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Humidity Effect and Its Influence on the Seasonal Distribution of Precipitation δ^{18}O in Monsoon Regions

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ABSTRACT

The humidity effect, namely the markedly positive correlation between the stable isotopic ratio in precipitation and the dew-point deficit $\Delta T_{\rm d}$ in the atmosphere, is put forward firstly and the relationships between the δ^{18}O in precipitation and $\Delta T_{\rm d}$ are analyzed for the Ürümqi and Kunming stations, which have completely different climatic characteristics. Although the seasonal variations in δ^{18}O and $\Delta T_{\rm d}$ exhibit differences between the two stations, their humidity effect is notable. The correlation coefficient and its confidence level of the humidity effect are higher than those of the amount effect at Kunming, showing the marked influence of the humidity conditions in the atmosphere on stable isotopes in precipitation. Using a kinetic model for stable isotopic fractionation, and according to the seasonal distribution of mean monthly temperature at 500 hPa at Kunming, the variations of the δ^{18}O in condensate in cloud are simulated. A very good agreement between the seasonal variations of the simulated mean δ^{18}O and the mean monthly temperature at 500 hPa is obtained, showing that the oxygen stable isotope in condensate of cloud experiences a temperature effect. Such a result is markedly different from the amount effect at the ground. Based on the simulations of seasonal variations of δ^{18}O in falling raindrops, it can be found that, in the dry season from November to April, the increasing trend with falling distance of δ^{18}O in falling raindrops corresponds remarkably to the great $\Delta T_{\rm d}$, showing a strong evaporation enrichment function in falling raindrops; however, in the wet season from May to October, the δ^{18}O in falling raindrops displays an unapparent increase corresponding to the small $\Delta T_{\rm d}$, except in May. By comparing the simulated mean δ^{18}O at the ground with the actual monthly δ^{18}O in precipitation, we see distinctly that the two monthly δ^{18}O variations agree very well. On average, the δ^{18}O values are relatively lower because of the highly moist air, heavy rainfall, small $\Delta T_{\rm d}$ and weak evaporation enrichment function of stable isotopes in the falling raindrops, under the influence of vapor from the oceans; but they are relatively higher because of the dry air, light rainfall, great $\Delta T_{\rm d}$ and strong evaporation enrichment function in falling raindrops, under the control of the continental air mass. Therefore, the δ^{18}O in precipitation at Kunming can be used to indicate the humidity situation in the atmosphere to a certain degree, and thus indicate the intensity of the precipitation and the strength of the monsoon indirectly. The humidity effect changes not only the magnitude of the stable isotopic ratio in precipitation but also its seasonal distribution due to its influence on the strength of the evaporation enrichment of stable isotopes in falling raindrops and the direction of the net mass transfer of stable isotopes between the atmosphere and the raindrops. Consequently, it is inferred that the humidity effect is probably one of the foremost causes generating the amount effect.

Key words: humidity effect, dew-point deficit, stable isotope, seasonal variation, precipitation

1. Introduction

The International Atomic Energy Agency (IAEA), in co-operation with the World Meteorological Organization (WMO), is conducting a worldwide survey of oxygen and hydrogen isotope content in precipitation. The programme was initiated in 1958 and became operational in 1961. Precipitation samples are collected

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monthly by national meteorological services and by national authorities, and then shipped to the IAEA Laboratory in Vienna or to co-operating laboratories for analysis of stable isotopes in precipitation. The oxygen-18 content of the samples are measured on a mass spectrometer as ratios. They are expressed in terms of the per mille deviation of the isotope ratio from a standard called SMOW (standard mean ocean water). The data are expressed in dimensionless delta values as defined by:

$$\delta^{18}\mathrm{O} = \left[\frac{\left(^{18}\mathrm{O}/^{16}\mathrm{O}\right)_{\mathrm{sample}}}{\left(^{18}\mathrm{O}/^{16}\mathrm{O}\right)_{\mathrm{SMOW}}} - 1\right] \times 1000 \qquad (1)$$

where $(^{18}\mathrm{O}/^{16}\mathrm{O})_{\mathrm{sample}}$ and $(^{18}\mathrm{O}/^{16}\mathrm{O})_{\mathrm{SMOW}}$ stand for the isotopic ratio $^{18}\mathrm{O}/^{16}\mathrm{O}$ in the water sample and in the standard mean ocean water, respectively. The measurements have a long term precision of about $\pm 0.1‰$ for oxygen-18 at one standard deviation level.

The global investigation on the stable isotopes in precipitation (Araguas et al., 1998; Dansgaard, 1964; Jouzel, 1986; Jouzel et al., 1997; Zhang et al., 2002) shows that there are marked positive correlations between δ^{18}O in precipitation and mean monthly temperature in middle-high-latitude inland, namely a temperature effect, but marked negative correlations between δ^{18}O and monthly precipitation amount in monsoon regions or in low-middle-latitude islands and coasts, namely an amount effect. The temperature effect arises from the fact that the phase temperature in the process of phase change controls the fractionation of stable isotopes in the atmosphere and in precipitation (Zhang et al., 2003). Based on the temperature effect, the stable isotopic compositions in different sediments can be quantitatively recovered as a temperature proxy (Jouzel, 1986; Tian et al., 2003; Yao, 1999). As for the amount effect, some scholars think that its generation is related to strong convective phenomenon (Dansgaard, 1964; Yapp, 1982; Zhang et al., 2001). The magnitude of stable isotopic ratios in precipitation indicates the strength of the monsoon in regions with the amount effect (Araguas et al., 1998; Rozanski et al., 1997; Zhang et al., 2002). Yapp (1982) once conducted a simulation in order to interpret the generation of the amount effect. He thought that the stable isotopic ratios in precipitation are in inverse proportion to the intensity of precipitation in a convective cloud. Zhang et al. (2001) simulated the stable isotopic effect generated in mixed cloud using a kinetic fractionation model. Their analyses show that there is a negative correlation between the stable isotopic ratios in condensate and possible maximum condensation amount. The above mentioned simulations give only the general trend of the stable isotopic ratios in condensation water against the condensation amount in cloud. They are incapable of interpreting the seasonal variations of stable isotopic ratios in precipitation that reaches the ground in monsoon regions. In fact, the summer rainfall in middle-high-latitude inland is also formed in a convective cloud system. The heavy convective rainfall does not generate the expectant amount effect. However, there is still an amount effect even in dry seasons with light rainfall and during less rainfall times in some regions located in low-middle latitudes (Araguas et al., 1998; Zhang et al., 2002), for example at Kunming station (Zhang et al., 2004). Therefore, it can be concluded that the intensity of precipitation amount is not a possible cause generating the amount effect.

After conducting correlation analyses between the stable isotopic ratios in precipitation and the corresponding meteorological elements for 29 sampling stations in China, it is found that there is a marked correlation between the δ^{18}O in precipitation and atmospheric humidity. Using this relationship, the possible cause generating the amount effect can be interpreted. Based on the data from two IAEA/WMO (2001) survey stations, Ürümqi and Kunming, with marked climatic differences, this paper analyzes the variations of δ^{18}O in precipitation and the relationships of the δ^{18}O with temperature, precipitation amount and atmospheric humidity. Furthermore, the paper simulates the seasonal variations of the δ^{18}O in precipitation at Kunming, and thus reveals the possible influence of the atmospheric humidity on the amount effect.

2. Some facts of the stable isotopic effect

2.1 *Definition of humidity effect*

So far, 30 sampling stations have been established in China by the IAEA/WMO for stable isotopic surveys of precipitation. After conducting correlation analyses for the 29 stations (Chongqing station is absent because the sampling period is less than 6 months), it was found that there is notable positive correlation between δ^{18}O in precipitation and the dew-point deficit in the atmosphere for 25 stations (86% of the total). The dew-point deficit, ΔT_{d}, is an important index indicating the atmospheric humidity situation: the greater the ΔT_{d}, the dryer the air, and the smaller the ΔT_{d}, the wetter the air; as ΔT_{d} equals 0, the air reaches saturation.

Analyses show that, as a raindrop falls in unsaturated atmosphere, the result of evaporation enrichment causes stable isotopic ratios in the raindrop to increase with falling distance due to the relatively faster

evaporation rate for pure water versus the heavier isotopes. The dryer the air, the stronger the function of evaporation enrichment (Zhang et al., 1998). This effect shows why there is a positive correlation between δ^{18}O and $\Delta T_{\rm d}$ to a certain degree.

This positive correlation between δ^{18}O and $\Delta T_{\rm d}$ is defined as the humidity effect.

In a humid atmosphere, the air near a raindrop surface reaches or approaches saturation. In this situation, the variations of stable isotopic ratios in the raindrop are mainly dependent on stable isotopic compositions in the atmospheric vapor because of the weak evaporation enrichment function in the raindrop (Stewart, 1975; Zhang et al., 1998). If the stable isotopic ratio in the atmospheric vapor is lower than in the vapor at the raindrop surface, the direction of net mass transfer of stable isotopes will be from the raindrop to the atmosphere, and thus the stable isotopic ratio in the raindrop will decrease; contrarily, in the opposite case, the direction of net mass transfer will be from the atmosphere to the raindrop, and thus the stable isotopic ratio in the raindrop will increase.

With completely different climatic conditions, the two sampling stations Ürümqi (43.80°N, 87.65°E; 947 m MSL) and Kunming (25.02°N, 102.68°E; 1900 m MSL) belong to the typical continental and monsoonal climates, respectively. Analyzing the stable isotopic effects in precipitation based on the stable isotopic ratios in precipitation and the corresponding meteorological data for both stations will be helpful to comprehend the variation features of stable isotopes in precipitation in different regions and the possible cause generating the amount effect.

2.2 *Seasonal variations of the elements*

Figure 1 and Figure 2 give the seasonal variations of δ^{18}O in precipitation and the corresponding meteorological elements at Ürümqi and Kunming, respectively.

The curves at Ürümqi all showing typical sine waves, of δ^{18}O in precipitation, of temperature, precipitation, and the $\Delta T_{\rm d}$, are similar. The maximums of each element appear in the warm half of the year, whereas the minimums appear in the cold half. The statistics show that the temperature effect is notable at Ürümqi:

$$\delta^{18}{\rm O}(‰) = 0.34T(^\circ{\rm C}) - 15.80 \quad (r = 0.88\ ,\ \ n = 99)\ , \tag{2}$$

where r is the correlation coefficient and n the sampling size.

Although the seasonal variations of temperature and precipitation at Kunming are basically similar to those at Ürümqi, the variations of the δ^{18}O in precipitation, and the $\Delta T_{\rm d}$, with markedly lower values in the rainy season and higher values in the dry season, are different from those at Ürümqi. The statistics show that the amount effect is notable at Kunming:

$$\delta^{18}{\rm O}(‰) = -0.03P({\rm mm}) - 5.37 \quad (r = -0.58\ ,\ n = 108)\ . \tag{3}$$

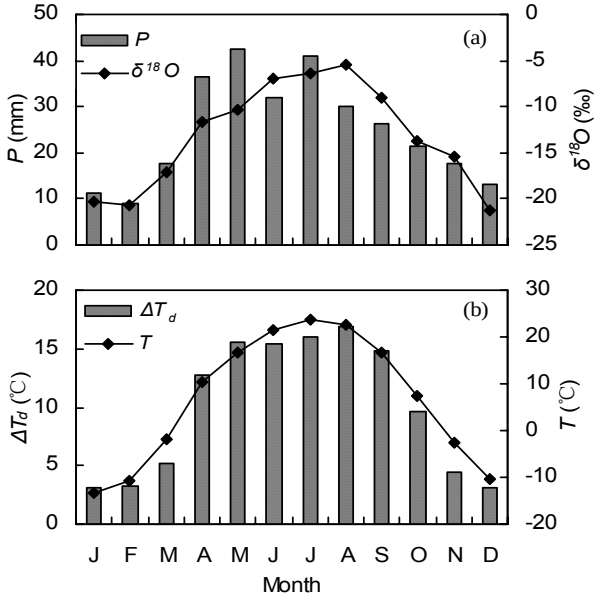

Fig. 1. Seasonal variations of (a) precipitation and δ^{18}O in precipitation, and (b) dew-point deficit and temperature at Ürümqi.

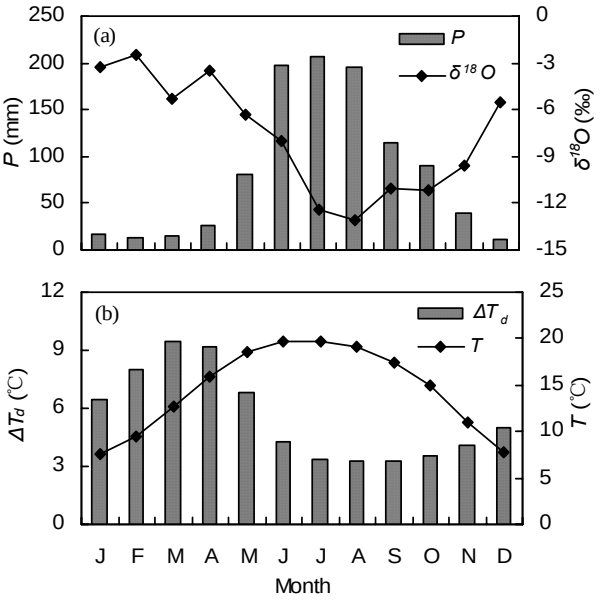

Fig. 2. Same as Fig. 1 but at Kunming.

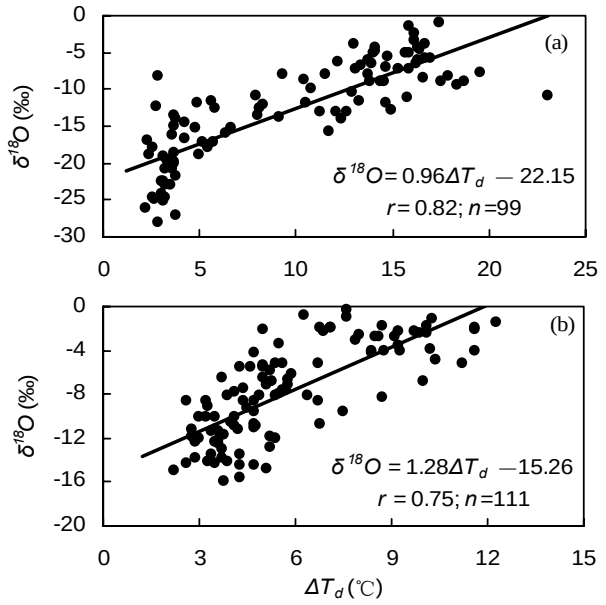

Fig. 3. Scatter plot of δ^{18}O in precipitation against dewpoint deficit at (a) Ürümqi and (b) Kunming.

It can be seen from Fig. 2, that the seasonal variations of the δ^{18}O in precipitation at Kunming are not synchronized with those of precipitation. A similar phenomenon has also been found at many sampling stations in monsoon regions (Araguas et al., 1998; Zhang et al., 2002).

Despite the marked differences in seasonal variations of the δ^{18}O in precipitation and of the $\Delta T_{\rm d}$ at both stations, their humidity effect is notable (see Fig. 3). Typically at Kunming, the correlation coefficient and the confidence level of the humidity effect are both greater than those of the amount effect, showing that the humidity situation in the atmosphere has a very marked influence on the stable isotopes in precipitation.

3. Simulation of seasonal variations of δ^{18}O in precipitation in monsoon regions

3.1 *Brief introduction of the basic model*

The simulations of the seasonal variation of precipitation δ^{18}O in monsoon regions will be divided into two steps: (1) the fractionation process of the stable isotopes in condensate in cloud, and (2) the evaporation enrichment and mass transfer between raindrops and the environmental air of stable isotopes in the raindrop as it falls in the free atmosphere.

For the first step, the variations of stable isotopic ratio in condensate can be described as (Zhang et al., 2003):

$$d\delta_{\rm l} = \frac{M_{\rm v} d\alpha_{\rm l} + \alpha_{\rm l}(\alpha_{\rm l}-1)dM_{\rm v}}{\alpha_{\rm l}(M_{\rm v}+\alpha_{\rm l}M_{\rm l})}(1+\delta_{\rm l})$$

and

$$\delta_{\rm i} = \alpha_{\rm k}\alpha_{\rm i}(1+\delta_{\rm v})\,, \tag{4}$$

where $\delta_{\rm l}, \delta_{\rm i}$ and $\delta_{\rm v}$ are the stable isotopic ratios in the liquid, ice and vapor phases in the cloud; $M_{\rm v}$ is the mixing ratio and $M_{\rm l}$ the liquid-water content in the cloud; and $\alpha_{\rm l}, \alpha_{\rm i}$ and $\alpha_{\rm k}$ are the fractionation factors of stable isotopes between vapor and liquid phases, between vapor and ice phases and under dynamical forcing, respectively.

For the second step, the variations of the stable isotopic ratio $\delta_{\rm l}$ in raindrops falling in the free atmosphere can be described as (Zhang et al., 1998):

$$d\delta_l = \frac{3\rho_r(Df)}{r^2\rho_l}\left\{\frac{D'f'}{Df}\left[(\delta_e+1)SA - \frac{\delta_l+1}{\alpha_l}\right] - (\delta_l+1)(SA-1)\right\}dt \tag{5}$$

and

$$\frac{dh}{dt} = V - U\,, \tag{6}$$

where $\rho_{\rm r}$ and $\rho_{\rm l}$ are the vapor density at the raindrop surface and the density of the raindrop, respectively; D and f are the diffusion coefficient and the ventilation factor of vapor in the atmosphere, and D' and f' the corresponding D and f for stable isotopes, respectively; r is the radius of the raindrop, t the time and S the relative humidity; $A = \rho_s/\rho_r$, in which ρ_s is the saturated vapor density under the environmental temperature T; δ_e is the ratio in the atmospheric vapor; h is the falling distance of the raindrop; and V and U are the terminal falling velocity of the raindrop and the constant ascending velocity of the air current.

3.2 *Simulation of the seasonal variation of* δ^{18}O *in condensate in the cloud*

Assuming that the altitude producing condensate is at the 500 hPa level, the seasonal variation of mean monthly temperature at 500 hPa is from the statistics for the meteorological data from 1971 to 2000 at Kunming (see Fig. 4).

Furthermore, assuming that the mean δ^{18}O in ocean surface water is 0, the ocean surface water temperature and air temperature are 26°C and 29°C, respectively, and the relative humidity is 80%; the super saturation ratio at the ice surface in mixing cloud is $S_i = 1.0 - 0.001T$ under the wet adiabatic cooling process, and the seasonal variation of δ^{18}O in condensate at 500 hPa at Kunming is simulated according to Eqs. (4) and (5). [For details of the simulations, refer to Zhang et al. (2003)].

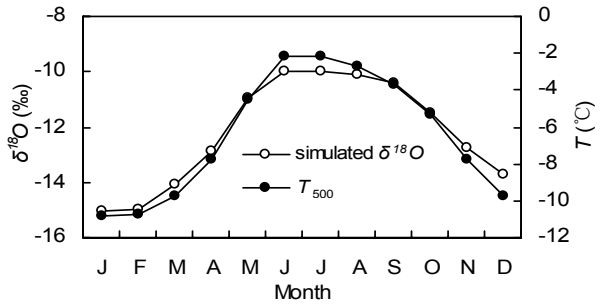

Fig. 4. Seasonal variations of simulated δ^{18}O in condensate and mean monthly temperature at 500 hPa at Kunming.

It can be seen from Fig. 4 that the seasonal variation of the simulated mean δ^{18}O values is very consistent with that of the actual mean monthly temperature, displaying that there is a temperature effect for the oxygen stable isotope in condensate in cloud at Kunming. Such an effect is different from the amount effect happening at the ground, but similar to that in the middle-high-latitude inland. For example, it is consistent with the seasonal variation of δ^{18}O in precipitation at Ürümqi.

3.3 *Simulation of* δ^{18}O *variations in falling raindrops*

Set the ascending velocity of the air current to U=10 cm s^{-1}, and take the simulated δ^{18}O in Fig. 4 as the initial δ^{18}O in the raindrop, i.e., the values as the raindrop leaves cloud base. The relative humidity S is estimated based on the relationship between $\Delta T_{\rm d}$ and T. The variation, with height z, of δ^{18}O in atmospheric vapor in the range of 0–5000 m is from the fitting to the actual observation by Rozanski and Sonntag (1982):

$$\delta^{18}{\rm O}_e(‰) = -3.625 \times 10^{-3} z({\rm m}) - 14.375\,. \qquad (7)$$

It shows that the δ^{18}O in atmospheric vapor decreases progressively with increasing altitude in the middle and low troposphere.

According to the above conditions and assumptions, and Eqs. (6) and (7), the variations from the cloud base (z=3100 m) to the ground (z = 0, but the altitude is 1900 m) at Kunming of the monthly δ^{18}O in falling raindrops are simulated. The results are shown in Fig. 5.

By Fig. 5, corresponding to the large $\Delta T_{\rm d}$, the increasing trend with increasing falling distance of the δ^{18}O in the falling raindrops is notable in the dry season from November to April, especially from January to April, when the differences between the δ^{18}O in the raindrops at the ground and at 500 hPa all exceed 9‰, reaching 10.0‰ in January, 12.32‰ in February, 13.02‰ in March, and 9.47‰ in April, showing the strong evaporation enrichment function in raindrops.

In the rainy season from May to October, corresponding to the small $\Delta T_{\rm d}$, the increasing trend with increasing falling distance of the δ^{18}O in the falling raindrops is unapparent except in May. The δ^{18}O in the raindrops decreases with falling distance in the initial stages before about 1500 m. This result shows that the direction of net mass transfer of stable isotopes is from the raindrop to the environmental air, although evaporation enrichment still possibly occurs in the raindrops. However, the δ^{18}O in the falling raindrops increases with falling distance below 1500 m, showing that the direction of net mass transfer is from the environmental air to the raindrop which says that the evaporation enrichment in the raindrops plays the dominant role. By our calculations, the differences between the monthly δ^{18}O at the ground and at 500 hPa are 3.4‰ in May, –0.1 ‰ in June, –0.85‰ in July, –0.70‰ in August, –0.33‰ in September and 1.44‰ in October. The δ^{18}O at 500 hPa is greater than at the ground from June to September instead, except in May and October.

It can be seen from Fig. 6, by comparing the simulated mean δ^{18}O at the ground (z=0) with the actual monthly mean δ^{18}O, that the two seasonal variations of δ^{18}O are quite consistent. Consequently, it is concluded that the humidity condition in the atmosphere

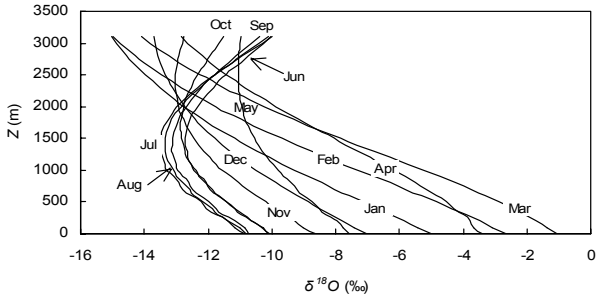

Fig. 5. Variations, with height, of mean monthly δ^{18}O in falling raindrops at Kunming.

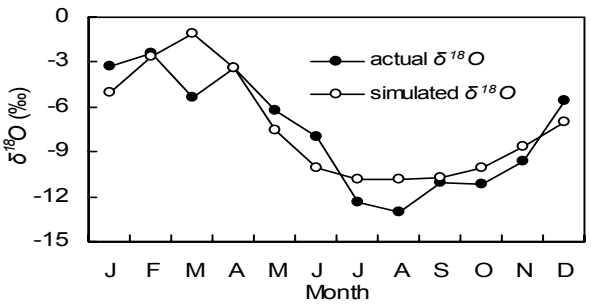

Fig. 6. Comparison between seasonal variations of actual and simulated δ^{18}O in precipitation at Kunming.

is an important factor influencing the seasonal distribution of stable isotopic ratios in precipitation in monsoon regions.

4. Discussion and conclusions

Previous analyses (Zhang and Yao, 1998; Zhang et al., 2004) have shown that the seasonal distributions of stable isotopic ratios in precipitation may be roughly divided into two types in China. A marked positive correlation between the stable isotopic ratio in precipitation and temperature happens in middle-high-latitude inland, and the seasonal distribution of δ^{18}O in precipitation remains in agreement with that of temperature and dew-point deficit under the influence of a continental climate. Ürümqi is a typical station of this type. However, a marked negative correlation between the stable isotopic ratio in precipitation and precipitation amount appears in coastal regions and regions influenced by monsoon, and the seasonal distribution of δ^{18}O in precipitation is opposite to that of precipitation but in agreement with that of dew-point deficit. Kunming is a typical station of this type.

In the simulations of Fig. 5 and Fig. 6, the humidity condition plays a very important role in estimating the seasonal distribution of δ^{18}O in precipitation at Kunming. The seasonal variation of δ^{18}O in precipitation that reaches the ground is markedly different from that in the upper air at Kunming because of the seasonal variation of atmospheric humidity. The correlation analyses show that there is a notable positive correlation between $\Delta T_{\rm d}$ and T at Ürümqi, namely, the higher the temperature, the greater the $\Delta T_{\rm d}$; and the lower the temperature, the smaller the $\Delta T_{\rm d}$, which characterizes the humidity variation in arid and semi-arid inland. The seasonal distribution of δ^{18}O in precipitation that reaches the ground remains parallel to that in the upper air because of the similar seasonal variations in $\Delta T_{\rm d}, T$ and δ^{18}O in the upper air at Ürümqi. However, at Kunming, no marked correlation between $\Delta T_{\rm d}$ and T is found; instead we find a marked negative correlation between $\Delta T_{\rm d}$ and precipitation, which is probably related to the features of the air mass. On average, the δ^{18}O values are relatively lower because of the high moist air, heavy rainfall, small $\Delta T_{\rm d}$ and weak evaporation enrichment function of stable isotopes in falling raindrops under the influence of vapor from the oceans; but relatively higher δ^{18}O occurs because of the dry air, light rainfall, large $\Delta T_{\rm d}$ and strong evaporation enrichment function in falling raindrop under the control of continental air mass. Therefore, the δ^{18}O in precipitation at Kunming can be used to indicate the humidity situation in the atmosphere to a certain degree, and thus indicate the intensity of the precipitation and the strength of the monsoon indirectly.

We must note that the vertical distribution of δ^{18}O in the atmospheric vapor we use here comes from the fitting of samplings in Europe that are assumed to be unchangeable each month. It is not suitable to the actual situation at Kunming. Also, the simulations do not take into account the variations in shape of raindrops. Perhaps, these problems contribute to the differences between simulated and actual δ^{18}O in certain months, such as in March and in August.

In conclusion, the humidity effect not only changes the magnitude of the stable isotopic ratio in precipitation but also its seasonal distribution due to its influence on the strength of the evaporation enrichment of stable isotopes in falling raindrops and the direction of the net mass transfer of stable isotopes between the atmosphere and the raindrops. Consequently, it is inferred that the humidity effect is probably one of the foremost causes generating the amount effect.

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REFERENCES

Araguas, L., K. Froehlich, and K. Rozanski, 1998: Stable isotope composition of precipitation over southeast Asia. *J. Geophys. Res.*, **103**, 28721–28742.

Dansgaard, W., 1964: Stable isotopes in precipitation. *Tellus*, **16**(4), 436–468.

IAEA/WMO, 2001: The GNIP Data Release 3. [Available online at http: //www. iaea. org. programs/ ri/ gnip/ gnipmain. htm.]

Jouzel, J., 1986: Isotopes in cloud: Multiphase and multistage condensation process. *Handbook of Environmental Isotope Geochemistry*, Vol. 2, P. Fritz and J. Ch. Fontes, Eds., Elsevier Scientific Publishing Company, 61–112.

Jouzel, J., K. Froehlich, and U. Schotterer, 1997: Deuterium and oxygen-18 in present-day precipitation: Data and modeling. *Journal of Hydrological Sciences*, **42**(5), 747–763.

Rozanski, K., and C. Sonntag, 1982: Vertical distribution of deuterium in atmospheric water vapor. *Tellus*, **34**(1), 135–141.

Rozanski, K., S. J. Johnson, and U. Schotterer, 1997: Reconstruction of past climates from stable isotope records of palaeo-precipitation preserved in continental archives. *Journal of Hydrological Sciences*, **42**(5), 725–745.

Stewart, M. K., 1975: Stable isotope fractionation due to evaporation and isotopic exchange of falling water drops: Application to atmospheric processes and evaporation of lakes. *J. Geophys. Res.*, **80**, 1133–1146.

Tian, L., T. Yao, P. F. Schuster, J. W. C. White, K. Ichiyanagi, E. Pendall, and J. Pu, 2003: Oxygen-18 concentrations in recent precipitation and ice cores on the Tibetan Plateau. *J. Geophys. Res.*, **108**, 4293–4298.

Yao Tandong, 1999: Abrupt climatic changes on the Tibetan Plateau during the Last Ice Age. *Science in China* (D), **42**(3), 358–368.

Yapp, C. J., 1982: A model for the relationship between precipitation D/H ratios and precipitation intensity. *J. Geophys. Res.*, **87**, 9614–9620.

Zhang Xinping, and Yao Tandong, 1998: Distributional features of δ^{18}O in precipitation in China. *Journal of Chinese Geography*, **8**(2), 157–164.

Zhang Xinping, Xie Zichu, and Yao Tandong, 1998: Mathematical modeling of variations on stable isotopic ratios in falling raindrops. *Acta Meteorologica Sinica*, **12**(2), 213–220.

Zhang Xinping, M. Nakawo, K. Fujita, Yao Tandong, and Han Jiankang, 2001: The variation of precipitation δ^{18}O in Langtang Valley, Himalayas. *Science in China*(D), **44**(9), 769–778.

Zhang Xinping, Yao Tandong, and M. Nakawo, 2002: Meridional variation of stable isotopic compositions in precipitation of the Tibetan Plateau and its adjacent regions. *Journal of Glaciology and Geocryology*, **24**(3), 245–253. (in Chinese)

Zhang Xinping, Yao Tandong, Liu Jingmiao, Tian Lide, and M. Nakawo, 2003: Simulations of stable isotopic fractionation in mixed cloud in middle latitudes—Taking the precipitation at Ürümqi as an example. *Adv. Atmos. Sci.*, **20**(2), 261–268.

Zhang Xinping, Liu Jingmiao, Tian Lide, Yao Tandong, 2004: Variations of δ^{18}O in precipitation along vapor transport paths. *Adv. Atmos. Sci.*, **21**(4), 562–572.