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Quantifying recycled moisture fraction in precipitation of an arid region using deuterium excess

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ABSTRACT

Terrestrial moisture recycling by evapotranspiration has recently been recognised as an important source of precipitation that can be characterised by its isotopic composition. Up to now, this isotope technique has mainly been applied to moisture recycling in some humid regions, including Brazil, Great Lakes in North America and the European Alps. In arid and semi-arid regions, the contribution of transpiration by plants to local moisture recycling can be small, so that evaporation by bare soil and surface water bodies dominates. Recognising that the deuterium excess (d-excess) of evaporated moisture is significantly different from that of the original water, we made an attempt to use this isotopic parameter for estimating moisture recycling in the semi-arid region of Eastern Tianshan, China. We measured the d-excess of samples taken from individual precipitation events during a hydrological year from 2003 to 2004 at two Tianshan mountain stations, and we used long-term monthly average values of the d-excess for the station Urumqi, which are available from the International Atomic Energy Agency–World Meteorological Organization (IAEA–WMO) Global Network of Isotopes in Precipitation (GNIP). Since apart from recycling of moisture from the ground, sub-cloud evaporation of falling raindrops also affects the d-excess of precipitation, the measured values had to be corrected for this evaporation effect. For the selected stations, the sub-cloud evaporation was found to change between 0.1 and 3.8%, and the d-excess decreased linearly with increasing sub-cloud evaporation at about 1.1‰ per 1% change of sub-cloud evaporation. Assuming simple mixing between advected and recycled moisture, the recycled fraction in precipitation has been estimated to be less than $2.0 \pm 0.6\%$ for the Tianshan mountain stations and reach values up to $15.0 \pm 0.7\%$ in the Urumqi region. The article includes a discussion of these findings in the context of water cycling in the studied region.

Keywords: deuterium excess, moisture recycling, sub-cloud evaporation, Eastern Tianshan, arid region

1. Introduction

Terrestrial moisture produced by evapotranspiration has been recognised as an important component of the atmospheric moisture balance (Savenije, 1995; Trenberth, 1999; Trenberth et al., 2003; Bisselink and Dolman, 2009; Seneviratne et al., 2010). For the Amazon Basin, the contribution of evapotranspiration to the precipitation in this area, defined as recycling fraction, has been estimated to range from 25% to 35% (Eltahir and Bras, 1994). In general, the recycling fraction increases with the size of the study area (Trenberth, 1999) and is subject to seasonal and inter-annual climatic variations. For example, for a region in North China from 33 to 40°N and 110 to 120°E, the recycled fraction was 14.1% in the relatively wet month of May 1969 while in the comparatively dry month of May 1971, the fraction was 22.8% (Shen et al., 2003). Above all, the contribution of local evapotranspiration to precipitation depends on the characteristics of the land surface and climate. While under humid conditions with dense plant cover, transpiration of plants controls the moisture recycling, in arid and semi-arid regions, evaporation from bare soil and surface water bodies is likely to dominate this process.

It is well established (Craig and Gordon, 1965) that evaporation changes the oxygen-18 (^{18}O) and deuterium (^{2}H) isotopic composition of the water in such a way that the deuterium excess (d-excess $= \delta^{2}H - 8*\delta^{18}O$,

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(Dansgaard, 1964)) of the evaporated vapour becomes higher than the one of the evaporating water (Salati et al., 1979; Gat and Matsui, 1991). In contrast to evaporation, transpiration and condensation practically do not affect the d-excess (Gat, 2005). Therefore, the d-excess in precipitation that includes recycled moisture can be used to estimate the evaporation component of the recycled fraction (Froehlich et al., 2008; Peng et al., 2011).

Water scarcity is quite critical to the large population in Central Asia, especially the thirsty Xinjiang Uygur autonomous Region of China, where Tianshan Mountains are located. This region suffers from extreme climatic events such as spring floods and droughts (Kong and Pang, 2012). To improve the water resources management, a better understanding of the regional moisture circulation, including moisture recycling is required. However, the contribution of moisture recycling to precipitation in Xinjiang has never been quantified due to difficulties in obtaining sufficient data for traditional meteorological methods.

Taking into consideration that evaporation from the ground (bare soil, surface water bodies) likely dominates moisture recycling in areas with low or even negligible plant cover, we have been able to quantify for the first time this recycling contribution in Xinjiang Uygur autonomous region of China by applying the new d-excess approach. In this way, it has been exemplified that traditional methods determining oceanic moisture sources can be supplemented by this d-excess method in studies of continental moisture sources and recycling in dry regions.

To this end, we measured the isotopic composition of water samples taken from individual precipitation events during a hydrological year from 2003 to 2004 at two Tianshan mountain stations (Pang et al., 2011), and we analysed the isotopic data for the meteorological station Urumqi which is available from the International Atomic Energy Agency–World Meteorological Organization (IAEA–WMO) Global Network of Isotopes in Precipitation (GNIP) (IAEA, 2006). The 'GNIP' is run as a database to provide a worldwide survey of the isotopic composition of precipitation, under the general coordination and guidance of IAEA. The d-excess values calculated from the corresponding $\delta^{18}O$ and $\delta^{2}H$ data have been corrected for the effect of sub-cloud evaporation on the falling raindrops (Froehlich et al., 2008). Finally, considering that the isotopic composition of precipitation is a result of a mixing of advected and recycled moisture of a given region, the fraction of recycled moisture has been estimated from the corrected d-excess. The obtained values are less than $2.0 \pm 0.6\%$ for the Tianshan mountain stations and reach values of up to $15.0 \pm 0.7\%$ in the Urumqi region. The article includes a discussion of these findings in the context of water cycling in the studied region.

2. The study area

Xinjiang accounts for about one-sixth of China's land area. Three mountain chains, which are Altai Mountains in the north, Tianshan Mountains in the middle and Kunlun Mountains in the south, border the total region. The Tianshan Mountains divide the province into two large basins, namely Junggar Basin in the north and Tarim Basin in the south (Fig. 1).

Advected moisture of westerlies is the primary source of precipitation in Xinjiang, and sometimes polar air masses reach there (Araguás-Araguás et al., 1998; Dai et al., 2006; Tian et al., 2007). Recycled moisture has been considered to be another source influencing local climatic patterns (Pang et al., 2011).

Xinjiang has typical continental arid climate. In Xinjiang, the average temperature and precipitation from 1951 to 2009 have been 6.8°C and 267 mm, respectively. In general, temperature is below 0°C during 7–8 months. There is sporadic precipitation and most of it occurs in the mountainous areas.

In the whole of Xinjiang, water surface potential evaporation is 800–1200 mm in alpine regions and 1600–2200 mm in basins; continental evaporation is 100–300 mm in the mountain regions, 250–400 mm in the agricultural development zone and 10–100 mm in deserts (Dong and Deng, 2005).

The two sampling sites of Houxia (87°11′E, 43°17′N, 2100 m a.s.l.) and Gaoshan station (86°50′E, 43°06′N, 3545 m a.s.l.) are located within the Urumqi River catchment in Eastern Tianshan, in the Xinjiang Uygur autonomous region of China (Fig. 1). Details about the two stations can be seen in Pang et al. (2011). The GNIP station of Urumqi (87°37′E, 43°47′N, 918 m a.s.l.) is located approximately 120 km north of Gaoshan station (Fig. 1).

3. Methods

3.1. Sampling and database

A total of 147 samples were collected from April 2003 to July 2004, with the corresponding meteorological parameters, that is, amount of precipitation, air temperature and humidity measured. Isotopes were analysed in the Stable Isotope Laboratory, Institute of Geology and Geophysics, Chinese Academy of Sciences, with a precision of 0.02‰ and 0.2‰, for $\delta^{18}O$ and $\delta^{2}H$, respectively. Results are reported as relative to the standard VSMOW (Vienna Standard Mean Ocean Water). Details of all sampling and analysis and isotope results are presented by Pang et al. (2011). The isotopic data of Urumqi station, and the relevant meteorological data, including the amount of

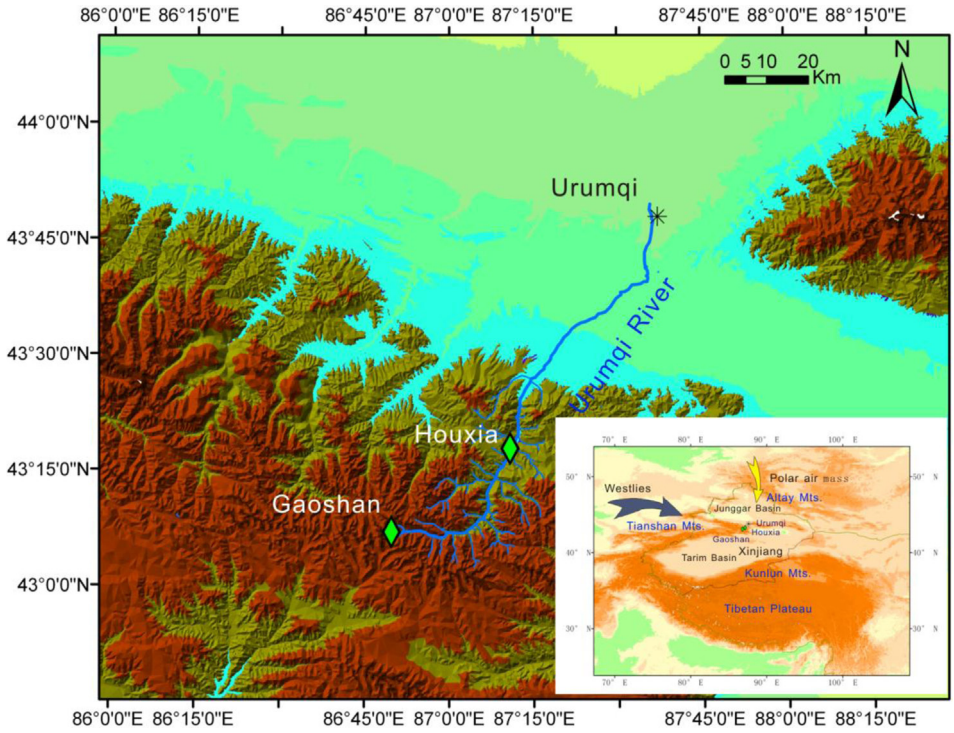

Fig. 1. Geographical distribution of sampling sites and Urumqi station, derived from database of the International Atomic Energy Agency–World Meteorological Organization (IAEA–WMO) Global Network of Isotopes in Precipitation (GNIP). The inset is schematic representation of the moisture-controlling weather patterns and rainfall regime in the study area (after Araguás-Araguás et al., 1998).

precipitation, air temperature and humidity, are derived from GNIP network (IAEA, 2006). Table 1 summarises the information on sampling and data. The full data set of eventful precipitation isotopes at Houxia and Gaoshan stations is available at http://www.isoh2o.org/cn/resource/2012-12-14/171.html.

3.2. *The effect of sub-cloud evaporation*

It is known that sub-cloud evaporation decreases the d-excess of precipitation while moisture recycling increases it (Froehlich et al., 2008). Thus, the calculation of the recycling fraction requires correcting the measured d-excess in precipitation for the effect of sub-cloud evaporation. Froehlich et al. (2008) were able to show that this effect can be determined by the expression:

$$d - d_c = {}^{2}F - 8\,{}^{18}F \tag{1}$$

where d and d_c are d-excess at the level of the sampling station and the cloud base, respectively. The parameters ^{2}F and ^{18}F are defined as follows:

$${}^{i}F = \left(1 - \frac{{}^{i}\gamma}{{}^{i}\alpha}\right)\left(f^{i_\beta} - 1\right) \tag{2}$$

where i is '2' (^{2}H) and '18' (^{18}O), respectively; α is the equilibrium fraction factor for deuterium and oxygen-18

Table 1. Summary of samples for isotopes in precipitation

Station	Location		Altitude,	Mean annual	Annual			
	Latitude	Longitude	m.a.s.l	temp., °C	precipitation, mm	Sampling	Sampling period	Data source
Gaoshan	43°06′	86°50′	3545	−2.6	390	Event-based	April, 2003–March, 2004	This study
Houxia	43°17′	87°11′	2100	1.1	424	Event-based	May, 2003–April, 2004	This study
Urumqi	43°47′	87°37′	918	7.7	306	Monthly	1968–2003	GNIP

which depends on the condensation temperature (Majoube, 1971). The parameters γ and β are given by the expressions

$$^{i}\gamma = \frac{^{i}\alpha h}{1 - {}^{i}\alpha(D/D')^{n}(1-h)} \quad (3)$$

$$^{i}\beta = \frac{1 - {}^{i}\alpha(D/D')^{n}(1-h)}{{}^{i}\alpha(D/D')^{n}(1-h)} \quad (4)$$

where h is the relative humidity, D and D′ are the diffusion constants of $^{1}H^{1}H^{16}O$ and $^{1}H^{2}H^{16}O$ ($^{1}H^{1}H^{18}O$) in air and the ratio D/D′ is 1.024 (1.0289) (Stewart, 1975). The parameter f is the remaining fraction of the water-drop mass, which depends on the evaporation rate (v_{evap}), initial radius (r_{in}) and fall time of the drop (t). The evaporation rate of falling drop has been determined by the expression (Kinzer and Gunn, 1951):

$$v_{evap} = 4\pi a D(1 + \frac{Ea}{s'})(\rho_a - \rho_b) \quad (5)$$

where a is the radius of falling drops, E is a dimensionless quantity, which measures the actual heat of vapour exchange, and s′ represents the effective thickness of a shell around the drop; ρ_a and ρ_b are density at the surface of the falling drop and in the ambient air, respectively. The first factor of eq. 5 ($4\pi a(1 + \frac{Ea}{s'})$) is mainly determined by the drop size and ambient temperature, and the second factor ($D(\rho_a - \rho_b)$) by humidity and temperature. Thus, the calculation of both factors requires information on drop size, humidity and temperature (Kinzer and Gunn, 1951).

The fall time of the water drop can be calculated by fall velocity (v) and distance between cloud base and ground. For the fall velocity, the relationship given by Best (1950) has been used:

$$v = 9.58\{1 - \exp[-(\frac{r}{0.885})^{1.147}]\} \quad (6)$$

where r is the water drop radius. Assuming that precipitation forms close to the cloud base at around the 850 hpa (corresponding to the average cloud base level), we can estimate the fall time of the water-drop. With the meteorological data (see section 3.1), the effect of sub-cloud evaporation can then be determined.

3.3. *Recycling of continental moisture*

To calculate the recycling fraction, we used a two-component mixing model suggested by Peng et al. (2005). Assuming that the precipitation represents a mixture of advected vapour and moisture recycled by evaporation from the ground, the recycling fraction can be derived from the relationship

$$f_c = \frac{d_c - d_{adv}}{d_{evap} - d_{adv}} \quad (7)$$

where f_c is the fraction recycled by continental evaporation, d_c is the d-excess of local precipitation corrected for the effect of sub-cloud evaporation, and d_{adv} and d_{evap} are d-excess of advected vapour and recycled evaporated moisture, respectively.

According to the vapour pressure–temperature relationship, it can be concluded that at ambient temperature below 0°C, both sub-cloud evaporation and terrestrial moisture recycling are negligible. This situation is given for several months during the winter season at the Tianshan stations Houxia and Gaoshan. Under such conditions, the d-excess measured in local precipitation corresponds to the one of the advected vapour. From the measured data, the following correlation has been found for these stations:

$$d_{adv} = -0.52T + 11.6 \quad (8)$$

where the ambient temperature T is in °C and the d-excess in ‰. Therefore, d-excess for the advected flux component can be determined through the d-excess–T relation when temperature is below 0°C at Houxia and Gaoshan stations. The d-excess of the evaporated moisture can be estimated from the Craig–Gordon model (Craig and Gordon, 1965):

$$R_{evap} = \frac{Rw/\alpha - hR_A}{(1-h)\alpha_k} \quad (9)$$

where R represents the isotopic ratio, and the subscript evap, w and A indicate evaporated moisture, evaporating water and atmospheric vapour. Other parameters are the same as in the equations above. α_k is the kinetic fraction factor (for deuterium: $^{2}\alpha_k$ and oxygen-18: $^{18}\alpha_k$), for which the values used by Froehlich et al. (2008) have been adopted:

$$^{2}\alpha_k = 1 + 0.024 \cdot n \quad (10)$$

$$^{18}\alpha_k = 1 + 0.0289 \cdot n \quad (11)$$

with n = 0.58 (Stewart, 1975).

4. Results and discussion

The effect of sub-cloud evaporation on d-excess in precipitation has been calculated assuming a radius of water drop of 0.37 mm, which is characteristic for Eastern Tianshan (Li et al., 2003). With eqs. 1–6, and the relevant meteorological parameter, the effect of sub-cloud evaporation was estimated for the months with temperatures above 0°C (Peng et al., 2005; Froehlich et al., 2008): for

Gaoshan from June to August, Houxia from April to August and Urumqi from April to October.

Figure 2 shows that the decrease in d-excess changes from $-0.1‰$ at an evaporated fraction of 0.1% to $-4.5‰$ at 3.8% evaporated fraction. It should be noted that the changes in d-excess for the three stations Gaoshan, Houxia and Urumqi are identical to each other, numerically between 1.1 and 1.2‰ per 1% evaporated fraction and to that found by Froehlich et al. (2008) for the humid Alps region (Table 2).

The evaporated fraction is a reflection of humidity and temperature: low temperature and high humidity at Gaoshan and Houxia stations result in less evaporation than that at Urumqi station. This can also be seen clearly in different months at Urumqi station: in April, the humidity is 49% and the temperature is 10.2°C, while both values turn out to be 41% and 22.7°C in August, leading to the significant difference of evaporated fraction. A relative low humidity and high temperature will generate a larger evaporation, which can further support the theory that snow samples have small or negligible sub-cloud evaporation; from November to March the humidity is permanently above 80% at Urumqi station and the temperature below 0°C.

To estimate the monthly averages of the recycled fraction by eq. 7, the monthly average d-excess has been calculated using the corrected d-excess values of the individual precipitation events in the given month. The d-excess of advected moisture (d_{adv}) and evaporated moisture (d_{evap}) are calculated by eq. 8 and eqs. 9–11, respectively. The annual weighted mean isotopic composition of precipitation is used to calculate the isotopic ratio of the evaporating water Rw (eq. 9) for ^{18}O and ^{2}H at each station.

The procedure used to quantify the processes affecting isotopes in precipitation is based on a chain of equations

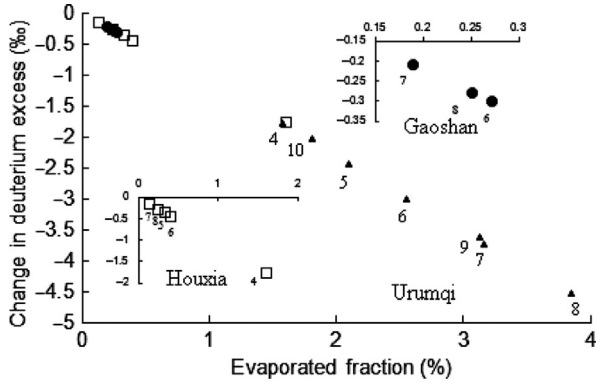

Fig. 2. Sub-cloud evaporation: change of the d-excess with increasing evaporated fraction estimated at Gaoshan, Houxia and Urumqi stations. The numbers near the triangle symbol represent the month (4 – April, 5 – May, etc.).

Table 2. Change of d-excess with increasing evaporated fraction

Station	K (‰/%)
Gaoshan	−1.1
Houxia	−1.1
Urumqi	−1.2
Alps mountains	−1.1

(eqs. 1–11) that propagates the uncertainty in the determination of the recycled fraction f_c. To assess the overall uncertainty in the determination of f_c by this method, a sensitivity analysis was performed showing how changes (uncertainties) in the main ambient parameters T, h and p affect the final result (f_c). We find that the annual average recycled fraction is most sensitive to temperature, as it increases by approximately 0.47% with average temperature rising by 1°C. The sensitivity to humidity and precipitation amount is lower because it only changes in a magnitude of less than 0.05%, with humidity changing by 10% or annual precipitation changing by 100 mm.

Subsequently, a Monte-Carlo analysis was conducted, which takes into account the uncertainties of these different parameters of $\delta^{18}O$, $\delta^{2}H$, d_{evap} and r introduced by eqs. 1–11. Water isotopes are analysed with an uncertainty of 0.02‰ and 0.2‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively. Radius of water drop varies between different observations with an uncertainty of 0.05 mm (Li et al., 2003). Eq. 8 is a fitted empirical equation with an uncertainty of 1.7‰ for d_{adv} under the significance level of 0.05. The final uncertainty of recycled fraction (f_c) is estimated via a Monte-Carlo simulation of 1000 trials during which the parameters ($\delta^{18}O$, $\delta^{2}H$, d_{evap} and r) are sampled in their respective normal distributions. The results suggest that the uncertainty of monthly recycled ratio is approximately 0.7%, while the uncertainty of annual recycled ratios for Urumqi, Houxia and Gaoshan stations are 0.4%, 0.6% and 0.4%, respectively. Thus, the 'd-excess' method to compute the recycled fraction can be useful as it has a relative lower uncertainty.

Table 3 shows that with increasing altitude from Urumqi to Gaoshan station, the recycling fraction decreases gradually, and nearly no recycling moisture is mixed in precipitation over Gaoshan station, which is consistent with the qualitative conclusions in Pang et al. (2011).

Figure 3 shows the estimated seasonal variation of the recycling fraction for the GNIP station, Urumqi. During the period from March to June, the values are lower than the annual average of $8.0 \pm 0.4\%$, while from August to November they are higher and reach values of more than $12.0 \pm 0.7\%$ in September and October. These figures are in fairly good agreement with the results of Tsujimura et al. (2001) for the region near Nagqu at the Tibetan Plateau.

Table 3. Results of monthly recycling fraction at Gaoshan, Houxia and Urumqi stations

	Recycling fraction (%)											
Station	1	2	3	4	5	6	7	8	9	10	11	12
Gaoshan	0	0	0	0	0	1.0	0	0	*	0	0	0
Houxia	0	0	0	0	1.2	1.8	0.9	0	0	0	0	0
Urumqi	0	7.0	1.7	7.4	5.7	6.8	11.0	12.0	12.4	15.0	4.3	3.5

*No data of humidity in September, 2003, at Gaoshan station.

Measuring oxygen-18 in soil water and precipitation, they estimated that '27% of precipitation might be lost by evaporation from soil surface'. The total precipitation falling at the ground might have been slightly higher because of surface runoff, and thus the value of 27% appears to be the upper limit of the recycled fraction (due to evaporation) as defined by our study.

It should be emphasised that the recycled fraction estimated by our approach is related to evaporation from bare soil and surface water bodies; the contribution of transpiration by plants is not taken into account. Yepez et al. (2003) found that evaporation accounts for 15% of the total evapotranspiration for semi-arid woodland conditions. Chen et al. (2001, 2005) calculated the evapotranspiration rate in northwest China and obtained a value of 0.17 mm/day or 62.05 mm/year. Since the annual precipitation in our study area is approximately 300 mm/year and the weighted average evaporation-recycling rate is 8% or 24 mm/year, the relative contribution of evaporation to the total recycling of moisture is $24/62 = 39\%$. Compared with the figure of 15% found by Yepez et al. (2003), this indicates that in our study area the contribution of transpiration is smaller, which is consistent with the rather desert conditions in Urumqi area.

In summary, our results show that the isotopic approach provides unique information about the water balance in an arid catchment area. The results help better understand cause and effect of the land surface–climate feedback. In particular, this approach to determine moisture recycling under arid and semi-arid conditions has great potential for hydrological studies and water resources management in Central Asia. For instance, regarding considerations to ameliorate the water availability in Xinjiang by water diversion from the sea, our study shows that such considerations should take into account our finding that the contribution of recycled moisture to precipitation would be rather limited.

5. Conclusions

We determined the d-excess of samples taken from individual precipitation events during a hydrological year from 2003 to 2004 at two Tianshan mountain stations, and we used long-term monthly average values of the d-excess for

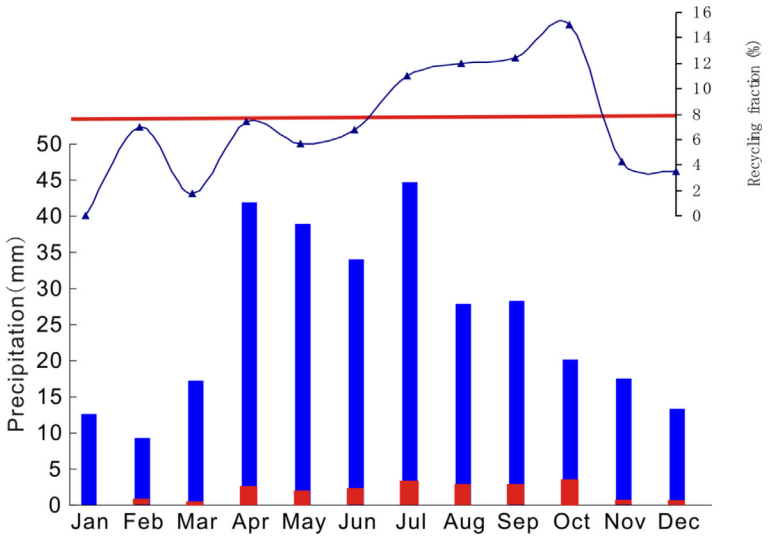

Fig. 3. Recycling fraction in precipitation and precipitation amount at Urumqi station. The blue column is precipitation amount and the red column represents the recycling amount during each month. The curve is the recycling fraction during each month and the red line is a weighted average recycling fraction with the value of 8%.

the station Urumqi, which are available from the IAEA–WMO GNIP. On the basis of the isotopic data of these stations, we estimated the fraction of recycled moisture in precipitation of this region in Eastern Tianshan, Central Asia. Since apart from recycling of moisture from the ground, sub-cloud evaporation of falling raindrops also affects the d-excess of precipitation the measured values had to be corrected for this evaporation effect. The evaporated fraction was found to decrease with increasing altitude of the precipitation collecting station. For the station Urumqi, a value of 3.8% was estimated and for the highest mountain station Gaoshan evaporation appeared to be negligible (0.1%). The d-excess in precipitation was found to decrease 1.1‰ at 1% increase of the evaporated fraction. Assuming simple mixing between advected and recycled moisture, the recycled fraction in precipitation was estimated to be less than $2.0 \pm 0.6\%$ for the Tianshan mountain stations, and it reaches values of up to $15.0 \pm 0.7\%$ in the Urumqi region. Our results are in good agreement with results derived from other methods applied in regions similar to Xinjiang. Thus, for the first time, it is shown that the d-excess approach can be used to study moisture-recycling processes and consequently improve water resources management in arid regions.

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