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ORIGINAL ARTICLE

Deuterium and oxygen 18 in precipitation and atmospheric moisture in the upper Urumqi River Basin, eastern Tianshan Mountains

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Abstract The contribution of stable isotopes in meteorological, climatological and hydrological research is well known. This study analyzed the deuterium and oxygen 18 contents (δD and δ^{18}O) of precipitation in event-based samples at three stations (Glacier No. 1, Zongkong, Houxia) along the upper Urumqi River Basin from May 2006 to August 2007. The δ^{18}O in precipitation revealed a wide range and a distinct seasonal variation at all three stations, with enriched values occurring in summer and depleted values in winter. A statistically significant positive correlation was observed between the δ^{18}O and δD and local surface air temperature, and better linear relationship existed between δ^{18}O and air temperature than that of δD. This suggests that paleoclimatic archives relating to precipitation δ^{18}O and δD can be useful for qualitative temperature reconstruction. The *d*-excess in precipitation also exhibited a seasonal variability. Based on NCEP/NCAR reanalysis data, three-dimensional isentropic back-trajectories in HYSPLIT model were employed to determine the moisture source for each precipitation event. Results indicate a dominant effect of westerly air masses in summer and the integrated influence of westerly and polar air masses in winter, and *d*-excess can be used as a sensitive tracer of the moisture transport history.

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Introduction

The stable isotopic composition of oxygen and hydrogen in natural waters has become an effective means for investigating the complex hydrological and climatic processes (Gat 1996; Sidle 1998; Gibson et al. 2005; Dutton et al. 2005; Liu et al. 2008). It is a valuable indicator of several aspects about the global water cycle, atmospheric circulation and paleoclimatic investigations (Jouzel et al. 1997a; Krinner and Werner 2003; Tian et al. 2003; He et al. 2006a). Such studies require that the oxygen and hydrogen isotope composition of meteoric precipitation be known as an important link in the hydrologic systems (Siegenthaler and Oeschger 1980; Rozanski et al. 1992; Jouzel et al. 1997b; He et al. 2006b; Kumar et al. 2010). Since 1961, the International Atomic Energy Agency (IAEA), in cooperation with the World Meteorological Organization (WMO), has set up the Global Network of Isotopes in Precipitation (GNIP) at numerous monitoring stations worldwide for measuring the isotopic composition of monthly precipitation, but few GNIP stations have recorded the δ^{18}O and δD data in western China.

Many researches have been conducted on mechanisms controlling isotopic fractionation in natural processes and obtained lots of valuable progress (Jouzel and Merlivat 1984; Kohn and Welker 2005). Craig (1961) defined $\delta D = 8\delta^{18}O + 10$ as the global meteoric water line (GMWL) as the majority of δD and δ^{18}O in precipitation are falling close to this line for parallel fractionation. There exists an excess value in the relationship between δD and δ^{18}O for water evaporation during water cycling, Dansgaard (1964) defined it as *d*-excess ($d = \delta D - 8\delta^{18}O$). The average *d*-excess is about 10 on the global scale. The seasonal and spatial patterns of stable isotopes in precipitation are mainly affected by the relative humidity of the area where the moisture came from, the degree of moisture recycling during water vapor transport and the temperature at the point of final condensation for heavy and light isotope species undergo different fractionation during phase changes (Dansgaard 1964; Merlivat and Jouzel 1979; Clark and Fritz 1997). Therefore, the $\delta^{18}O$ and δD, local meteoric water lines (LMWLs) and *d*-excess values in precipitation vary temporally and spatially, and they can provide useful information about moisture sources, local climatic conditions and hydrological cycle (e.g. Welker 2000; Zhang et al. 2002; Jonesl et al. 2007; Price et al. 2008; Feng et al. 2009; Lutz et al. 2011).

Yao et al. (1999) evaluated the relationship between $\delta^{18}O$ in precipitation and surface air temperature along the whole Urumqi River. Zhang et al. (2003) analyzed the variations of $\delta^{18}O$ in precipitation, surface firn, meltwater and stream samplings in the Urumqi River Basin. However, the study of the LMWLs and *d*-excess in precipitation is comparatively limited so far due to lack of hydrogen isotope data. Similarly, there have been no reports on the combination variations of *d*-excess in precipitation with the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis data in this area. This paper presents the $\delta^{18}O$ and δD values in precipitation at three stations along the upper Urumqi River Basin during May 2006–August 2007. The temporal and spatial variations of $\delta^{18}O$ and δD in precipitation and their relationships with local meteorological conditions were investigated in this study. Based on the *d*-excess and NCEP/NCAR reanalysis data, the origin of moisture was also discussed using the three-dimensional isentropic back-trajectories in HYSPLIT model.

Study area

The Urumqi River Basin is located in the eastern Tianshan mountain range, one of the largest mountain systems of central Asia. It originates from the north slope of Tiager Peak (43°07′N, 86°49′E), and flows northward to the city of Urumqi, the capital of Xinjiang Uygur Autonomous Region. The river length is 214 km and the total area is 4,684 km^2, of which 1,070 km^2 is in mountainous terrain. It is surrounded by vast desert areas: the Taklimakan Desert to the south, Gurbantunggut Desert to the north, and the Gobi Desert to the east (Fig. 1a). The nearest sea is located at a distance of more than 3,000 km from the study area. The Urumqi River Valley belongs to typical continental arid climate, where most of the precipitation occurs in the high-altitude mountain areas.

This paper focuses on the areas in the upper Urumqi River Basin (Fig. 1b). There are two long-term hydro-meteorological stations (Glacier No.1, Zongkong) at the headwaters of the Urumqi River Basin for measuring runoff and meteorological parameters. Glacier No.1 station is located at an elevation of 3,693 m and controls the catchment of 3.34 km^2, while Zongkong station is located at an elevation of 3,404.8 m and controls the catchment of 28.9 km^2 (Li et al. 2009). Two meteorological stations in the upper reaches of the Urumqi River Basin: Daxigou station (3,539 m a.s.l.) is located 3 km downstream of Urumqi Glacier No. 1, and started to operate in 1959;

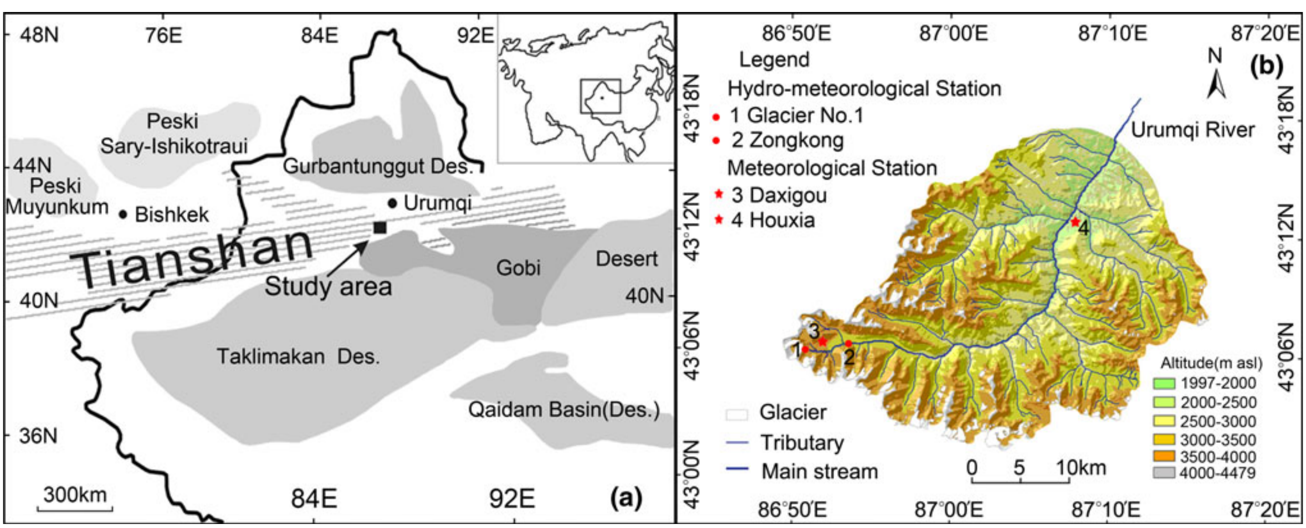

Fig. 1 Sketch maps showing the study area and location of hydro-meteorological and meteorological stations. Stations 1, 2 and 4 are precipitation sampling sites

Table 1 Information of the hydro-meteorological and the meteorological stations

Station	Elevation (m a.s.l.)	Catchment area (km^2)	Starting year of observation
Hydro-meteorological station			
Glacier No. 1	3,693.0	3.34	1959
Zongkong	3,404.8	28.9	1981
Meteorological station			
Daxigou	3,539		1959
Houxia	2,130		1985

observation at Houxia station (2,130 m a.s.l.) situated 35 km northeast and downstream of Urumqi Glacier No. 1, started in 1985 (Table 1). The mean annual air temperature at Houxia and Daxigou stations is around 1.4 and −4.5 °C, respectively. Most precipitation in the study area occurs during the summer months of June through August. The average annual precipitation from 1959 to 2003 provided by the Daxigou meteorological station was 450 mm, of which 85 % occurred during summer months.

Precipitation sampling and analytical methods

Precipitation samples were simultaneously collected at three stations (Glacier No.1, Zongkong, Houxia) along the upper Urumqi River Basin from May 2006 to August 2007 (Fig. 1b). All precipitation samples were collected as individual events. Meanwhile, the meteorological parameters (surface air temperature, amount of precipitation, wind direction, and wind speed) were also measured at the meteorological stations (Table 1). A total of 324 precipitation samples were collected during the investigation period (90 s at Glacier No.1 station, 129 s at Zongkong station and 105 s at Houxia station).

Rain samples were collected in polyethylene bottles through funnels (14 cm diameter), while snow samples were collected in polyethylene containers (50 × 50 × 50 cm). Samples were then stored in 60 ml polyethylene plastic bottles containing a thin layer of mineral oil to prevent evaporation, and with rubber-seal caps. Liquid samples were collected immediately after the end of rainfall; solid precipitation samples were collected and melted thoroughly at room temperature in a plastic bag before being sealed in bottles. The bottles were then tightly sealed to avoid evaporation or diffusion.

All samples were stored in the low-temperature laboratory of the State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Lanzhou, China, at −15 °C until the analyses were carried out. The stable isotopic analysis was completed on the Los Gatos Research liquid water isotope analyzer (LWIA DLT-100). The measurement method had been introduced in detail by Lis et al. (2008), consisting of injecting every sample and isotope laboratory standard sequentially six times. Using the systematic sample analysis and data normalization procedure routine, the analytical precision achieved ±0.78 ‰ for δD and ±0.21 ‰ for $\delta^{18}O$, respectively. The measured results were expressed as parts per mil of their deviations relative to the Vienna Standard Mean Ocean Water (VSMOW):

$$\delta^{18}O = [(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{VSMOW}]/(^{18}O/^{16}O)_{VSMOW} \times 10^3 ‰ \quad (1)$$

$$\delta D = [(D/H)_{sample} - (D/H)_{VSMOW}]/(D/H)_{VSMOW} \times 10^3 ‰ \quad (2)$$

Results and analysis

Seasonal variation of stable isotopic compositions in precipitation

Figure 2 demonstrates the variations of $\delta^{18}O$ values of individual precipitation events and average daily air temperatures at three stations from May 2006 to August 2007. Precipitation was mainly concentrated in summer. During the observation period, there were only a few precipitation events in some months (for example, from November to January), or even no precipitation at all (as in February). As Fig. 2 shows, the $\delta^{18}O$ values in precipitation at the three stations display a wide range and exhibit similar patterns of variation. The maximum varying range of $\delta^{18}O$ in precipitation was from −27.56 to 1.67 ‰ at Houxia station, while the δD values of precipitation ranged from −190.75 to 18.94 ‰. The average $\delta^{18}O$ value was −7.68 ‰ at Glacier No.1 station, −8.31 ‰ at Zongkong station, and −6.67 ‰ at Houxia station, respectively.

Positive $\delta^{18}O$ values appeared in nine precipitation events during the whole sampling period, of which $\delta^{18}O$ in precipitation event on June 23, 2007 at Glacier No.1 station with a precipitation amount of 1.0 mm and average daily temperature of 14.4 °C, reaching the maximum value. The $\delta^{18}O$ value in precipitation was as high as 4.31 ‰. The minimum values of $\delta^{18}O$ at three stations all occurred in winter, which were −25.12 ‰ on December 6, 2006, −24.97 ‰ on January 2, 2007 and −27.56 ‰ on January 3, 2007 at Glacier No.1, Zongkong and Houxia stations, respectively. This extremely large range of stable isotope composition in precipitation reflects the extremes in climate, experienced by the high-altitude, typical continental local climate of the study area.

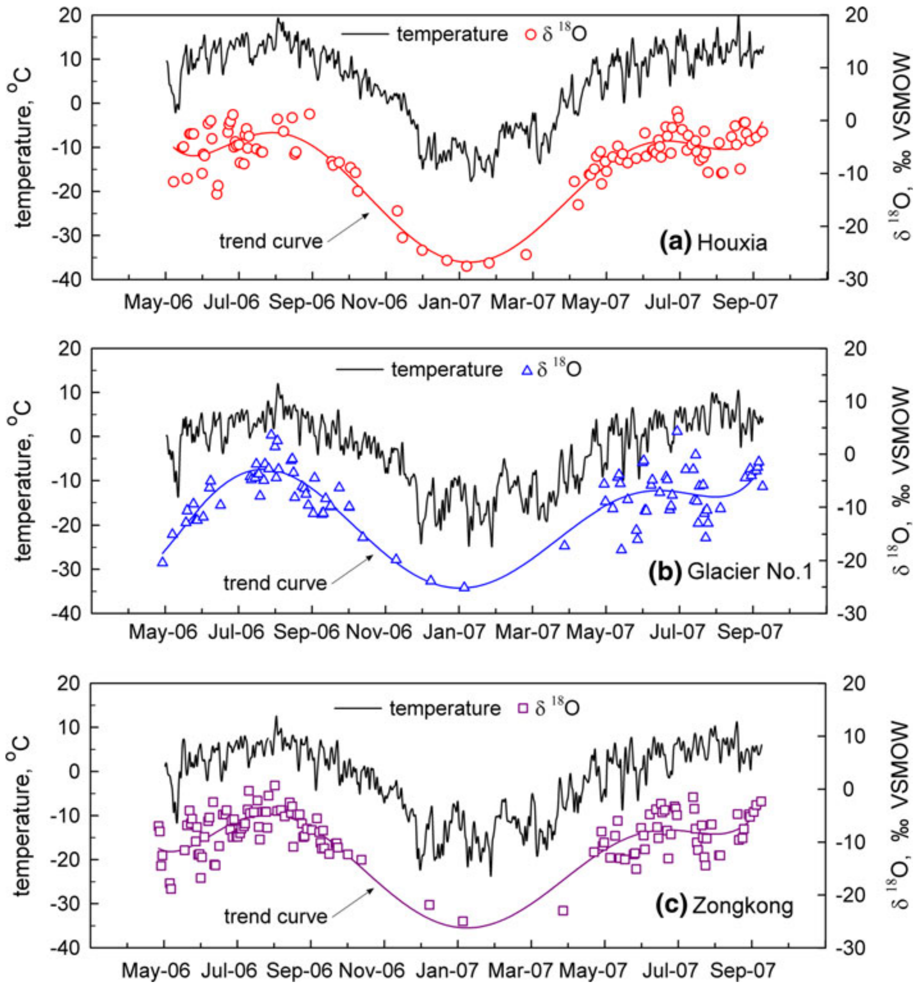

Fig. 2 Time series of δ^{18}O in precipitation and average daily temperature at three stations in the upper Urumqi River Basin

The δ^{18}O values in precipitation show a striking similar trend at the three stations in Fig. 2, indicating that stable isotopes in precipitation are mainly controlled by the same large-scale synoptic conditions throughout the region. The temporal variation of δ^{18}O values in precipitation and the average daily temperature trends are highly coincident, and the δ^{18}O generally increased with average daily temperature. The seasonal variation of δ^{18}O values in precipitation at the three stations is especially remarkable, with the enriched values occurring in summer and depleted values in winter. The occurrence of high δ^{18}O values in summer precipitation and low δ^{18}O values in winter precipitation at the three stations in this study coincides with the distribution of oxygen isotopes in precipitation in other inland areas of central Asia (Aragúas-Aragúas et al. 1998). This demonstrates the temperature effect on δ^{18}O values in precipitation from the seasonal variations in the upper Urumqi River Basin.

Hou et al. (1998) also have investigated the δ^{18}O in precipitation from June 1995 to June 1996 at the headwaters of Urumqi River. Compared with results of Hou et al. (1998), good consistency was found, with similar seasonality patterns: higher δ^{18}O in summer and lower δ^{18}O in winter. The δ^{18}O variation at Zongkong station (3,404.8 m a.s.l.) is similar to that of precipitation samples collected from the alpine station (3,551 m a.s.l.) during June 1995–June 1996, with varying range of δ^{18}O from −38.24 to 0.97 ‰. Moreover, Yao et al. (1999) reported that δ^{18}O of precipitation responded positively to temperature in the whole Urumqi River Basin. These findings indicate that temperature effect is the main controlling factor of the variation of δ^{18}O in precipitation over the study region.

Variations of the LMWLs and *d*-excess in precipitation

In order to analyze the spatial variations of stable isotope composition in precipitation along the upper Urumqi River Basin, the δ^{18}O and δD values of every rain and snow samples were used to construct the LMWLs for the three stations. On the plot of δD versus δ^{18}O in Fig. 3, the derived equation was $\delta D = 7.78\delta^{18}O + 13.75$ at Glacier No. 1 station, and defined a clear linear trend ($r^2 = 0.97$, $p < 0.01$); the slope was 7.61, and intercept was 12.63 ($r^2 = 0.98$, $p < 0.01$) at Zongkong station, while the

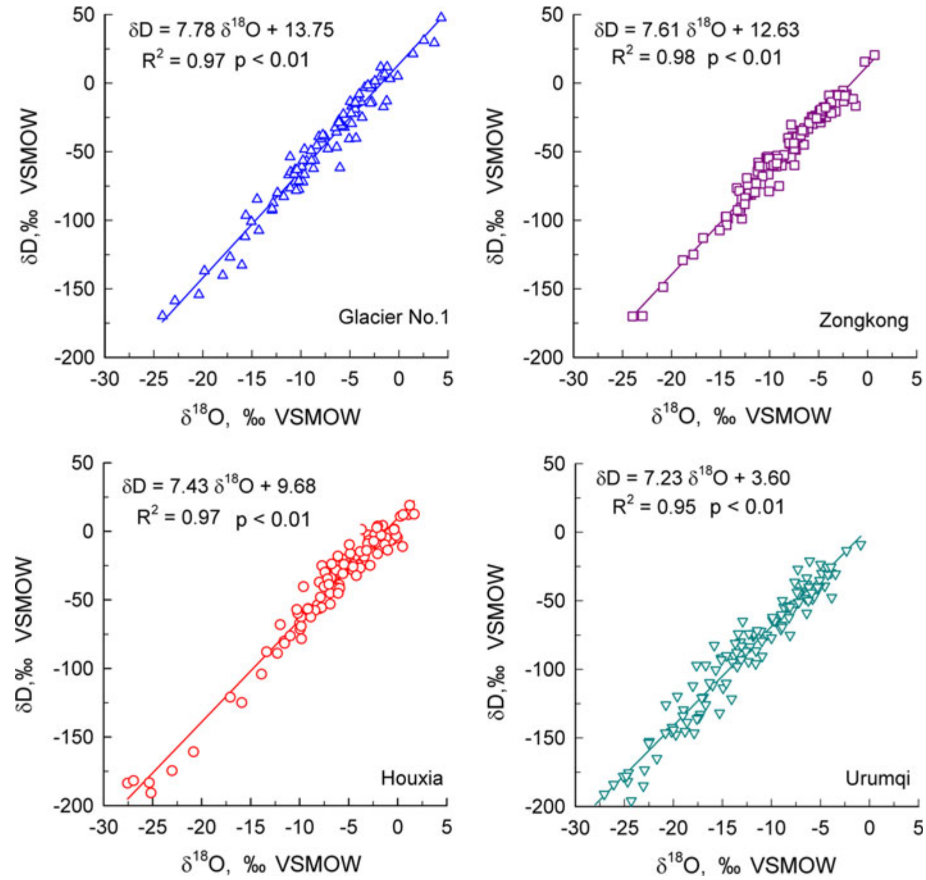

Fig. 3 Local meteoric water lines at four stations along the Urumqi River Basin

LMWL at Houxia station was $\delta D = 7.43\delta^{18}O + 9.68$, with a correlation coefficient (r^2) of 0.97 ($p < 0.01$). The analysis of covariance (ANCOVA) of the spatial variations of the waterborne isotopes was performed in order to test the significance of the variations. The results showed that there were significant differences in the slope of the relationship between $\delta^{18}O$ and δD at the three stations (ANCOVA, interaction term, $F_{(1,\ 86)} = 46.528$, $p < 0.01$), and the slopes of the LMWLs along the Urumqi River Basin were Glacier No.1 > Zongkong > Houxia station.

Compared with the GMWL ($\delta D = 8\delta^{18}O + 10$), the slopes of LMWLs at Glacier No. 1 (7.78), Zongkong (7.61) and Houxia station (7.43) are gentler than the GMWL (8), and the intercepts at the three stations (13.75, 12.63 and 9.68) are higher than or very close to the GMWL (10). Observations at the nearest GNIP station, Urumqi (43.78°N, 87.62°E, 918 m a.s.l) located at the lower reaches of the Urumqi River were used as a reference. The LMWL of Urumqi station was $\delta D = 7.23\delta^{18}O + 3.60$ ($r^2 = 0.95$, $p < 0.01$) in Fig. 3, using the monthly isotopic data from the database of GNIP. Both the slope and the intercept of LMWL at Houxia station (7.43, 9.68) are slightly gentler than of those for the two stations at the headwaters, whereas they are higher than of those for the Urumqi station. These spatial variations suggest that moisture sources of the Urumqi River Basin are mainly related to similar atmospheric circulation patterns, but the local climatic factors such as re-evaporation of raindrops and seasonality of precipitation also affected the precipitation isotope ratios in different sites.

In arid regions due to re-evaporation of falling raindrops, the evaporation effect would cause both the slope and intercept of the LMWL to decrease (Stewart 1975; Clark and Fritz 1997). The slight diversity of LMWLs along the Urumqi River can be explained through the special microclimate that the four sites are all located at inner continent of the northwest China, but in different elevations. The air temperature and precipitation amount vary across this region, with the increasing temperature and decreasing precipitation from west to east (Yao et al. 1999). The headwaters of the Urumqi River are located in an alpine region, typically glaciated area, where annual precipitation is around 450 mm and the mean annual air temperature is about −4.5 °C. Houxia station is located in the middle reaches, covered with forest and grassland, and annual precipitation is in the range 300–400 mm and the mean annual air temperature is about 1.4 °C. At Urumqi station (918 m a.s.l), the lower reaches of the Urumqi River, which disappears in the desert, annual precipitation is lower than 100 mm and the mean annual air temperature is about 7.1 °C.

The *d*-excess parameter can provide complementary information to δ^{18}O and δD values of precipitation, and it is strongly influenced by water vapor source and trajectory history, and hence can be used as a tool for the reconstruction of atmospheric circulation (Merlivat and Jouzel 1979). Pang et al. (2004) analyzed the relationships between *d*-excess in summer monsoon precipitation at New Delhi and relative humidity from the NCEP/NCAR reanalysis data, and found that the western Arabian Sea was the major source for the summer rainfall. Liu et al. (2008) investigated the seasonal *d*-excess of Nagqu precipitation in the middle of the Tibetan Plateau, and found that the lower *d*-excess values were related to warm and humid Indian Ocean moisture transport in summer, while *d*-excess values were higher in spring and winter due to the cold and dry westerly and northern moisture transport.

Here, the temporal variations of *d*-excess values in individual precipitation events at three stations were presented. As Fig. 4 shows in detail, *d*-excess values in precipitation range from −15.06 to 36.87 ‰, with a weighted average of 13.76 ‰ at Houxia station; at Glacier No.1 station, *d*-excess values range from −13.51 to 35.03 ‰, with a weighted average of 15.46 ‰; and *d*-excess values range from −6.99 to 32.01 ‰ at Zongkong station, with a weighted average of 16.00 ‰, respectively.

One can find high *d*-excess values of precipitation throughout the year, especially in winter much higher than the global average of 10 ‰. In addition, most of the *d*-excess values are around 10–20 ‰ at the three stations. The *d*-excess values also display a comparatively distinct seasonal trend at the three stations, with lower values occurring during summer (from June to August) and higher values (>20 ‰) during winter (from November to February) (Fig. 4). Tian et al. (2007) found a similar seasonality of *d*-excess in precipitation at Urumqi station (data from GNIP) in east Tianshan Mountains, with the monthly *d*-excess values lower in summer, but high values in other seasons, especially in winter. Zhao et al. (2011) also found a similar variation in *d*-excess of individual precipitation samples at headwaters of the Heihe River Basin, northwest China, with lower *d*-excess values in summer and extremely higher values in winter (>20 ‰).

Discussions

Temperature effect on δD and δ^{18}O in precipitation

The temperature effects on stable isotopes in precipitation can provide useful information, especially at high-altitude areas of low and mid latitudes for the stable isotopes in ice cores can be quantitatively recovered as a temperature proxy (Jouzel et al. 1997a). However, the isotope-temperature relationship shows variation in different regions. Tian et al. (2007) found that there was an apparent temperature effect on δ^{18}O in Tianshan Mountains, and the regression slope between δ^{18}O and temperature at Avalanche station, west Tianshan Mountains, was 0.81 δ^{18}O ‰ per °C ($r^2 = 0.67$). Yu et al. (2008) analyzed the correlation between δ^{18}O in precipitation and air temperature on the Tibetan Plateau, and found a significant positive relationship between δ^{18}O in precipitation and air temperature at

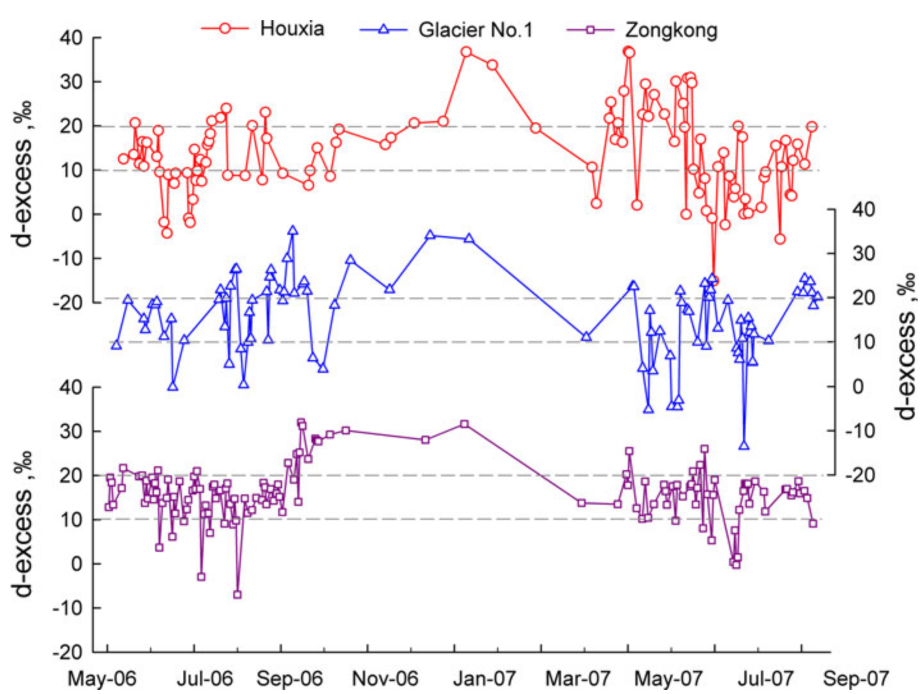

Fig. 4 Variation of *d*-excess in precipitation at three stations during May 2006 to August 2007

the Delingha station ($\delta^{18}O = 0.60T + 11.69$), in the northern Plateau. The correlation coefficient was 0.75, within a 0.01 confidence limit.

Figure 2 shows closely similar varying tendency between $\delta^{18}O$ in precipitation and average daily temperatures at the three stations. In order to further determine the

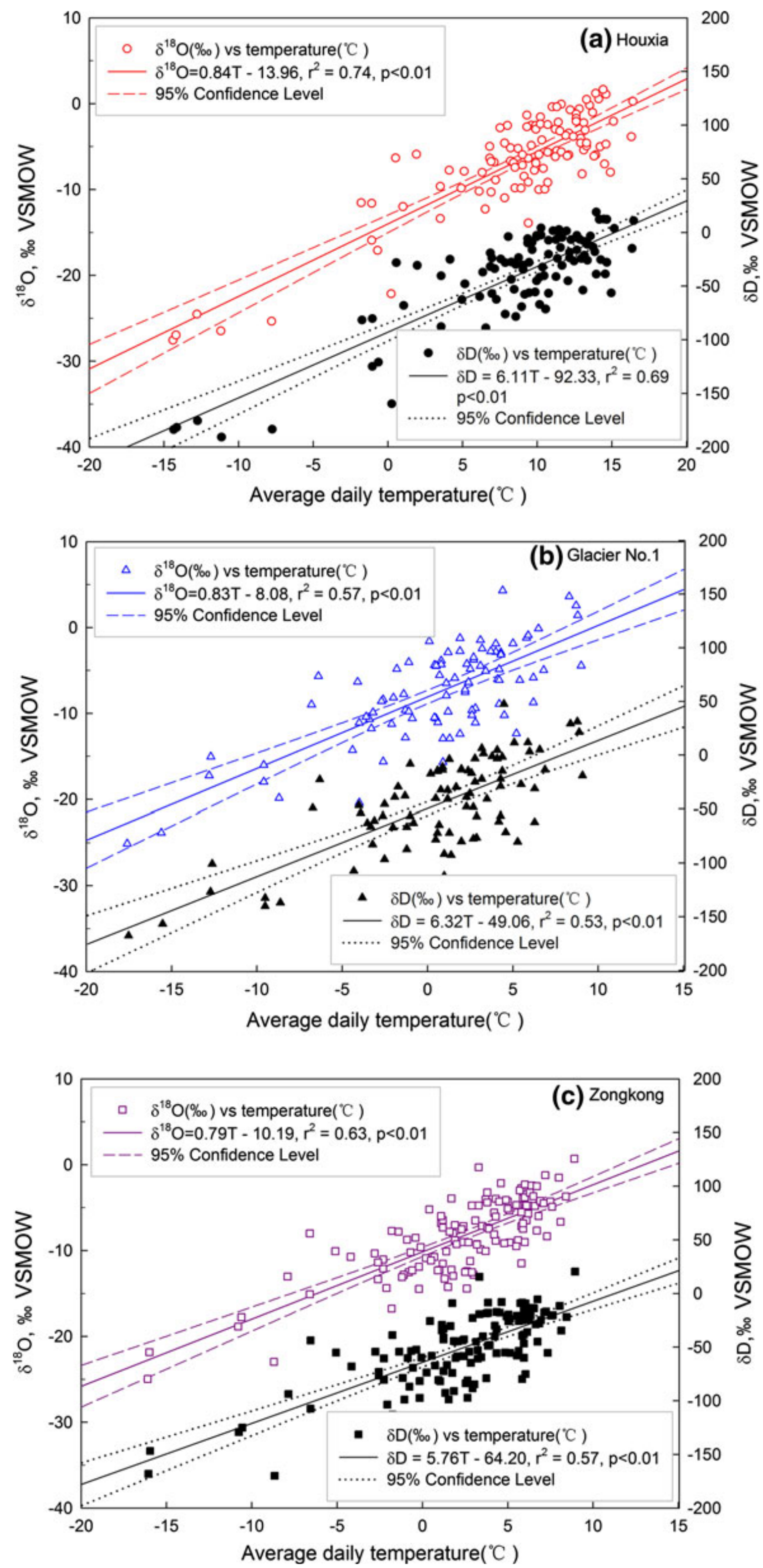

Fig. 5 Relationship between δD and $\delta^{18}O$ values of precipitation and average daily temperature at three stations

influence of temperature on δ^{18}O and δD in precipitation, linear regressions using the δ^{18}O and δD values of individual precipitation events and average daily temperatures were analyzed in Fig. 5. Results show an overall clear positive correlation at the three stations, indicating that temperature effects control δ^{18}O and δD in precipitation. For Houxia station, the δD and δ^{18}O of precipitation increased 6.11 ‰ per °C ($r^2 = 0.69, p < 0.01$) and 0.84 ‰ per °C ($r^2 = 0.74$, $p < 0.01$), respectively, in Fig. 5a. The δD and δ^{18}O in precipitation at Glacier No. 1 station increased 6.32 ‰ per °C ($r^2 = 0.53$, $p < 0.01$) and 0.83 ‰ per °C ($r^2 = 0.57$, $p < 0.01$), respectively, in Fig. 5b. At Zongkong station, the δD and δ^{18}O of precipitation increased 5.76 ‰ per °C ($r^2 = 0.57$, $p < 0.01$) and 0.79 ‰ per °C ($r^2 = 0.63$, $p < 0.01$), respectively, in Fig. 5c. Furthermore, the slightly better linear relation is between δ^{18}O and temperate than that of δD (Fig. 5). Results suggest that precipitation δD and δ^{18}O can be reliable indicators of regional temperate fluctuations in the upper Urumqi River Basin.

Moisture trajectory analysis and *d*-excess values in precipitation

Identifying the source area of precipitated water is very important for understanding the detailed structure of the hydrological cycle. The *d*-excess variations in precipitation can help us to better understand the spatial and temporal variations of moisture sources and moisture recycling conditions (Stewart 1975; Jouzel and Merlivat 1984). Based on NCEP/NCAR reanalysis datasets for the upper Urumqi River Basin and its adjacent regions, the preliminary proposed origins for the water entering the study area could be identified. Using datasets from the monthly mean NCEP/NCAR reanalysis data, the mean wind and relative humidity fields (%) at 500 hPa during 2006 summer (June–August) and winter (December–February) were calculated over China and adjacent regions (Fig. 6), which represent the summer and winter moisture origin conditions, respectively. According to Fig. 6, the water sources of the upper Urumqi River Basin and its adjacent regions were relatively simple compared to other parts of China, and the westerly air masses dominated this area in both summer and winter seasons.

Different moisture origins and water recycling mechanisms result in the temporal and spatial distribution of *d*-excess parameter, which has been used as a diagnostic tool to interpret the contribution of water vapor from different sources at a specific location (Gat 1996; Yamanaka et al. 2002; Liu et al. 2008). Figure 4 exhibits the seasonal variation of *d*-excess in precipitation at the three stations along the upper Urumqi River Basin. In order to more precisely determine the origin of the moisture, three-dimensional isentropic back-trajectories of air masses delivering precipitation to the study sites were derived using the HYSPLIT model, version 4 from the NOAA Air Resources Laboratory. This model provides insight into the history of air masses for precipitation events sampled in this study, and which has been performed in other similar studies relevant to air parcel trajectories with the isotopic composition of rainfall (Lee et al. 2003; Burnett et al. 2004; Pfahl and Wernli 2008; Sjostrom and Welker 2009; Ersek et al. 2010). HYSPLIT model relies on gridded meteorological data sets and uses a predictor–corrector method for calculating particle trajectories.

In order to determine the source of air masses and history of precipitation events occurred in the study area, air mass isentropic back-trajectory models have been employed for the analysis of 324 precipitation samples. All back-trajectories were started at 3,500, 2,500, and 1,500 m above the ground level (AGL) and were traced back 96 h

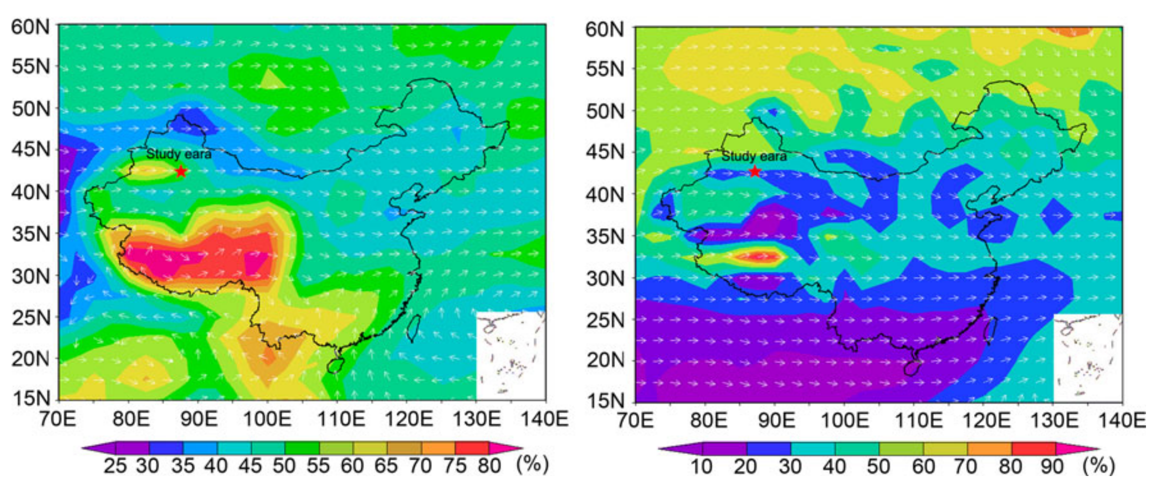

Fig. 6 Spatial distributions of the mean wind fields (*arrows*) and relative humidity fields (*colors*) at 500 hPa during 2006 summer (June–August) (**a**) and winter (December–February) (**b**) over China and adjacent regions. *Arrows* indicate wind direction and *colors* represent humidity (%)

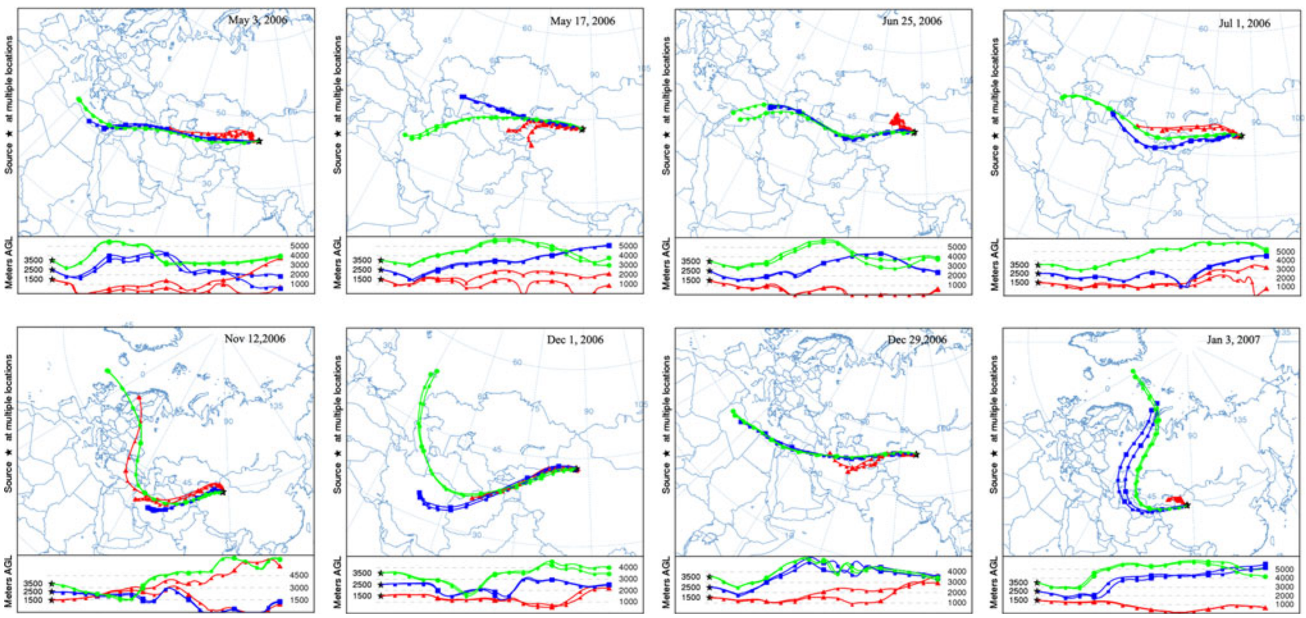

Fig. 7 HYSPLIT reverse-calculated 96 h trajectories ending at Glacier No.1 and Houxia stations. For each trajectory model, the *green*, *blue*, and *red lines* in map view represent the path of air parcels terminating at 3,500, 2,500, and 1,500 m AGL for the 96 h period prior to the specified date. *Vertical motion* for each air parcel as calculated by HYSPLIT is shown below each map

before arrival using archived data from the Global NOAA-NCEP/NCAR reanalysis data on a latitude–longitude grid (2.5 degree) meteorological dataset. Results from four representative examples of 3 May 2006, 17 May 2006, 25 June 2006, and 1 July 2006 were reported in Fig. 7 representing summer moisture origin conditions; and four representative examples of 12 November 2006, 1 December 2006, 29 December 2006 and 3 January 2007 representing winter moisture origin conditions, reverse-calculated 96 h trajectories ending from the Glacier No. 1 and Houxia stations at 12:00 (04:00 UTC) Beijing time. These results adequately indicate a dominant effect of westerly air masses in summer and the integrated influence of westerly and polar air masses in winter for precipitation in the study area.

The upper Urumqi River Basin is located in the arid inner continent of northwest China, extreme continental location, most distant from the oceans of the world. The stable isotopic compositions in precipitation are greatly depleted due to the long distance from the coast. Higher *d*-excess values (>10 ‰), throughout the year, demonstrate that water vapor is intensively recycled. In winter, due to the cold and dry westerly and northern moisture transport, *d*-excess values in precipitation are usually higher than other seasons (>20 ‰). In summer, the high relative humidity over the Atlantic Ocean carried by westerly air masses gives rise to comparatively lower *d*-excess in the subsequent precipitation events. In addition, in summer the re-evaporation of raindrops below the cloud base in arid areas, especially in the case of long-lasting light rain, might give rise to extremely low *d*-excess values in subsequent precipitation (Stewart 1975; Gat 1996). While in winter, the non-equilibrium effect during snow formation in <−10 °C clouds, where vapor was supersaturated with respect to snow, might result in much higher *d*-excess values (Jouzel and Merlivat 1984; Fritz et al. 1987). The characteristic of *d*-excess in individual precipitation events therefore varied on a seasonal scale in the study area, with relatively lower *d*-excess values occurring in summer and extremely high values in winter.

Conclusions

Based on measured δ^{18}O and δD values, meteorological data, and the NCEP/NCAR reanalysis data, this study reveals the spatial and temporal variations of δ^{18}O and δD in the event-based precipitation along the upper Urumqi River Basin. Observations at three stations showed that δ^{18}O and δD values in precipitation varied significantly, especially at Houxia station with an extremely large range in δ^{18}O from −27.56 to 1.67 ‰. The seasonal variation of δ^{18}O in precipitation was especially remarkable, with high values in summer and low values in winter. Moreover, the δ^{18}O and δD in precipitation exhibited a significant temperature effect and can be used as reliable temperature indicators in the upper Urumqi River Basin.

Both the slope and intercept of the LMWLs at the three stations along the upper Urumqi River Basin were Glacier No.1 > Zongkong > Houxia station. Results also showed that the *d*-excess values displayed a seasonal fluctuation.

In winter, precipitation was rather limited with extremely high *d*-excess values, but during summer, precipitation was fairly abundant with comparatively lower *d*-excess. Based on the NCEP/NCAR reanalysis data and three-dimensional isentropic back-trajectories in HYSPLIT model, this study indicates that dominant westerly air masses in summer and the integrated westerly and polar air masses in winter are the moisture origins for precipitation events in the upper Urumqi River Basin.

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