Wang et al. (2009) in the Heihe River Basin. However, it was lower



**Fig. 2** Variability of  $\delta^{18}\text{O}$  in precipitation of the Extensive Hexi Corridor. **a, b** Variation of  $\delta^{18}\text{O}$  in the mountains and plain stations in the Extensive Hexi Corridor. **c** Comparison of the monthly weighted average  $\delta^{18}\text{O}$  variation in mountain area, plain area, and the Extensive Hexi Corridor. **d, e,** and **f** show the difference between the monthly weighted average

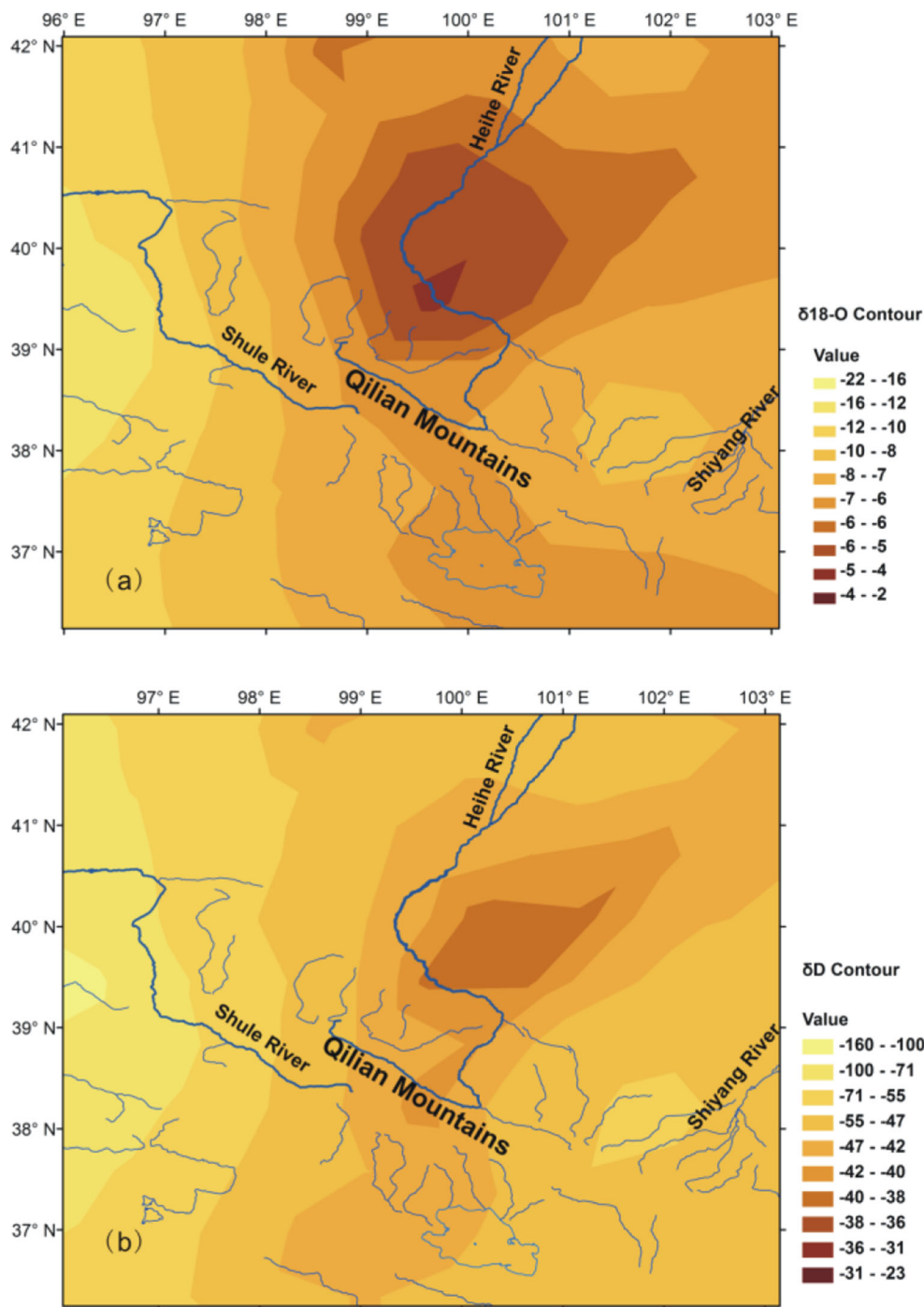
$\delta^{18}\text{O}$  variation in the Extensive Hexi Corridor and southeast monsoon region, the southwest monsoon region, and the westerly region (the monthly isotopic data of Qilian and Zamashi from Wang et al. (2009), Yingluoxia and Xishui from Wu et al. (2010), and Yeniugou from Zhao et al. (2011)). The location of those stations has been marked in Fig. 1

than the  $\delta^{18}\text{O}$ –altitude gradient of  $-0.47\text{‰}/100\text{ m}$  during 2002–2004 in the Heihe River Basin (Wu et al. 2010), and the difference may be attributed to the different sampling sites and observation time.

Generally, the causes of the variability of stable isotope composition in precipitation with altitude can be explained by two aspects: (1) The lowering of temperature

with increasing elevation in mountainous regions usually leads to enhanced moisture condensation in air mass and therefore to a progressive depletion in heavy isotopes of precipitation with altitude and (2) sub-cloud evaporation may impact the formation of precipitation. Strong evaporation in these regions also made rain become increasingly enriched in  $\delta^{18}\text{O}$  and  $\delta\text{D}$ . The altitude effect appears

**Fig. 3** Interpolated annual mean  $\delta^{18}\text{O}$  (a) and  $\delta\text{D}$  (b) values in precipitation in the Extensive Hexi Region



higher due to the kinetic fractionation in the sub-cloud evaporation.

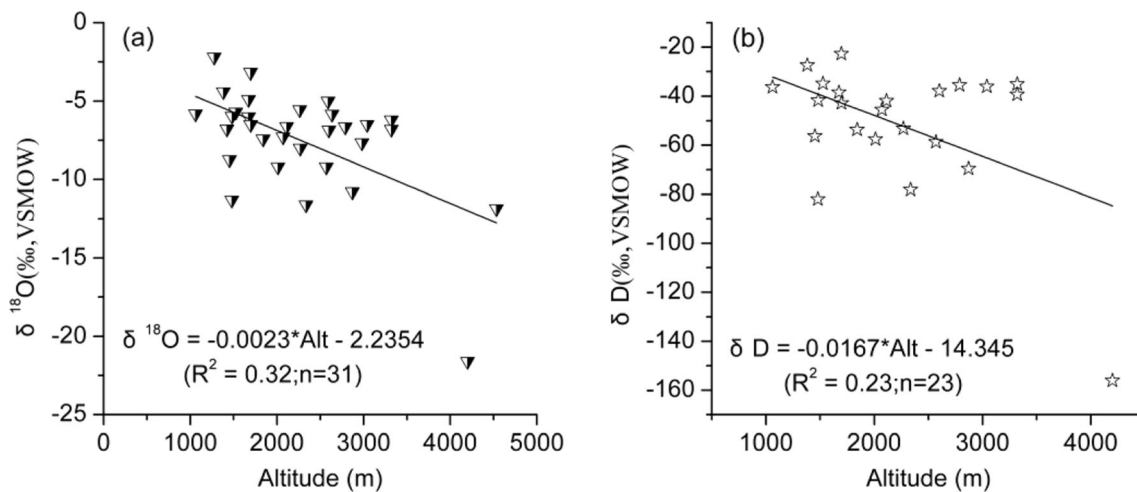
Climatic effects

*The local meteoric water line*

The relationship between  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in precipitation on globally is well understood and is defined by the global

meteoric water line (GMWL):  $\delta\text{D} = 8\delta^{18}\text{O} + 10$  (Craig 1961). Such a relationship can also be described by an LMWL in different regions, which may have slightly different slopes and intercepts compared to the GMWL (Gat 1980; Jonsson et al. 2009).

Figure 5a shows a significant linear relationship ( $R^2 = 0.98$ ) between the annual mean  $\delta\text{D}$  and  $\delta^{18}\text{O}$  based on the 23 sites listed in Table 1, and both the slope (7.48) and intercept (8.01) of the linear regression line were smaller than the GMWL,



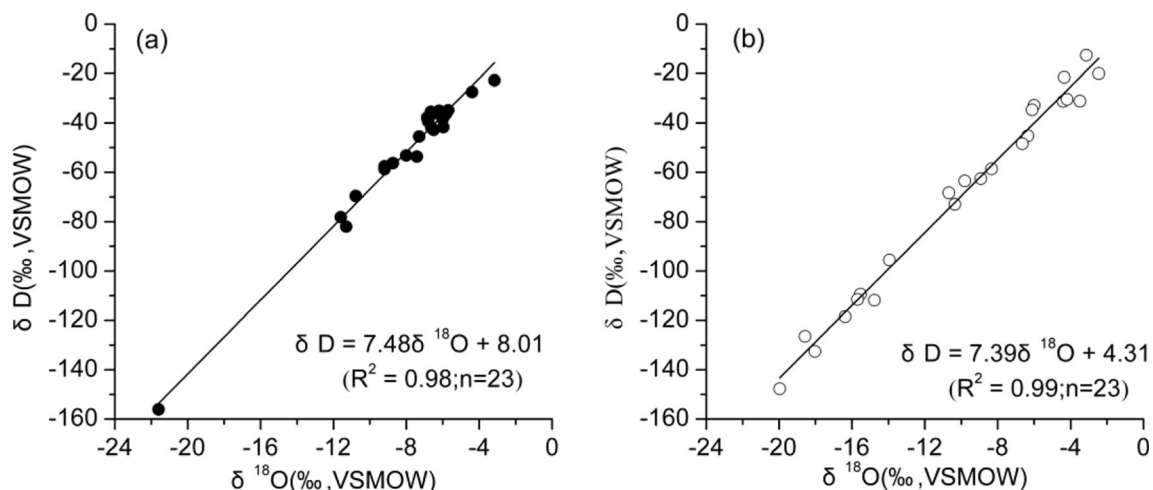
**Fig. 4** Altitude effect of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in the Extensive Hexi Region based on the annual mean values in the analyzed sites. **a** The  $\delta^{18}\text{O}$ –altitude relationship based on 31 sites. **b** The relationship of  $\delta\text{D}$ –altitude based on 23 sites

mainly as a result of partial evaporation of rain in a relatively dry atmosphere below the cloud base. For comparison purposes, a linear regression curve was drawn (Fig. 5b) according to the long-term monthly mean stable isotope data for precipitation at Zhangye (the GNIP monitoring station in the study areas) and Yinchuan (the GNIP monitoring station near the study areas). Remarkably, the slope of the line for 23 sites (Fig. 5a) is close to the value of the slope at Zhangye and Yinchuan which was derived from monthly mean  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in precipitation over 10 years (Fig. 5b). The equations in Fig. 5 were based on the annual mean values in a relatively wider region and may be more accurate in estimating the long-term relationship between  $\delta\text{D}$  and  $\delta^{18}\text{O}$  of precipitation in the Extensive Hexi Region than the results obtained from a single or limited sampling site. Compared with other arid or semiarid regions in the world, the slope of the LMWL in Extensive Hexi Region is higher than the arid Australian. For example, the Alice Springs station, the slope, and intercept of  $\delta\text{D}$  and

$\delta^{18}\text{O}$  relationship for rainfall events ( $\delta\text{D}=6.14\delta^{18}\text{O}-2.7$ ) is significantly different from the LMWL in Extensive Hexi Region (Dogramaci et al. 2012). But, the situation in North Africa was opposite, and the slope of the LMWL was close to 8 due to the local climate impact (Hamed et al. 2008), which may be attributed to the influence of the North Atlantic.

#### Temperature effect

The distribution patterns of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  concentration in precipitation are closely related to surface air temperature in mid and high latitude regions (Rozanski et al. 1992), and this relationship will be enhanced inland (Araguás-Araguás et al. 1998). But, the isotope signatures of precipitation over mid- and high-latitude regions are controlled mainly by regional-scale processes, such as conditions at the vapor source region, transport patterns of vapor in the atmosphere, and cloud-base temperature (Rozanski et al. 1992). Therefore, it is necessary



**Fig. 5** Regional  $\delta\text{D}$ – $\delta^{18}\text{O}$  relationship based on the annual mean  $\delta\text{D}$  and  $\delta^{18}\text{O}$  values in the Extensive Hexi Region (the data used in **a** are from 23 sites in Table 1 and in **b** were obtained by monthly weighted mean stable isotope values from Zhangye and Yinchuan)



to investigate the relationships between the isotope composition of precipitation and relevant meteorological parameters in order to quantitatively interpret the isotope records preserved in environmental archives in terms of past climate change (Araguás-Araguás et al. 2000).

Paleohydrology and paleoclimatology over different time scales were reconstructed using  $\delta^{18}\text{O}$  values of ice cores (Thompson et al. 1989) and tree rings taken from the Qilian Mountains (Liu et al. 2009), lake sediment from the Qinghai Lake (Henderson et al. 2003), and Suga Lake in the Qaidam Basin (Holmes et al. 2007; Zhang et al. 2009). The isotope composition of those materials is directly or indirectly derived from the past precipitation, so information on  $\delta^{18}\text{O}$  from modern meteoric precipitation and its relationships with temperature in those regions should be determined.

As vapor condensation is controlled by temperature, the relationship between  $\delta^{18}\text{O}$  in precipitation and monthly mean temperature can reflect the local climate. In South and East Asia where the monsoon climate prevails, the temperature effect generally does not exist or even inverse in monthly or shorter time intervals due to significant changes in moisture sources supplied by the monsoon (Araguás-Araguás et al. 1998). However, the correlation between  $\delta^{18}\text{O}$  and temperature was significant in northwest China, such as the Extensive Hexi Region (Liu et al. 2008a, b, c). In the Shiyang River Basin of the Hexi Corridor, the slope and correlation coefficient of the  $\delta^{18}\text{O}$ – $T$  relationship decreases from the lower reaches to the upper (from 0.65 ‰/°C in Hongya to 0.58 ‰/°C in Nanying), due to the increasing moisture contents from local recycling of evaporated water from land surfaces in the upper reaches of the basin (Ma et al. 2012). Temperature effect plays a very important role in the variations of  $\delta^{18}\text{O}$  in precipitation in the Heihe River Basin. The relation between  $\delta^{18}\text{O}$  and surface air temperature was significant in Xishui and Yingluoxia (the two region located in the middle reaches of the Heihe River Basin) with gradients of 0.91 ‰/°C and 0.76 ‰/°C, respectively; meanwhile, the gradient was 0.55 ‰/°C in Qilian and 0.57 ‰/°C in Zamashi in the upper reaches of the Heihe River Basin. Zhang and Wu (2007a, b) indicated that the temperature effect was weaker in summer than in winter. Thus, the temperature effect not only showed spatial difference but also displayed seasonal variation in the study area and gradually decreased from lower reaches to upper reaches of inland rivers or plains to mountains. Here, we list and summarize the previous limited results in sampling sites due to the few published data for temperature and stable isotope in precipitation. The temperature effect in the study area is more significant than for northwest China in general, and it is probably beneficial for studying the temperature change in the past.

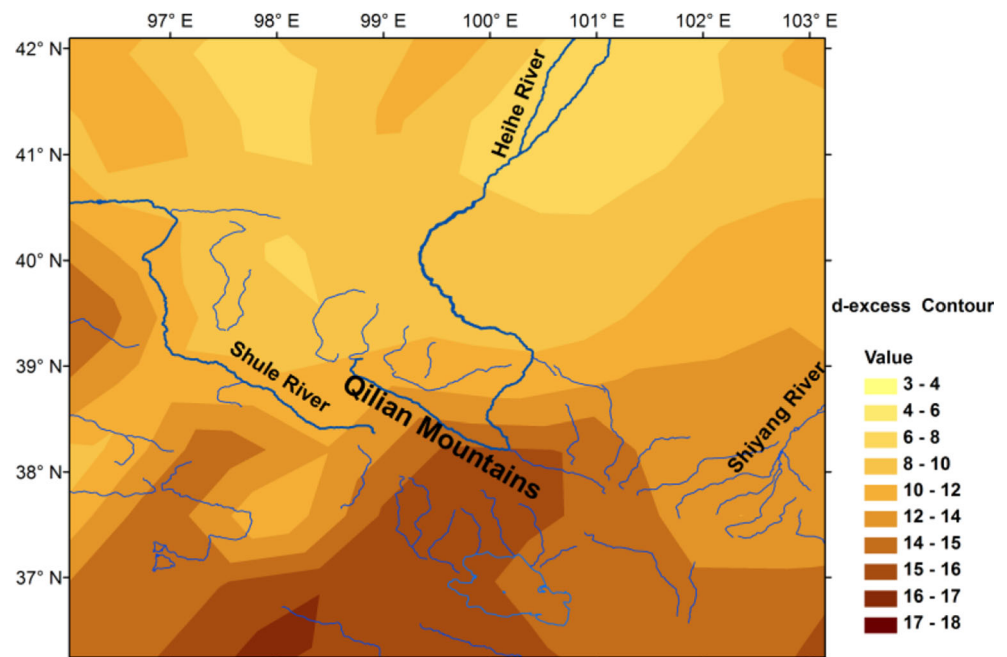
### Amount effect

In China, the effect of amount of precipitation is significant in the Southeast and southwest monsoon region, and it was generally decreased from the coast to inland (Zhang and Yao 1998). Amount effect is not evident in Extensive Hexi Region because of the limited annual precipitation. The precipitation in the study area mainly occurred in summer months from May to September, which accounted for 80 % of the total annual precipitation. Zhang and Wu (2007a) indicated that the amount effect has been found in the Heihe River Basin in summer months, but Wu et al. (2010) suggested that the effect was significant in precipitation events and weak in the monthly scale. Therefore, the amount effect could not be ignored in summer months, especially for the Qilian Mountains where the intensive precipitation occurred in the summer with the average amounts over 254 mm from June to August (Zhang and Wu 2007a; Wu et al. 2010). Similar results were also found in Tuotuohe and Xining (Zhang et al. 1995).

### Deuterium excess in precipitation

The d-excess values in Table 1 were calculated from the corresponding annual mean  $\delta\text{D}$  and  $\delta^{18}\text{O}$  in each site. The annual mean d-excess values in the study area ranged from 2.61 to 17.81 ‰, with an average value of 12.10 ‰, slightly higher than the mean value of GWML (10), which may be caused by local moisture recycling. The spatial distribution of d-excess was evident as shown in Fig. 6 with low d-excess values in lower reaches of rivers and high d-excess values in the Qilian Mountains. According to Fig. 7, the d-excess increased gradually with the altitude, with the higher d-excess values occurring at mountains sites. Zhang and Wu (2009) also found this phenomenon in the Heihe River and indicated that the d-excess values in the Qilian Mountains were higher than those in the plain of the Hexi Corridor. Similar variability of d-excess occurred in the Shiyang River Basin (Ma et al. 2012). The annual mean d-excess values in precipitation fluctuate significantly at different sites (Table 1). It is well known that sub-cloud evaporation decreases the d-excess and moisture recycling increases the d-excess in precipitation. The distance between cloud base and ground and the saturation deficit are lower at high-altitude than at low-altitude sites. It is possible that sub-cloud evaporation is remarkably reduced in precipitation over mountains (Froehlich et al. 2008). Meanwhile, the high-altitude precipitation associated with low cloud temperature (Tian et al. 2001), and sub-cloud evaporation could be weaker. Another possible reason for high d-excess in mountain sites was attributed to the recycled moisture and the markedly different evapotranspiration;

**Fig. 6** Interpolated annual mean d-excess values of precipitation in the Extensive Hexi Region



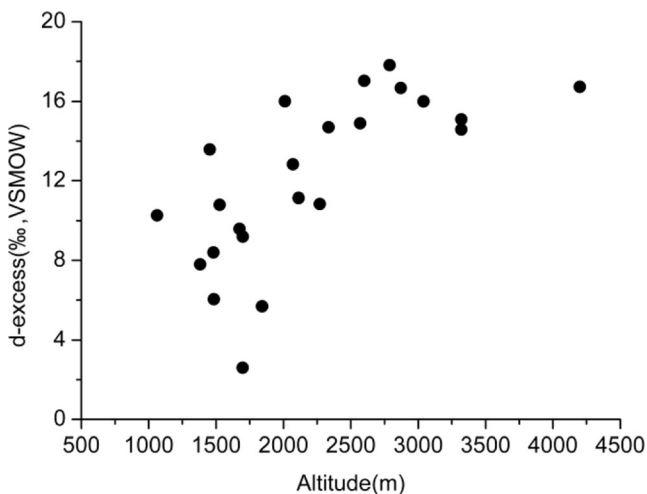
they were higher in moist forest mountain areas than in arid plains or foothill regions (Cui et al. 2009; Peng et al. 2011). Such processes may have led to higher d-excess values in winter and lower values in summer months in the Qilian Mountains (Zhang and Wu 2009).

The seasonality of d-excess was attributed to varying moisture conditions in the source areas and enhanced secondary evaporation such as raindrop evaporation and moisture recycling (Gat et al. 1994; Araguás-Araguás et al. 1998; Froehlich et al. 2008). The lower d-excess in summer in the study region was associated with high vapor deficit and warm temperature which leads to the enhancement of secondary evaporation as raindrops fall below the cloud base. Meanwhile, the high proportion of convective precipitation

(Chen et al. 2007), a strong vertical mixing of the air in this area (Zhou et al. 2012), and summer monsoon moisture transport (Wu et al. 2010) in summer also contribute to the relatively low d-excess values. The high d-excess indicated the presence of continental air masses producing precipitation during winter months (Araguás-Araguás et al. 1998). Additionally, snow is the precipitation pattern of the Extensive Hexi Region in winter, and the fractionation in snow formation at cold temperatures should also be considered when trying to understand the higher d-excess.

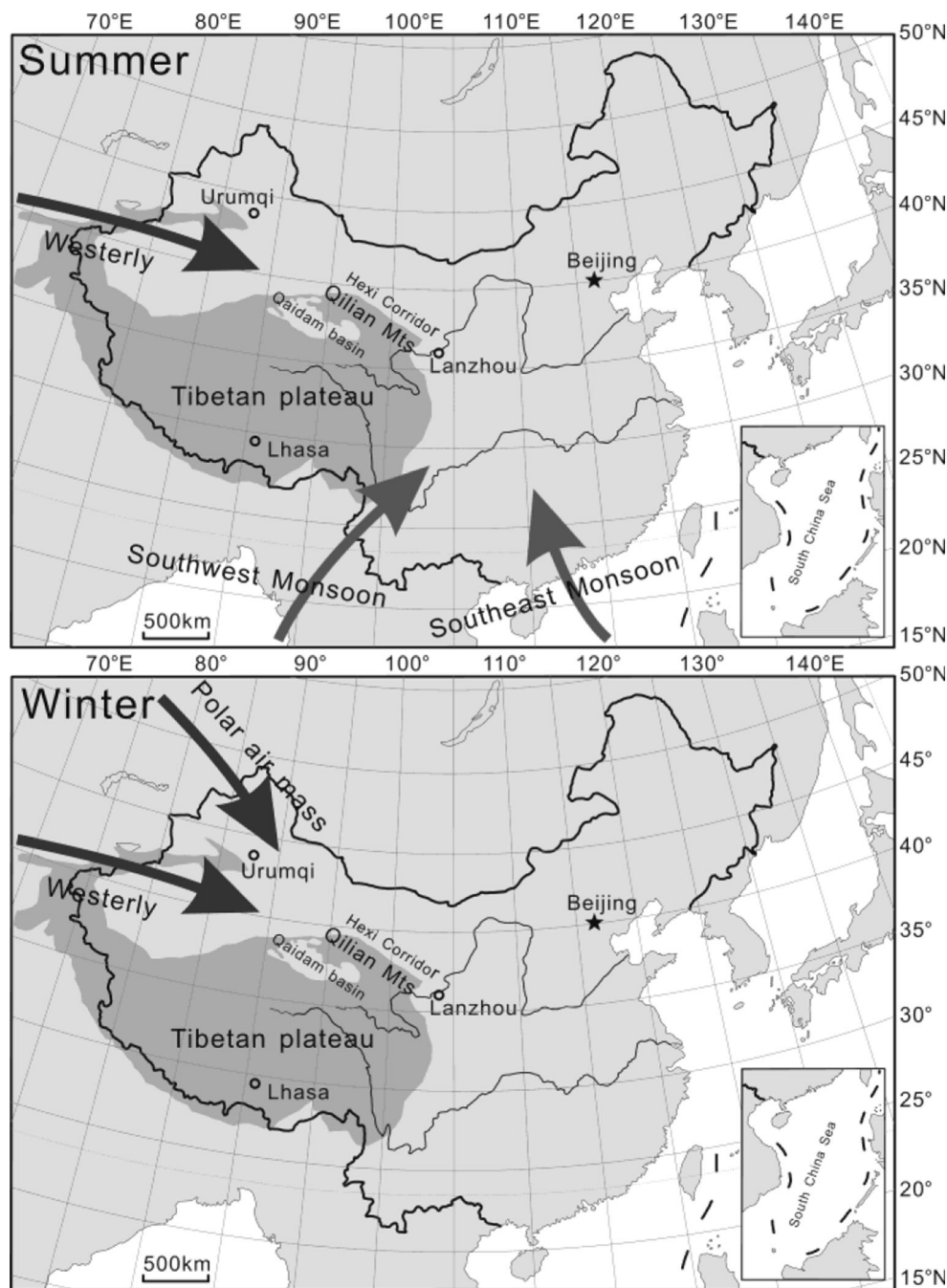
#### Sources of moisture

There are three moisture sources in northwest China in the summer (westerly, southeast monsoon, and southwest monsoon air masses) and two in the winter (westerly and polar air masses) that affect the seasonal isotope patterns in northwest China (Fig. 8). The Extensive Hexi Region is located in the northeast boundary of Tibetan Plateau and belongs to a transitional area between the summer monsoon and the westerly, so the atmospheric circulation pattern is very complex (Wang et al. 2006). The high values of d-excess probably demonstrate that the recycled moisture probably plays a very important role in local precipitation (Tian et al. 2005). In the Heihe River Basin, higher d-excess values result mainly from continental moisture sources from the westerly air masses or neighboring inland areas, whereas lower d-excess values result from the monsoons of southeast China or Southwest Asia (Zhang and Wu 2007a, b; Wu et al. 2010). However, recent work by Zhao et al. (2011) suggested that the seasonal variability of d-excess in precipitation at the



**Fig. 7** Regional d-excess–altitude relationship based on the annual mean  $\delta D$  and  $\delta^{18}O$  values for the analyzed sites of the regions

**Fig. 8** The general patterns of moisture sources in summer and winter in northwest China



Heihe River Basin is similar to that of the Urumqi. They recognized that the moisture in the source area of the Heihe River mainly originates from moisture transport from the westerly air masses and is slightly influenced by the polar air masses, which may interrupt the formation of precipitation. To determine more precisely the origin of the moisture entering the Shiyang River Basin, Ma et al. (2012) combined the synoptic and published isotopic data in northwest China and found that the majority of precipitation reaching the Shiyang River Basin in both summer and winter is due to the westerly

cyclonic system, meanwhile the polar air masses originating from the Arctic impact the local precipitation during the winter as well. To conclude, the evidence from stable isotope in precipitation suggests that the lower values of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  and higher values of d-excess in winter can be ascribed to the control of the westerly air masses and polar air masses, the interpretations about the higher values of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  and the lower values of d-excess in the summer are still debatable. However, the variability of  $\delta^{18}\text{O}$ ,  $\delta\text{D}$ , and d-excess presents marked differences between summer and winter, which are most likely related

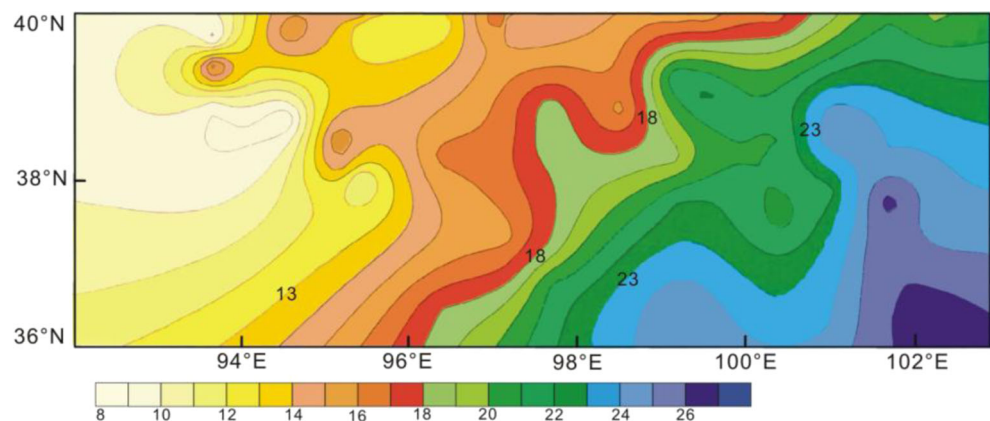
to different moisture sources in the study area, and the westerly air masses may not be a unique moisture source in summer precipitation.

The meteorological data for the recent decades are used to describe the annual moisture transport patterns in the study region. Wang et al. (2006) recognized that there were two moisture transports in the Extensive Hexi Region, one is the westerly from the Mediterranean Sea and the Caspian Sea and the other is the southwest monsoon originating from the ocean of the Bay of Bengal and the Arab Sea. The westerly transports moisture from the Mediterranean Sea and the Caspian Sea to the study area during winter and spring, but in summer and autumn, the situation is quite different and the precipitation is alternatively influenced by the two moisture transports. Guo et al. (2007) noted that the mean transport of atmospheric moisture from the westerly is gradually weaker along with the enhanced southwest monsoon from winter to summer in the Qilian Mountains and the moisture content presents remarkable seasonal variations (higher in summer and lower in winter). However, the moisture from the westerly still supplies over half of the total moisture in summer. Based on the remote sensing data, the radiosonde data, and the precipitation data in the Qilian Mountains and its adjacent regions, Zhang et al. (2007a, b) found that the atmospheric moisture contents decrease from southeast to northwest in the study area (Fig. 9) because of the influence of the southwest monsoon and the southeast monsoon. Therefore, the distribution of atmospheric moisture and precipitation in this region is affected by the westerly, the southwest monsoon, and the southeast monsoon. Although the westerly may dominate in the frequency of moisture transports, the southwest monsoon and the southeast monsoon contribute to non-negligible moisture content. Additionally, Zhou et al. (2012) analyzed the UVW anemometer and surface observation data from July to August in 2007 and found that the precipitation

mainly occurred when the dominant wind direction is southwest in the Qilian Mountains. Therefore, the analysis of meteorological data suggests that there are different moisture sources through a year in this region. The westerly mainly controls the moisture source in winter and spring, and the north boundary of southwest monsoon and southeast monsoon can transport moisture to southeast Extensive Hexi Region in summer, adding to the westerly moisture transport.

The precipitation usually comes from three sources: the moisture already in the atmosphere, moisture advected into the region by winds, and the regional recycling moisture from evapotranspiration. Over long periods, the first contributes little, whereas the majority of moisture for precipitation is supplied with advection and evapotranspiration (Trenberth 1999). In the Extensive Hexi Region, the advected moisture is mainly provided by large-scale atmospheric circulation (the westerly and monsoon), which has been discussed above. There are three inland rivers and several inland lakes (the Qinghai Lake is the largest inland lake in China) that mainly provide moisture through evaporation. Evaporation is enhanced by reducing runoff (such as constructing dam and reservoirs) or by leading runoff back onto the land (such as by irrigating on previously bare soil) (Van der Ent et al. 2010). The agricultural irrigation at the oases in the study areas depends on the river water and groundwater. Such water is lost by evapotranspiration of plant and soil and only a small part recharges to groundwater. The recycled moisture by evapotranspiration has been recognized as an important source of precipitation. Moreover, the summer mean  $\delta^{18}\text{O}$  values show a “heavy spot” along the Hexi Corridor (Araguás-Araguás et al. 1998; Liu et al. 2008a, b, c). The high  $\delta^{18}\text{O}$  values in precipitation in summer suggest a significant contribution of recycled moisture from evaporation, which are also indicated by the seasonal trend of d-excess values discussed above. Thus, locally recycled moisture plays an important role in precipitation

**Fig. 9** Distribution of annual mean moisture content in the Qilian Mountains and its adjacent regions (units,  $\text{kg}/\text{m}^2$ ) (Zhang et al. 2007a)



associated with regional atmospheric circulation. Consequently, the moisture source in this region during the summer is likely related to the contribution of summer monsoon, the westerly, and recycled moisture. More investigation is needed to determine if the westerly provides the main moisture in this region.

### Conclusions and perspective

The isotopic compositions of precipitation in the Extensive Hexi Region are summarized from the data observed over the past decade. The spatial–temporal features of  $\delta^{18}\text{O}$ ,  $\delta\text{D}$ , and the d-excess values are discussed. We reach the following conclusions: (1) The stable isotopes in precipitation reflect a well-defined seasonal trend with the higher values of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in summer and lower values in winter, (2) the temperature effect of  $\delta^{18}\text{O}$  is significant in the Extensive Hexi Region, but the slopes of  $\delta^{18}\text{O}$ –T are distinctly different due to the topographic and climate conditions. The precipitation amount effect is not evident in the annual year scale, but it could have impact on the stable isotopes in the summer (rainfall season). The altitude effect of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  is remarkable with gradients of  $-0.23\text{‰}/100\text{ m}$  and  $-1.67\text{‰}/100\text{ m}$ , respectively, (3) the annual weighted mean  $\delta^{18}\text{O}$  and  $\delta\text{D}$  define an LMWL as  $\delta\text{D}=7.48\delta^{18}\text{O}+8.01$ , which is close to the relationship between  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in Zhangye and Yinchuan that were observed by GNIP, (4) the d-excess in precipitation shows pronounced seasonal cycles with higher values in winter and lower values in summer, associated with different moisture sources. It increases gradually with altitude due to the sub-cloud evaporation during rainfall beneath the cloud base and the different moisture recycling processes in this region. Because of the complexity, sources of moisture in the Extensive Hexi Region require further investigation and exploration.

Despite the large body of research that has advanced our understanding of the stable isotopes of precipitation in this region, more work remains to be done to recognize the moisture source in the Extensive Hexi Region. Monitoring and observation at more sites and over longer periods are required to improve our understanding of stable isotopes in precipitation in this region.

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