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Contribution of recycled moisture to precipitation in oases of arid central Asia: A stable isotope approach

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Abstract Terrestrial moisture contributed by surface evaporation and transpiration, also known as recycled moisture, plays an important role in hydrological processes especially across arid central Asia. The stable hydrogen and oxygen isotopes can be used for water budget analysis to calculate the contribution of recycled moisture to precipitation between two locations along the moisture flow. Based on a three-component isotopic mixing model, the moisture recycling in oasis stations of arid central Asia during summer months is assessed. At large oases of Urumqi, the proportional contribution of recycled moisture to local precipitation is approximately 16.2%, and the mean proportions of surface evaporation and transpiration are 5.9% ± 1.5% and 10.3% ± 2.2%, respectively. At small oases like Shihezi and Caijiahu the contribution of recycled moisture is less than 5%, and the proportion of surface evaporation is much less than that of transpiration. The vegetative cover in arid central Asia is generally sparse, but the evapotranspiration contribution to precipitation cannot be ignored at the widely distributed oases. The oasis effect shows great variability depending on locations and water availability for evapotranspiration.

Key Points:
- Moisture recycling in oases under an arid climate is assessed using an isotope method
- Contribution of recycled moisture to precipitation varies from 3.4% to 16.2% in different oases
- Uncertainty of three-component isotopic mixing model is discussed

Supporting Information:
- Supporting Information S1

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1. Introduction

Terrestrial moisture contributed by evapotranspiration (surface evaporation and transpiration), also known as recycled moisture, plays an important role in the water cycle [*Trenberth*, 1999; *van der Ent et al*., 2010, 2014; *Zemp et al*., 2014] (Figure 1). If precipitating vapor is assumed as an intensive mixture of advected and recycled vapor, the relative contributions of each flux (advection, surface evaporation and transpiration) to precipitation remain the same as those to precipitating vapor, and the proportion of recycled moisture to precipitation (f_{re}) can be determined using multiple methods including analytical models [e.g., *Dominguez et al*., 2008; *Pathak et al*., 2014], numerical models [e.g., *Bosilovich and Chern*, 2006; *Goessling and Reick*, 2011] and isotope-based models [e.g., *Froehlich et al*., 2008; *Aemisegger et al*., 2014]. Usually, the value of f_{re} for regions with dense vegetation is larger than that for bare soil, and the growing season has larger f_{re} than the nongrowing season; a large study area generally has greater f_{re} than a small domain, and f_{re} may show great variability at interannual time scales [*van der Ent et al*., 2010; *Hua et al*., 2015].

Among the above-mentioned methods to estimate f_{re}, the isotopic technique is a practical approach due to fractionation processes, such as condensation and evaporation, that leave a characteristic imprint on the water isotopes. The stable hydrogen and oxygen isotopes can be used for water budget analysis to calculate the recycling contribution to precipitation between two locations along the moisture trajectory. If the isotopic compositions of advection, surface evaporation and transpiration fluxes are different from each other, the relative contributions for these sources to precipitation can be solved using isotopic mixing models. Generally, the models can be classified into two-component [e.g., *Peng et al*., 2005; *Froehlich et al*., 2008; *Xu et al*., 2011] and three-component [e.g., *Phillips and Gregg*, 2001; *Peng et al*., 2011] mixing models. Compared with two-component models, which usually do not consider transpiration flux, three-component models are better at distinguishing the relative contributions of advection, surface evaporation and transpiration.

In arid central Asia, water is a critical resource for regional development and most inhabitants live at the oases surrounded by deserts. Over bare unvegetated ground, soil evaporation, instead of transpiration, is dominant in moisture recycling. However, in oases of central Asia, especially the Tianshan Mountains Corridor, the contribution of transpiration vapor from natural vegetation, urban green areas and cropland cannot be ignored. Although a two-component mixing model was previously applied to this region [*Kong et al*., 2013], the moisture contribution of transpiration was not considered. So far, an integrated assessment of

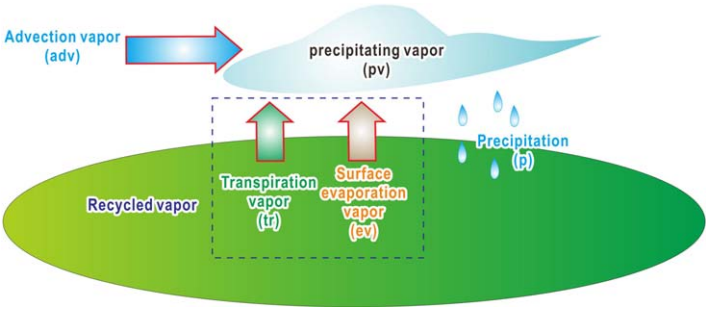

Figure 1. Schema diagram of moisture recycling in precipitation. The precipitating vapor is mixture of advection vapor, transpiration vapor and surface evaporation vapor, and the latter two are called recycled vapor or recycled moisture. The proportional contributions for each flux (advection, transpiration, and surface evaporation) to precipitating vapor are usually assumed to be the same as those to precipitation.

recycled moisture including surface evaporation and transpiration is needed for the oases region. In this study, based on the measured stable isotopic compositions of precipitation during 2012–2013 [*Wang et al.*, 2016], the contributions of recycled moisture to local precipitation at three oasis sites in arid central Asia are estimated, and the oasis effect in an arid climate as well as the uncertainty of the isotopic mixing model are analyzed.

2. Data and Method

2.1. Study Area

The Tianshan Mountains (also known as Tien Shan), a large mountain range in central Asia, is located at the border region of Kyrgyzstan, Kazakhstan and northwestern China (Figure 2). The total length of the range is approximately 2500 km from west to east, and vast deserts (e.g., the Taklimakan Desert and the Gurbantunggut Desert) are located to the north and south of the mountains. In arid central Asia, the Tianshan Mountains are considered a large "wet island" [*Sorg et al.*, 2012]. Many interior rivers originate from the mountains, and glaciers are widely distributed at high elevations. Around the Tianshan Mountains, airflow is dominated by westerly wind all year round [*Bothe et al.*, 2012]. As shown in Figure 3, water vapor flux is very small in winter, and surface air is dry and cold; in contrast, water vapor transport in summer is much stronger than that in winter. Consistent with the seasonality of water vapor flux, most precipitation occurs during summer months from April to October [*Wang et al.*, 2013b; *Zhu et al.*, 2015].

2.2. Observation Network

In this study, four oasis sites on the northern slope of the Tianshan Mountains were selected, including Yining (43°57′N, 81°20′E), Shihezi (44°19′N, 86°03′E), Caijiahu (44°12′N, 87°32′E) and Urumqi (43°47′N, 87°39′E) (Table 1 and Figure 2). The sampling procedures at these stations were implemented by the full-time weather observers in the Yining National Reference Climatological Station (Yining City Meteorological Bureau), the Shihezi National Ordinary Meteorological Observing Station (Shihezi City Meteorological Bureau), the Caijiahu National Basic Meteorological Observing Station and the Urumqi National Basic Meteorological Observing Station (Urumqi City Meteorological Bureau), respectively. In order to eliminate evaporation of precipitation, the rain samples were collected immediately after the end of precipitation events, and stored in 60 mL HDPE (high-density polyethylene) narrow-mouth bottles with waterproof seals. The solid samples were melted at room temperature in a zip lock bag before being sealed in HDPE bottles.

The precipitation samples were stored frozen, and then analyzed using a liquid water isotope analyzer DLT-100 (Los Gatos Research, Inc.) in the Stable Isotope Laboratory, College of Geography and Environmental Science, Northwest Normal University. Every sample and isotopic standards were injected sequentially six times using a microliter syringe, and the average of last four injection results was accepted as the final value with the first two injections being discarded [*Lis et al.*, 2008]. Isotope ratio of the samples is expressed as parts per mil (‰) relative to the Vienna Standard Mean Ocean Water (V-SMOW) using δ notation:

$$\delta_{\text{sample}} = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \times 1000‰, \quad (1)$$

where δ_{sample} is isotope ratio of the samples relative to V-SMOW, R_{sample} is the ratio of D/H or $^{18}O/^{16}O$ in the samples, and R_{standard} is the ratio of D/H (0.00015576) or $^{18}O/^{16}O$ (0.0020052) in V-SMOW. The precision of measurement is ±0.6% for δD and ±0.2% for $\delta^{18}O$, respectively.

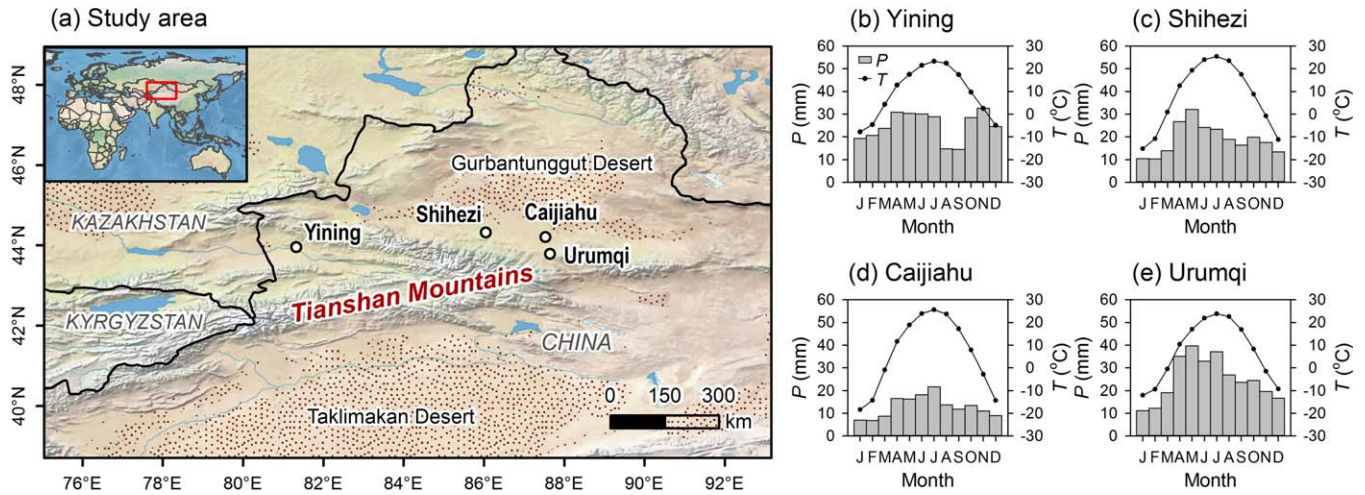

Figure 2. (a) Map showing locations of the Tianshan Mountains and sampling stations in central Asia. Satellite-derived land cover is acquired from Natural Earth (http://www.naturalearthdata.com), and areas of deserts are based on *Wang et al.* [2005]. (b–e) Monthly variations of air temperature and precipitation amount at Yining, Shihezi, Caijiahu and Urumqi during 1981–2010. The line represents air temperature (*T*) and histogram represents precipitation amount (*P*).

The observation period was from August 2012 to September 2013, and the basic characteristics of seasonal variation and meteorological controls of stable isotopes at these stations were analyzed by *Wang et al.* [2016]. During winter months from November to March, surface air temperature is usually below 0°C, and surface evaporation from frozen soil and open water as well as transpiration from plants is very limited [*Gao et al.*, 2006; *Liu et al.*, 2010]. In this study, we focused on recycled moisture in precipitation during summer months, and a subset from April to October was applied. The event-based isotope ratios were precipitation-weighted for each station, and the weighted averages during summer months in this study were acquired from *Wang et al.* [2016].

2.3. Three-Component Mixing Model

2.3.1. Theoretical Considerations

Precipitating vapor is assumed to be a mixture of advected vapor and recycled vapor, where the proportion of each component in precipitation remains the same as that in precipitating vapor [*van der Ent et al.*, 2010]. The proportion of recycled moisture in precipitation (f_{re}) can be expressed as

$$f_{re} = \frac{P_{re}}{P_{re} + P_{adv}}, \tag{2}$$

where P_{re} and P_{adv} are precipitation originated from recycled and advected moisture, respectively.

Recycled moisture includes fluxes from surface evaporation (e.g., from ocean, lake, river and soil) and transpiration (from plant stomata) [*Brubaker et al.*, 1993], and then equation (2) is transformed to

$$f_{re} = \frac{P_{tr} + P_{ev}}{P_{tr} + P_{ev} + P_{adv}}, \tag{3}$$

where P_{tr}, P_{ev} and P_{adv} are precipitation originated from transpiration, surface evaporation and advection, respectively.

A three-component mixing model can be expressed as follows:

$$\delta_{pv} = \delta_{tr} f_{tr} + \delta_{ev} f_{ev} + \delta_{adv} f_{adv}, \tag{4}$$

$$f_{tr} + f_{ev} + f_{adv} = 1, \tag{5}$$

where f_{tr}, f_{ev} and f_{adv} are proportional contributions of transpiration, surface evaporation and advection to precipitation, respectively, and values of δ_{pv}, δ_{tr}, δ_{ev} and δ_{adv} are stable isotope (D or ^{18}O) in precipitating vapor, transpiration vapor, surface evaporation vapor and advection vapor, respectively.

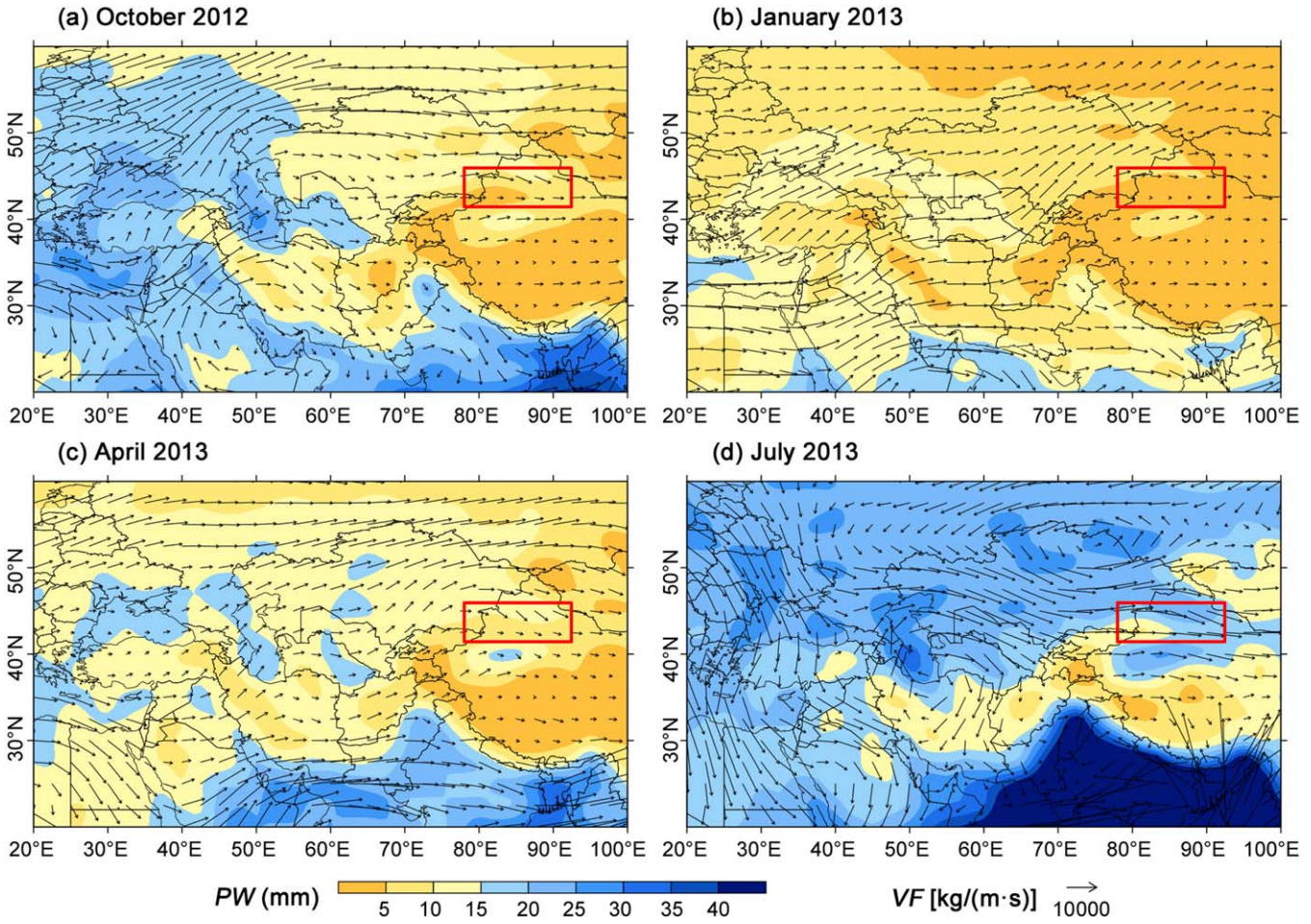

Figure 3. Monthly mean precipitable water (*PW*) and vapor flux (*VF*) from surface to 300 hPa in central Asia in October 2012, January, April, and July 2013 based on National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1. The study region is marked in red frame.

In this study, a three-component mixing model was solved using the software IsoError [*Phillips and Gregg*, 2001] (Ver. 1.04, available at http://www.epa.gov/eco-research), and the estimates (mean and standard error) and confidence intervals (upper and lower 95%) of proportional contributions of each source to the mixed vapor (δ_{pv}) can be calculated.

2.3.2. Isotopic Compositions in Precipitating Vapor

With the rapid development of isotope ratio infrared spectroscopy, the in-situ measurements of isotopic compositions in water vapor have been greatly improved across the globe, but vapor isotopic observations are still limited in arid central Asia. In this study, the isotopic compositions in precipitating vapor (δ_{pv}) were calculated using the measured isotopes in precipitation (δ_p) corrected by local evaporation line (LEL), and the calculation for δ_{pv} was processed using the Hydrocalculator software [*Skrzypek et al.*, 2015] (Ver. 1.03, available at http://hydrocalculator.gskrzypek.com). The vapor is not assumed to be in isotopic equilibrium with precipitation, but is calculated by coupled scaling of the vapor and water fractionation as a common fraction to achieve a

Table 1. Latitude, Longitude, Altitude and Long-Term Climatology (*T*—Air Temperature, *P*—Precipitation Amount, *e*—Vapor Pressure and *h*—Relative Humidity) During 1981–2010 at Sampling Stations

				Annual Climatology				Summer Months Climatology			
Station	Latitude	Longitude	Altitude (m)	*T* (°C)	*P* (mm)	*e* (hPa)	*h* (%)	*T* (°C)	*P* (mm)	*e* (hPa)	*h* (%)
Yining	43°57′	81°20′	662.5	9.5	298.9	8.3	65	17.8	178.0	11.2	57
Shihezi	44°19′	86°03′	442.9	7.8	226.9	7.7	64	18.7	161.3	10.9	53
Caijiahu	44°12′	87°32′	440.5	6.5	153.8	6.7	62	18.4	111.4	9.6	49
Urumqi	43°47′	87°39′	935.0	7.3	298.6	6.2	58	17.3	219.8	8.4	45

best-fit to the slope of evaporative enrichment trend for local surface water [*Bennett et al.*, 2008; *Gibson and Reid*, 2014]. A comparison of atmospheric vapor isotopes using classical method with isotopic equilibrium assumption and this method (best-fit to evaporation line) was presented by *Gibson and Reid* [2014].

The value of δ_{pv} [*Gibson and Reid*, 2014] is calculated using precipitation isotopes:

$$\delta_{pv}=\frac{\delta_p-k\varepsilon^+}{1+k\varepsilon^+}, \tag{6}$$

where δ_p is isotopic compositions in precipitation acquired from *Wang et al.* [2016], k is adjusting parameter, and ε^+ is equilibrium fractionation factor between water and vapor and is expressed as

$$\varepsilon^+=\alpha^+-1, \tag{7}$$

where α^+ is equilibrium fractionation factor [*Horita and Wesolowski*, 1994] depending on temperature:

$$10^3\ln{}^2\alpha^+=\frac{1158.8T^3}{10^9}-\frac{1620.1T^2}{10^6}+\frac{794.84T}{10^3}-161.04+\frac{2.9992\times10^9}{T^3}, \tag{8}$$

$$10^3\ln{}^{18}\alpha^+=-7.685+\frac{6.7123\times10^3}{T}-\frac{1.6664\times10^6}{T^2}+\frac{0.35041\times10^9}{T^3}, \tag{9}$$

where T is temperature in K. Note that equations in this study are formulated for values of δ, ε and later h in decimal notation.

To acquire the parameter k in equation (6) [*Skrzypek et al.*, 2015], equation (6) was initially solved using $k=1$ and then the LEL slope (S_{LEL}) can be calculated as:

$$S_{LEL}=\frac{\left(h-10^{-3\,18}\varepsilon\right)\left[h\left({}^2\delta_{pv}-{}^2\delta_p\right)+{}^2\varepsilon\left(1+10^{-3\,2}\delta_p\right)\right]}{\left(h-10^{-3\,2}\varepsilon\right)\left[h\left({}^{18}\delta_{pv}-{}^{18}\delta_p\right)+{}^{18}\varepsilon\left(1+10^{-3\,18}\delta_p\right)\right]}, \tag{10}$$

where h is relative humidity, δ_{pv} and δ_p are isotopic compositions in precipitating vapor and precipitation, and ε is the total fractionation factor [*Skrzypek et al.*, 2015] defined as:

$$\varepsilon=\varepsilon^+/\alpha^++\varepsilon_k, \tag{11}$$

where kinetic fractionation factor (ε_k) [*Gat*, 1996] is calculated as:

$$\varepsilon_k=(1-h)\theta nC_D, \tag{12}$$

where h is relative humidity; the weighting value θ for small water body (evaporation flux does not influence ambient humidity) is 1, and for larger water body (like the Great Lakes and the Mediterranean Sea) is 0.5; the value n for a stable layer (like soil and leaf cover) is 1, and for a large open water body is 0.5; the values of C_D are 25.1‰ for hydrogen and 28.5‰ for oxygen, respectively [*Merlivat*, 1978; *Araguás-Araguás et al.*, 2000]. As suggested by *Skrzypek et al.* [2015], the values of θ and n were set to 1 and 0.5, respectively, for calculating vapor isotopes using precipitation isotopes. Then calculations were repeated using k between 0.6 and 1.0 with step width of 0.0001; the final value of k was determined when the difference between S_{LEL} and the measured LEL slope was the lowest or k reached the boundary values (0.6 and 1.0). More details about the procedure were described by *Skrzypek et al.* [2015]. The measured LEL slope applied for correction of δ_{pv} can be derived from pan evaporation experiments and field sampling of surface waters. Based on the stable isotope ratios in lake waters available on the northern slope of the Tianshan Mountains (see supporting information Table S1) [*Li et al.*, 2015; *Yin et al.*, 2010, 2015], a LEL slope of 4.75 ($r^2=0.90$, $p<0.0001$, $n=16$) was determined using least squares regression for this study.

2.3.3. Isotopic Compositions in Transpiration Vapor

Under steady state conditions, the isotope ratios in transpiration vapor (δ_{tr}) from plants are unfractionated with respect to the source water utilized by local plants, and can be measured using the plant stem water especially xylem water [*Yakir and Sternberg*, 2000; *Williams et al.*, 2004]. However, the stable isotopes of water taken up by plants may greatly vary depending on plant water-use strategy, isotopic profile of soil water and many other factors.

The stable isotopic compositions in xylem water of several typical plants as well as soil water were investigated on the northern slope of the Tianshan Mountains during recent years. For example, the average $\delta^{18}O$

values in xylem water of *Reaumuria songarica*, *Nitraria tangutorum* and *Tamarix ramosissima* during growing season were −6.8‰, −9.5‰ and −10.5‰, respectively [*Wu et al*., 2014], and those of *N. sibirica* in spring, summer and autumn were −7.0‰, −11.0‰ and −9.4‰, respectively [*Zhou et al*., 2015], which corresponded to precipitation isotopes between −22.8‰ and 1.7‰ during the same period; the average oxygen isotopes in xylem water of *Haloxylon ammodendron* and *H. persicum* were −9.9‰ and −12.0‰, respectively, which were also within the precipitation isotopic ranges between −26.5‰ and 2.7‰ [*Dai et al*., 2015]; the long-term average $\delta^{18}O$ values in precipitation for this region was −9.9‰, ranging between −24.6‰ and −2.1‰ [*Liu et al*., 2014]. Although it is not technically difficult to measure isotopic composition of xylem water for a specific plant, it is logically complex to use the limited measurements to describe the regional mean covering a great number of species. Considering the great fluctuations of isotopic compositions in xylem water as well as the similarity of xylem and precipitation isotope ratios, in this study the weighted mean precipitation isotopes values were used for δ_{tr}, as suggested by *Peng et al*. [2011].

2.3.4. Isotopic Compositions in Surface Evaporation Vapor

The Craig-Gordon model [*Craig and Gordon*, 1965; *Gat et al*., 1994; *Gat*, 1996] is used to estimate the isotopic composition in surface evaporation vapor (δ_{ev}):

$$\delta_{ev} = \frac{\delta_s/\alpha^+ - h\delta_{adv} - \varepsilon}{1 - h + \varepsilon_k}, \tag{13}$$

where δ_s is isotopic composition of liquid water at the evaporating front, δ_{adv} is isotopic composition of advection vapor, h is relative humidity, α^+ is equilibrium fractionation factor, ε_k is kinetic fractionation factor, and ε is total fractionation factors. For kinetic fractionation factor (ε_k) of soil surface evaporation, $\theta=1$ and $n=1$ in equation (12), as suggested for dry soil similar to this study region [*Wang et al*., 2013a]. Based on data for the northern slope of the Tianshan Mountains (see supporting information Table S1), the averaged isotopic composition in surface water (δ_s) was set to $\delta D = -48.6‰$ and $\delta^{18}O = -5.8‰$.

2.3.5. Isotopic Compositions in Advection Vapor

In a three-component mixing model, the advection direction and isotope in precipitation at the upwind station should be known [*Peng et al*., 2011]. According to the vapor flux (Figure 3) and backward air trajectory [e.g., *Feng et al*., 2013], Yining, the most westerly station, was selected as the upwind station for Shihezi, and then Shihezi was selected for Caijiahu and Urumqi. These sampling stations mainly lie along a west-east trajectory, which share a similar advection direction. In this study, we treated the rainout process in stages, i.e., Stage I from Yining to Shihezi (section 3.1) and then Stages II and III from Shihezi to Caijiahu and Urumqi (section 3.2).

To estimate the isotope ratios in advection vapor (δ_{adv}) from upwind site to target site, when vapor isotopes show a depleting trend along the transport path isotopic fractionation was assumed to be due to Rayleigh distillation:

$$\delta_{adv} = \delta_{pv\text{-}adv} + \left(\alpha^+ - 1\right)\ln F, \tag{14}$$

where $\delta_{pv\text{-}adv}$ is the isotopic composition in vapor at the upwind station and can be calculated using equation (6), α^+ is equilibrium fractionation factor, and F is a ratio between final and initial vapor. It is difficult to acquire a ratio between final and initial vapor, so the parameter F is sometimes estimated using atmospheric water content (e.g., precipitable water amount, humidity mixing ratio or specific humidity) for the two sites [*Peng et al*., 2011]. Because precipitable water positively correlates with surface vapor pressure across the study region ($c=1.657e$ where c is water vapor content in mm and e is surface vapor pressure in hPa, $r^2=0.94$) [*Hu et al*., 2015], we use the surface vapor pressure for each station to calculate the value of F. Here the recycled moisture that has entered the air mass was not considered, because the contribution of recycled moisture in the total air column was very limited and most precipitable water does not cause rainfall but flows outside [*Li and Zhang*, 2003]. If there is no depletion of isotope ratios along the transport trajectory, the vapor isotope ratios derived from the upwind station are directly applied (as suggested by *Peng et al*. [2011]), and the Rayleigh distillation equation was not applied.

3. Results

3.1. From Yining to Shihezi (Stage I)

In Stage I, the moisture was transported from Yining to Shihezi via a westerly trajectory (Table 2). Based on the isotopic composition in precipitation at Yining ($^2\delta_p = -47.4‰$ and $^{18}\delta_p = -7.1‰$) and corresponding

meteorological parameters (T=18.9°C), the isotope ratios of precipitating vapor at Yining are estimated to be $^{2}\delta_{pv}=-100.1‰$ and $^{18}\delta_{pv}=-13.8‰$ using equation (6). Similar procedure is applied to Shihezi, and the estimated hydrogen and oxygen isotope ratios in precipitating vapor at Shihezi are $^{2}\delta_{pv}=-99.0‰$ and $^{18}\delta_{pv}=-13.8‰$. There is no significant depletion of isotope between Yining and Shihezi, and the stable isotope ratios in advection vapor at Shihezi are considered to be same with that in precipitating vapor at Yining ($^{2}\delta_{adv}=-100.1‰$ and $^{18}\delta_{adv}=-13.8‰$). Using a Craig-Gordon model, i.e., equation (13), the isotopic composition of surface evaporation vapor at Shihezi is calculated ($^{2}\delta_{ev}=-170.0‰$ and $^{18}\delta_{ev}=-44.7‰$). The isotope ratios in transpiration vapor are based on weighted mean value in precipitation [*Wang et al*., 2016], i.e., $^{2}\delta_{tr}=-46.1‰$ and $^{18}\delta_{tr}=-7.1‰$.

As shown in Table 3, the proportional contributions for the three components (advection, surface evaporation and transpiration) in precipitation along the path from Yining to Shihezi (Stage I) can be calculated, i.e., f_{tr}=2.8% ± 3.6%, f_{ev}=0.6% ± 1.7% and f_{adv}=96.6% ± 5.3%. In order to have a better understanding about the process, the results above are also visualized in Figure 4. It is clear that advection vapor is dominant source for precipitation at Shihezi.

3.2. From Shihezi to Caijiahu and Urumqi (Stages II and III)

In Stages II and III, the rainout path is considered to be from Shihezi to Caijiahu/Urumqi along the northern slope of the Tianshan Mountains. Caijiahu, a rural site, is close to Urumqi, and the linear distance between the two sampling sites is ~70 km. The calculation procedure for isotope of precipitating vapor (δ_{pv}), transpiration vapor (δ_{tr}) and surface evaporation vapor (δ_{ev}) at Caijiahu and Urumqi in Stages II and III is similar as that in Stage I. For the stable isotope in advection vapor (δ_{adv}), equation (14) is applied. The isotope ratios in precipitating vapor at Caijiahu ($^{2}\delta_{pv}=-106.1‰$, $^{18}\delta_{pv}=-14.7‰$) and Urumqi ($^{2}\delta_{pv}=-114.6‰$, $^{18}\delta_{pv}=-17.0‰$) are much more depleted than the upwind station Shihezi ($^{2}\delta_{pv}=-99.0‰$, $^{18}\delta_{pv}=-13.8‰$), therefore the Rayleigh distillation equation is applied. The ratio between the original and reacted vapor is based on the measured surface vapor pressure (also shown in Table 2). For example, the value F at Caijiahu is a ratio of surface vapor pressure at Caijiahu (9.5 hPa) and Shihezi (11.0 hPa).

Although the two sites of Caijiahu and Urumqi are neighboring, the estimated proportional contributions from each flux (transpiration, surface evaporation and advection) to precipitation are much different. The contributions of transpiration and surface evaporation at Urumqi (f_{tr}=10.3% ± 2.2%, f_{ev}=5.9% ± 1.5%) are larger than those at Caijiahu (f_{tr}=4.3% ± 3.2%, f_{ev}=0.6% ± 1.7%). The value of f_{adv} at Caijiahu is 95.1% ± 4.8%, which is much higher than that at Urumqi (83.8% ± 3.7%). The proportions for each flux at Caijiahu are generally similar to that estimated at Shihezi in Stage I. In addition, if the more distant station Yining is selected as the upwind station for Caijiahu and Urumqi (instead of Shihezi), the proportional contribution of

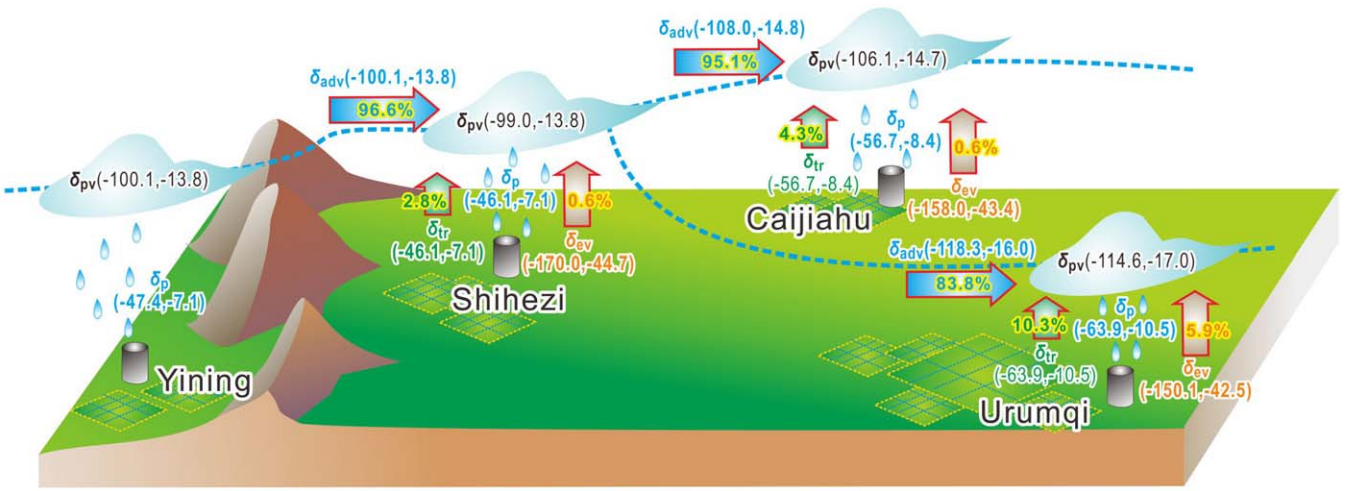

Figure 4. Schema diagram of isotopic composition in precipitation (δ_p) and water vapor (δ_{pv}—precipitating vapor, δ_{tr}—transpiration vapor, δ_{ev}—surface evaporation vapor, and δ_{adv}—advection vapor) along the trajectory of Yining-Shihezi-Caijiahu/Urumqi during summer months based on a three-component mixing model. The isotope ratios (δD and δ^{18}O) in the parentheses for each component are in ‰ using δ-notation. Percentages in % on the arrows denote the average contributions of each flux to local precipitation.

Table 2. Meteorological Parameters (*T*—Air Temperature, *h*—Relative Humidity and *e*—Vapor Pressure), Isotopic Composition of Different Components at Yining, Shihezi, Caijiahu, and Urumqi During Summer Months of the Sampling Period

		Yining	Shihezi	Caijiahu	Urumqi
Meteorological parameters	T (°C)	18.9	18.9	19.0	18.3
	h (%)	53	52	46	43
	e (hPa)	10.7	11.0	9.5	8.6
δD (‰)	δ_p[a]	−47.4	−46.1	−56.7	−63.9
	δ_{pv}	−100.1	−99.0	−106.1	−114.6
	δ_{tr}		−46.1	−56.7	−63.9
	δ_{ev}		−170.0	−158.0	−150.1
	δ_{adv}		−100.1	−108.0	−118.3
δ^{18}O (‰)	δ_p[a)]	−7.1	−7.1	−8.4	−10.5
	δ_{pv}	−13.8	−13.8	−14.7	−17.0
	δ_{tr}		−7.1	−8.4	−10.5
	δ_{ev}		−44.7	−43.4	−42.5
	δ_{adv}		−13.8	−14.8	−16.0

[a]Data are taken from *Wang et al*. [2016].

advection vapor decreases from 95.1% ± 4.8% to 92.0% ± 4.5% at Caijiahu and from 83.8% ± 3.7% to 81.7% ± 3.5% at Urumqi.

4. Discussion

4.1. Oasis Effect Evidenced by Recycled Moisture

In arid central Asia, the widely-distributed oases are considered to greatly influence local climate [e.g., *Lü et al*., 2004], by increasing precipitation and water vapor as well as lowering air temperature and diurnal temperature range within an oasis. Usually, the recycled moisture from surface evaporation and transpiration has relatively depleted isotope ratios. If the recycled vapor from local surface evaporation greatly contributes to the precipitating vapor, the stable isotopes in precipitation may show a depleting trend. As shown in Figure 4, the surface evaporation vapor isotopes are more depleted for each station, than those of precipitation and precipitating vapor.

Because of anthropogenic modification of hydrological process in arid central Asia, a large number of artificial reservoirs and water channels have been constructed to irrigate cropland, and the recycled moisture from urban green areas and irrigated land is much greater than that from bare soil. In large oases (like Urumqi with permanent resident population of ∼3.5 million) with vast urban green areas and reservoirs surrounded by large tracts of irrigated cropland, the moisture recycling is more significant than that in small oases like Shihezi and Caijiahu. In this study, the estimated recycled moisture is up to approximately 16.2% at Urumqi, whereas the ratio is less than 5% at Shihezi and Caijiahu. Compared with Urumqi, the other two stations, Shihezi (a small oasis city) and Caijiahu (a rural town at the margin of oasis), have very different landcover. The oasis effect shows great variability depending on locations and water availability for evapotranspiration.

In arid deserts, the vegetative cover is extremely sparse, and almost all the recycled moisture is sourced from soil evaporation. However, in oases surrounded by deserts, the transpiration vapor from urban green

Table 3. Proportional Contributions of Each Flux (f_{tr}—Transpiration, f_{ev}—Surface Evaporation and f_{adv}—Advection) During Summer Months Based on a Three-Component Mixing Model

	f_{tr} (%)		f_{ev} (%)		f_{adv} (%)	
Path	Mean[a]	CI_{95}[b]	Mean[a]	CI_{95}[b]	Mean[a]	CI_{95}[b]
Yining to Shihezi (Stage I)	2.8 ± 3.6	0.0–10.0	0.6 ± 1.7	0.0–3.9	96.6 ± 5.3	86.1–100.0
Shihezi to Caijiahu (Stage II)	4.3 ± 3.2	0.0–10.6	0.6 ± 1.7	0.0–3.9	95.1 ± 4.8	85.6–100.0
Shihezi to Urumqi (Stage III)	10.3 ± 2.2	5.8–14.7	5.9 ± 1.5	3.0–8.8	83.8 ± 3.7	76.6–91.1
Yining to Caijiahu (Stages I and II)	6.8 ± 3.0	1.0–12.6	1.2 ± 1.6	0.0–4.3	92.0 ± 4.5	83.1–100.0
Yining to Urumqi (Stages I and III)	12.0 ± 2.1	7.9–16.2	6.2 ± 1.4	3.5–9.0	81.7 ± 3.5	74.9–88.6

[a]Mean, average ± standard error.
[b]CI_{95}, lower 95% to upper 95% confidence interval.

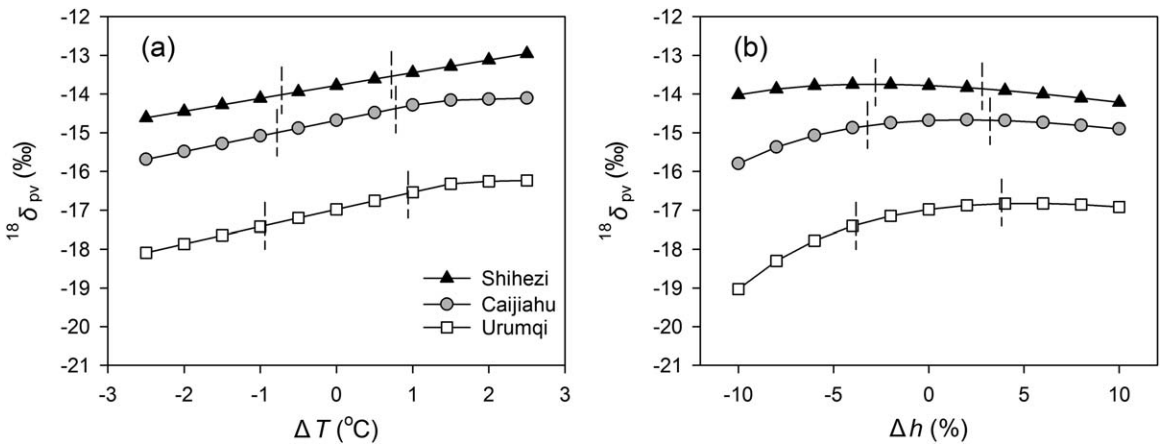

Figure 5. Variation of oxygen isotope ratios in precipitating vapor ($^{18}\delta_{pv}$) under different conditions of temperature (ΔT) and relative humidity (Δh) at Shihezi (triangle), Caijiahu (circle) and Urumqi (square). The dashed vertical lines denote the standard deviation for each line. The standard deviations of temperature and relative humidity are based on the annual average data during summer months (April–October) from 1981 to 2010.

spaces and irrigated cropland may play an important role in moisture recycling. As shown in Figure 4, the recycled moisture from transpiration is always larger than that from surface evaporation. In this study, the ratios of transpiration in evapotranspiration, i.e., $f_{tr}/(f_{tr}+f_{ev})$, are generally comparable with previous studies in oases of arid Northwestern China [e.g., *Liu et al*., 2012; *Wen et al*., 2015]. However, at Urumqi (63.5%), the value of $f_{tr}/(f_{tr}+f_{ev})$ is much lower than at Shihezi (82.2%) and Caijiahu (87.5%).

Similar three-component mixing models have been applied to other regions with different climatic conditions. For example, at Taiwan Island in the western Pacific Ocean [*Peng et al*., 2011], the value of f_{tr} in summer ranges between 29% and 41%, and f_{ev} ranges between 1% and 2%. In contrast, the proportional contribution of recycled moisture in arid central Asia estimated from this study is much less and is consistent with previous results using other methods in the Tianshan Mountain region. Using Urumqi GNIP (Global Network of Isotopes in Precipitation) data, a two-component isotopic mixing model [*Kong et al*., 2013] indicated that the contribution of surface evaporation (f_{ev}) was approximately 8%, and the estimated contribution of recycled moisture including transpiration was approximately 15% using an empirical coefficient; in a nationwide assessment of summertime recycled ratio in precipitation in China based on reanalysis data [*Hua et al*., 2015], the proportional contribution on the northern slope of the Tianshan Mountains was estimated to be 14%. Generally, the three-component mixing model is a practical approach in assessing moisture recycling in an arid condition.

4.2. Model Uncertainty Analysis

In this study, a LEL slope-calibrated method was applied to estimate the stable isotopes in precipitating vapor (and advection vapor as a primary step). Figure 5 and supporting information Table S2 show the variation of $\delta^{18}O$ in precipitating vapor under different conditions of temperature ($\pm 3°C$) and relative humidity ($\pm 10\%$) at each sampling station. For different stations, the sensitivity of stable isotopic compositions varies. It should also be mentioned that the calculation method in this study does not use an assumption of isotopic equilibrium [*Skrzypek et al*., 2015], although this assumption is widely used [e.g., *Peng et al*., 2011; *Xu et al*., 2011]. Logically, a method that does not assume equilibrium is more suitable in an arid climate.

The uncertainty from transpiration vapor isotopes is controlled by the estimation of xylem water isotopes in this study. It is difficult to accurately estimate the regional mean of isotope ratios in xylem or stem water, and the species and coverage should be considered especially for the oases where the surface landcover is greatly modified by human activities. According to *Wu et al*. [2014], *Zhou et al*. [2015], and *Dai et al*. [2015], the measured isotopes in xylem water showed a large fluctuation mainly depending on species and season. Instead the precipitation isotopes were used to estimate transpiration vapor isotopes for each station, as the range of precipitation and xylem water isotopes generally shows a good agreement and the

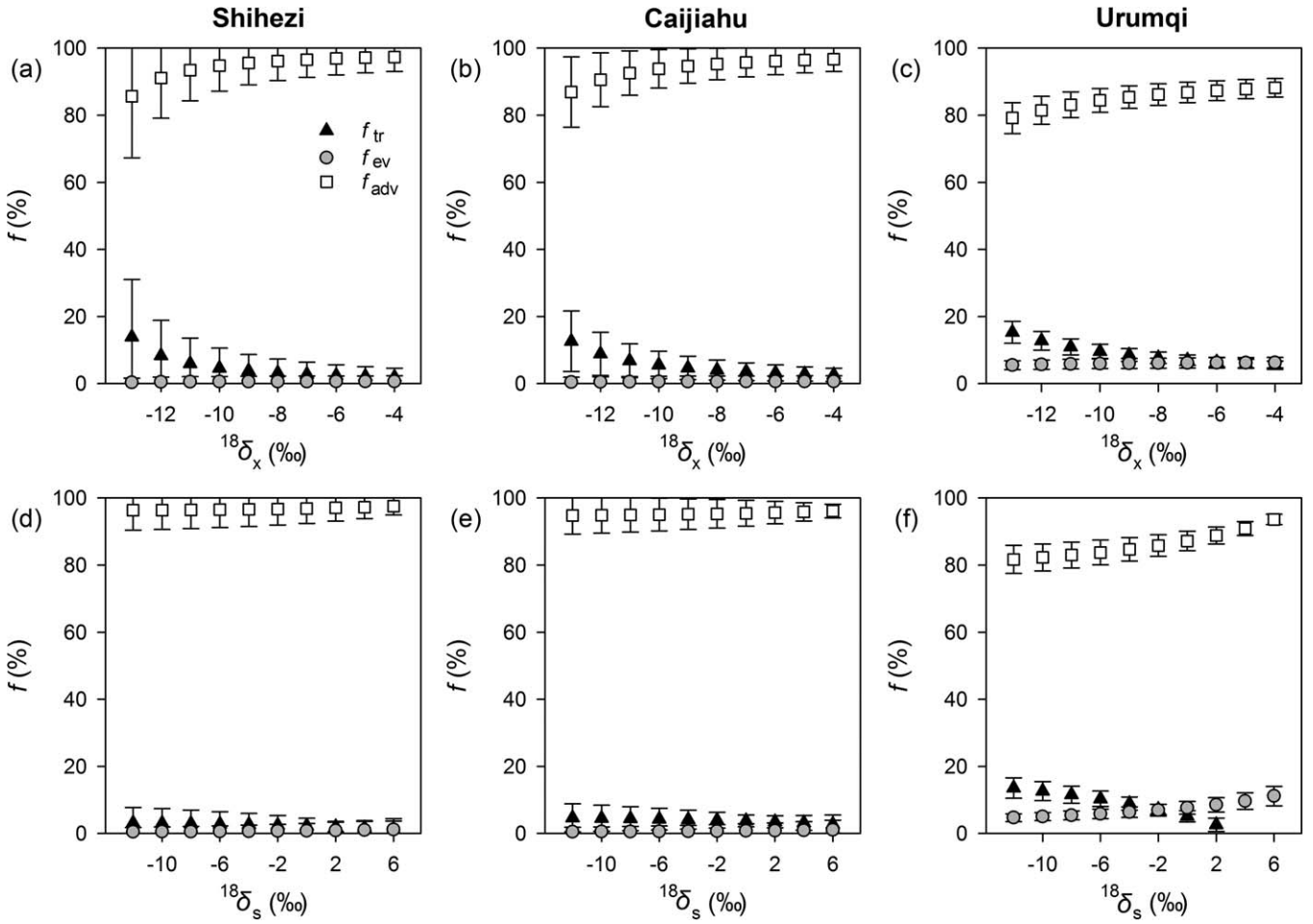

Figure 6. Variations of proportional contributions (*f*) with different oxygen isotope ratios in xylem water ($^{18}\delta_x$) and surface water ($^{18}\delta_s$) at Shihezi, Caijiahu and Urumqi. The xylem waters are applied to calculate vapor isotopes from transpiration, and surface waters are used to calculate vapor isotopes from surface evaporation. The error bars denotes standard errors for each component. The hydrogen isotope covariates as oxygen isotope changes, using local meteoric water line at the northern slope of the Tianshan Mountains [*Wang et al*., 2016] for xylem water and local evaporation line for surface water at the northern slope presented in supporting information Table S1.

precipitation isotopes capture the spatial variability. As shown in Figures 6a–6c and supporting information Table S3, generally, the contributions for the three fluxes are not very sensitive to xylem water isotopes, especially when the δ^{18}O value is greater than $-10‰$. The potential uncertainty of surface evaporation vapor isotopes is mainly attributed to surface water isotopes and related meteorological variables (temperature and relative humidity). Figures 6d–6f and supporting information Table S4 presents the contributions for each component with varying input of surface water isotopes and shows that they are also not very sensitive to the surface water isotopes, especially at Shihezi and Caijiahu.

In the study region, the dominant westerly wind direction seen all year round provides a good platform to investigate the contribution of recycled moisture as the air mass can be considered to always flow from west to east along the mountain ranges. The calculation procedure of advection vapor isotopes is based on the estimated precipitating vapor (mentioned in Figure 5) and an assumption that the Rayleigh equation is valid when an isotopic depleting trend is detected from upwind station to target station. The fraction of remaining moisture is determined by the ratio of surface vapor pressure between the two sites. The surface vapor pressure is widely considered to positively correlate to precipitable water amount in total air column, and can reflect the vapor loading at the neighboring stations [*Hu et al*., 2015]. Due to the great difference between precipitable water and measured precipitation at surface [*Li and Zhang*, 2003], the recycled moisture entering the air mass in transport is insignificant in this study, and therefore estimation using surface vapor pressure is appropriate.

5. Conclusions

Based on a three-component isotopic mixing model, the proportional contribution of recycled vapor (surface evaporation and transpiration vapor) to precipitation in oases of arid central Asia was assessed. Usually, the recycled moisture originating from surface evaporation and transpiration has relatively depleted isotope ratios, and precipitation isotopes supplied by the recycled vapor may show a depleting trend, which is consistent with the results in this study. For the large oasis of Urumqi, the proportion of recycled moisture was approximately 16.2%, which was much larger than that in other small oases; for small oases, the contribution of moisture recycling was <5%. The recycled moisture for different oases greatly varies depending on locations and water availability for evapotranspiration; an oasis effect in arid central Asia is clearly evidenced using an isotope approach in this study. The vegetation in an arid climate is generally sparse; however, the contribution of evapotranspiration to local precipitation cannot be ignorable for the oases. With the development of isotope ratio infrared spectroscopy, isotopes in water vapor can now be directly measured with high time resolution. Therefore, it is possible in the future to accurately measure the isotope ratios in these fluxes in order to reduce the uncertainties.

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