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Characteristics of atmospheric precipitation isotopes and isotopic evidence for the moisture origin in Yushugou River basin, Eastern Tianshan Mountains, China

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ABSTRACT

Based on the variations in stable hydrogen and oxygen isotope ratios (δD and $\delta^{18}O$) of precipitation and NCEP/NCAR (National Centers of Environmental Prediction/National Center for Atmospheric Research) re-analysis data, we investigated the characteristics of the precipitation isotopes and the moisture origin during spring and summer seasons (from May to August) in the Yushugou River basin, East Tianshan Mountains. The more negative $\delta^{18}O$ and higher d-excess values in spring and more positive $\delta^{18}O$ and lower d-excess values in summer indicated the different moisture sources and temperature effects on isotope variations. By studying the meteoric water line, we found that the slope and intercept of local meteoric water line (LMWL) were lower than the global meteoric water line (GMWL) and China LMWL, which indicated arid climate. The temperature effect of δD and $\delta^{18}O$ in precipitation was obvious with correlation coefficients of 0.41 and 0.48, respectively, and there was no rainfall effect. The research of water vapor transfer showed that the moisture origin was predominantly from westerly air masses during the observation period. $\delta^{18}O$ and d-excess values variations in precipitation and the HYSPLIT4.0 air mass trajectory model suggested that there were accidental events, and sometimes the moisture was from drier polar air masses during the spring.

1. Introduction

Atmospheric precipitation, as an important part of water cycle in nature, is the initial water sources of land water (including surface water, groundwater, and ice and snow). The study of the composition of environmental isotopes in atmospheric precipitation is a necessary premise to study the global and local water cycle. Scientists are increasingly using isotope observations to study atmospheric water vapor sources and influencing factors. Stable water isotopes in precipitation are used as an observational method to gain understanding of the atmospheric hydrological cycle and the moisture origin (Dansgaard, 1964; Rozanski et al., 1982; Hoffman et al., 2000; Tian et al., 2005; Yamanaka et al., 2007; Kebede and Travi, 2012). Based on the study of precipitation δD, $\delta^{18}O$, and d-excess values, Zhao et al. (2011) reported that the amount of water entering the headwaters of the Heihe River basin was strongly determined by the atmospheric circulation patterns. Gopal et al. (2013) used isotopes to track the movement of monsoon vapors and regional influx of moist vapor, and found that the extent of depletion in isotopic composition of moisture and period over this depletion continued was directly linked with monsoon strength. Isotopes in precipitation are affected by the geographical and meteorological conditions of the local precipitation (Schoch-Fischer et al., 1984; Kumar et al., 2010; Liu et al., 2013). Liebminger et al. (2006) indicated that mountains within alpine regions had a significant influence on the geographic distribution of precipitation and on local-to-regional-scale climatic and meteorological conditions. Consequently, the oxygen and hydrogen isotope compositions of precipitation were affected by alpine topography. Changes of atmospheric precipitation δD and $\delta^{18}O$ are closely related to the physical processes of precipitation, and the most obvious factors in water cycle process are evaporation and condensation (Schotterer et al., 1997). During the resulting rain

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event, the interaction between the falling drops and the surrounding atmosphere may change the original isotope content (Peng et al., 2007). Because of the physicochemical differences, heavy isotopes ($\delta^{18}O$ and ^{2}H) in water vapor are depleted more easily than lighter isotopes (^{16}O and ^{1}H) in moisture condensation during long-distance transport. As a result, δD and $\delta^{18}O$ in precipitation become more negative with increasing distance along the transportation path (Siegenthaler and Oeschger, 1980). At the same time, owing to kinetic fractionation during water evaporation, parallel fractionation is destroyed, which results in differences in the relationship between δD and $\delta^{18}O$. Dansgaard (1964) defined this difference as the “deuterium excess” (d-excess = δ D − 8.0 $\delta^{18}O$), which averages about 10.0 on a global scale. The precipitation d-excess generated from kinetic fractionation during water evaporation, and is mainly influenced by the relative humidity and temperature of the moisture source (Merlivat and Jouzel, 1979; Jouzel et al., 1982, 1997). Because the degree of kinetic fractionation provides clues to the moisture origin, the d-excess in precipitation has many applications in hydrology (Feng et al., 2009). Therefore, by analyzing the $\delta^{18}O$ and δ D, local meteoric water line (LMWL), and precipitation d-excess values, we can determine the water vapor origin (Lawrence et al., 1982; Yamanaka et al., 2007) and monitor the atmospheric circulation patterns in the study area (Hoffman et al., 2000; Birks et al., 2002; Tian et al., 2005).

The Eastern Tianshan Mountains is located in the centre of Xinjiang Uygur Autonomous Region, China. Moisture transportation is influenced by the high mountains, and precipitation decreases gradually from west to east and increases from south to north in the Tianshan Mountains (Wei and Hu, 1990). However, research of atmospheric precipitation isotopes and the water vapor sources in Eastern Tianshan Mountains region has mainly focused on the Urumqi River basin in the central region (Yao et al., 1999; Tian et al., 2007; Pang et al., 2011; Feng et al., 2013; Kong et al., 2013). The isotopic characteristics for the eastern region with more droughts have not been reported before, and need further investigation. The Yushugou River basin is located in the southern slope of the most eastern regions of the Tianshan Mountains, and is considered as a vital water tower for Hami city, Xinjiang, especially for the oasis with large population and vast farmland. Precipitation is one of the important water sources for basin runoff (Guangxiao et al., 2002). However, the isotopic features in precipitation may provide more detailed information on moisture origin. Because of the uneven annual distribution of precipitation in Yushugou River basin (79.6% concentrated in May–September; Guangxiao et al., 2002), late spring and summer is a critical period for precipitation research. In this study, the temporal variations of $\delta^{18}O$ and δD in precipitation, and their relationships with local meteorological conditions in Yushugou River basin, were investigated. Based on NCEP/NCAR reanalysis data, the origin of moisture was also discussed, combining the $\delta^{18}O$ and d-excess with the three-dimensional isentropic back-trajectories in HYSPLIT. This study aims to (1) provide basic data on the water cycle in the Yushugou River basin, (2) understand the water vapor source of atmospheric precipitation and regional climate background at the most Eastern Tianshan Mountains, and (3) provide an isotopic approach for future study in assessing the role of precipitation on the regional water resources.

2. Study area

The Yushugou River basin (43°02′~43°11′N; 93°57′~94°19′E) is located in the eastern Tianshan Mountains and at the southern slope of Harlik Range. The downstream of the river is close to the Hami basin, and is adjacent to the Guxiang River basin to the west and the Miaoergou basin to the east. The basin is in Hami Prefecture, Xinjiang. The only hydrological station in the river basin, Yushugou Hydrometric Station, is located at 1670 m°asl, and the catchment area above the station is 308 km^2. The average slope of the basin is 38.2‰ and the average height is 3091 m.

Modern glaciers and permanent snow cover are distributed in the headwaters of the river. There are 9 glaciers which cover an area of 22.85 km^2. The altitudes of glacier terminals range from 4360 m to 3500 m. Yushugou River basin is the largest, and has the greatest ice volume of glaciers among all the rivers in Hami Prefecture (Glacier Inventory of China, 1986).

The climate of this river basin is mainly affected by the westerly circulation in summer. Precipitation is mainly from May to September, accounting for 79.6% of the annual precipitation. From October to March, the study area is controlled by a powerful Mongolia High (Luo, 1999), and during these dry and cold months precipitation is limited and mainly exists in solid form in the high mountainous areas. Annual average precipitation of Yushugou Hydrometric Station is 149 mm, ranging from 211 mm to 76 mm, and the annual average potential evaporation is 936 mm (Zhang and Liu, 2011). Annual average temperature of Yushugou Hydrometric Station is 5.9 °C, with maximum of 34.9 °C and minimum of −25.8 °C. Average temperatures in July and January are 20.5 °C and −10.9 °C, respectively (Guangxiao et al., 2002; Zhang and Liu, 2011).

3. Precipitation sampling and method

Precipitation samples were collected at Yushugou Hydrometric Station from May to August, 2013 (Fig. 1). The observed

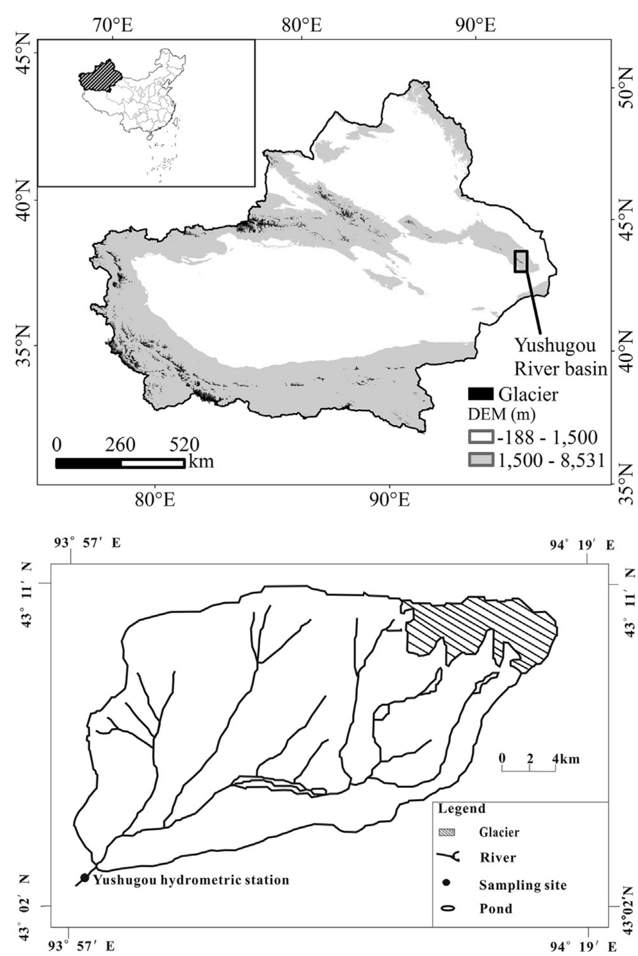

Fig. 1. Map showing the study area and locations of sampling sites in Yushugou River basin.

precipitation in March and April is 0 and 2.1 mm, respectively, which is insufficient for equipment analyses for each precipitation event. There was relatively more precipitation in May (20.1 mm), so the precipitation in May was collected as representative of spring. June to August is the summer season in the study area. All precipitation samples were collected as individual events. Meanwhile, the meteorological parameters (surface air temperature, amount of precipitation) were also measured. A total of 33 precipitation samples were collected during the observation period.

Event-based precipitation samples were collected by water collectors and stored in polyethylene plastic bottles with inner and outer caps. The liquid samples (rainfall) were collected immediately when the rain stopped, and the solid samples (snowfall) were kept at room temperature for melting before being filled into bottles. The start and terminal time of each precipitation events were recorded as well as the related meteorological parameters (temperature and precipitation). All the samples were kept frozen and transported to the State Key Laboratory of Cryosphere Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, for measurement. All samples were stored in the low-temperature laboratory, at −15 °C, until the analyses were carried out. The stable isotopic analysis was completed on the Los Gatos Research liquid water isotope analyzer (LWIA DLT-100). Accuracy of measurement was ±0.5‰ for δD, and ±0.2‰ for δ^{18}O. Final results were expressed in ‰ by the relative to Vienna Standard Mean Ocean Water (V-SMOW) value (Craig, 1961):

$$\delta^{18}O = \left[({}^{18}O/{}^{16}O)_{sample} - ({}^{18}O/{}^{16}O)_{SMOW}\right] \Big/ ({}^{18}O/{}^{16}O)_{SMOW} \times 10^3‰ \tag{1}$$

$$\delta D = \left[(D/H)_{sample} - (D/H)_{SMOW}\right] \Big/ (D/H)_{SMOW} \times 10^3‰ \tag{2}$$

The results are shown in Table 1.

Table. 1
The δ^{18}O and δD values for the precipitation samples of Yushugou River basin.

Sampling data	δ^{18}O/‰	δD/‰
2013-5-7	−5.66	−31.71
2013-5-15	−10.65	−69.55
2013-5-27	−3.74	−19.03
2013-5-31	1.28	7.21
2013-6-6	0.99	2.96
2013-6-7	−5.31	−35.23
2013-6-8	−6.28	−41.55
2013-6-12	5.74	44.23
2013-6-19(A)	−4.80	−42.86
2013-6-19(B)	−6.69	−53.61
2013-6-19(C)	−8.29	−58.51
2013-6-20(A)	−7.00	−38.59
2013-6-20(B)	−10.14	−63.88
2013-6-21(A)	−12.11	−84.04
2013-6-21(B)	−14.65	−96.20
2013-6-21(C)	−4.78	−53.53
2013-6-28	−0.77	−7.70
2013-7-6	0.52	1.84
2013-7-9	−12.32	−82.88
2013-7-13	−0.47	−3.19
2013-7-14	−5.41	−40.38
2013-7-20	−3.93	−32.89
2013-7-25	−4.47	−30.83
2013-7-27(A)	−5.70	−48.14
2013-7-27(B)	−2.77	−21.66
2013-7-29(A)	−1.90	−12.18
2013-7-29(B)	−3.78	−20.48
2013-8-26	−3.49	−16.88
2013-8-27(A)	−2.68	−23.44
2013-8-27(B)	−0.58	−11.27

To calculate the monthly precipitation isotope value, we used the volume weighted average value (VWA) (Liu et al., 2008). Taking ^{18}O for an example, the expression of the VMA can be written:

$$\delta^{18}O_e = \sum_{i=1}^{N} M_i \delta^{18}O_{m \cdot i} \Big/ \sum_{i=1}^{N} M_i \tag{3}$$

where $\delta^{18}O_e$ and $\delta^{18}O_{m \cdot i}$ express the isotope values of the calculation and actual measurement, respectively. M_i is the precipitation amount.

4. Results

4.1. Variation of stable isotopic compositions in precipitation

During the monitoring period, the precipitation δ^{18} O and δD values from May to August varied from −14.65‰ to 5.74‰ and from −96.2‰ to 44.23‰, respectively (Table 1). The variation was very large. Global average stable isotopic composition of precipitation δ^{18}O values varied between −50‰ and 10‰, and that of δD was between −350‰ and 50‰ (IAEA/WMO, 2001). Liu et al. (2014) reported that China precipitation δ^{18}O values ranged from −29.47‰ to 9.15‰, and δD values ranged from −229.6‰ to 45.4‰. Thus, the hydrogen and oxygen isotopes values in precipitation of the Yushugou River basin were both within the Chinese and global range.

Hydrogen and oxygen isotopic values were increased from May to August (Fig. 2). The isotopic values and temperature exhibited similar variation patterns. Owing to the increased temperatures and strong evaporation during the condensation and precipitation of the rain, precipitation δ^{18} O and δD were more positive. In addition, different moisture sources also made the differences of δ^{18} O and δD in rainwater month by month.

The precipitation d-excess depleted rapidly from May to June (from 14.87‰ to 7.49‰). However, from June to August the precipitation d-excess was relatively stable (from 7.49‰ to 8.73‰). Variation in the precipitation d-excess was related to the moisture origin and re-evaporation of raindrops during condensation and precipitation.

4.2. Local meteoric water line (LMWL)

The local meteoric water line is a linear (LMWL) relationship between δ^{18}O and δD for a region within a certain phase precipitation. The LMWL can reflect the regional natural geographical and meteorological conditions, and there are obvious advantages to investigate historical climate change and water vapor sources (Price et al., 2008). Craig (1961) studied hydrogen and oxygen

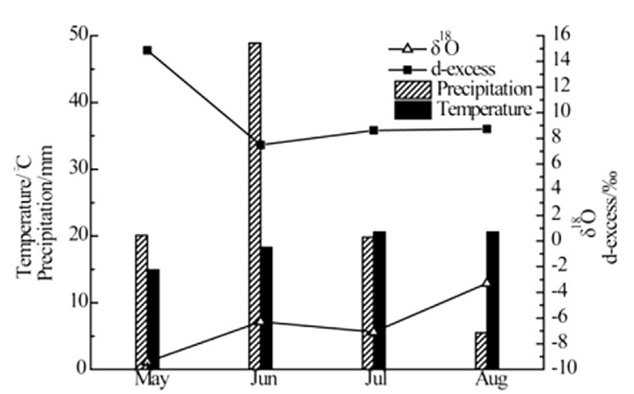

Fig. 2. The variations of δ^{18} O and d-excess with the monthly precipitation and average temperature.

isotopes composition in precipitation within the global scope, and proposed the global meteoric water line (GMWL) equation: $\delta D = 8.0\delta^{18}O + 10.0$. Liu et al. (2014) reported the local meteoric water line equation of China: $\delta D = 7.48\delta^{18}O + 1.01$.

According to the experimental δD and $\delta^{18}O$ data, we obtained the local meteoric water line equation ($\delta D = 6.614\delta^{18}O - 2.953, R^2 = 0.98$) for Yushugou River basin during spring and summer by the least square method (Fig. 3). A significant linear correlation ($R^2 = 0.98$) exists between $\delta^{18}O$ and δD. The slope of LMWL at Yushugou (6.614) was gentler than the GMWL (8.0) proposed by Craig and the China LMWL (7.48) reported by Liu et al. (2014), and the intercept of the Yushugou LMWL (6.614) was lower than that of the GMWL (10.0) and China LMWL (1.01). The slope, slightly less than 8, shows that the moisture of the local precipitation was from a source with different stable oxygen isotope ratios. At the same time this also indicates that precipitation experienced a certain degree of evaporation, and evaporation is slightly greater than rainfall (Zhang et al., 2005). This process was the result of sub-cloud raindrop evaporation in a relatively dry atmosphere (Araguás-Araguás et al., 1998). Therefore, the smaller slope and intercept value of the Yushugou LMWL reflect the status of the natural geographical and meteorological conditions. The Yushugou River basin is far away from the ocean, and part of the water vapor originated from local evaporation. δD and $\delta^{18}O$ of surface water in arid regions are high, so δD and $\delta^{18}O$ of the moisture evaporation are high. In addition, in dry climate conditions, re-evaporation of raindrops during precipitation enriches heavy isotopes, which results in the enrichment of precipitation in $\delta^{18}O$.

In reference to the GMWL, isotopic data can be distinguished into three groups: the first group comprises data points with low $\delta^{18}O$ values and plots above the GMWL, the second group with medium $\delta^{18}O$ values fits the GMWL, and the third group with high $\delta^{18}O$ values are below the GMWL. Data points above the GMWL (deuterium excess above 10‰) represent mainly spring precipitation at relatively lower temperatures and lower absolute moisture content. The data fitting the GMWL are located between the first and third group. The last group below the GMWL signifies the effect of subcloud evaporation during the summer with d-excess below 10‰ (Pang et al., 2011).

4.3. Temperature and precipitation amount effects on $\delta^{18}O$ and δD in precipitation

The variation of $\delta^{18}O$ and δD in precipitation is closely related to the physical processes. The evaporation and condensation in water cycle process are the most obvious factors affecting $\delta^{18}O$ and δD values (Schotterer et al., 1997). One of the important factors of restricting the evaporation and condensation process is temperature (Yapp, 1982). Positive correlation between $\delta^{18}O$ and δD and temperature is called the temperature effect.

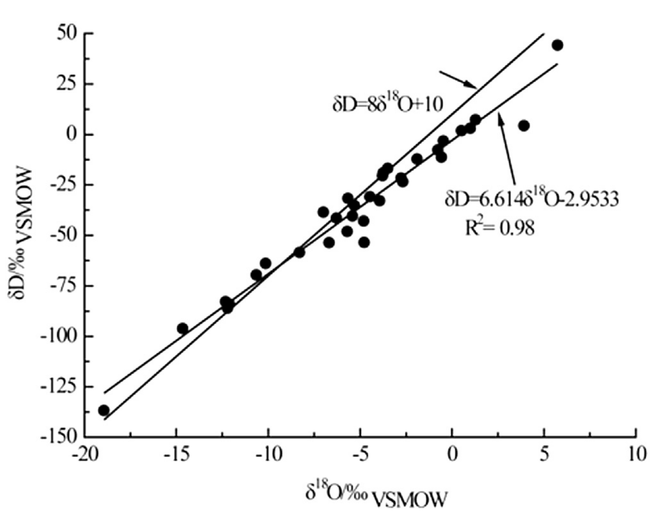

Fig. 3. Local meteoric water line at Yushugou River basin.

FRom regression analysis between precipitation isotope values and daily temperature in wet season in Yushugou River basin, we obtained the linear equations: (Fig. 4).

$$\delta^{18}O = 0.53T - 12.8\left(r = 0.48\right),$$

$$\delta D = 3.15T - 79.7(r = 0.41).$$

There is a good positive correlation between $\delta^{18}O$ and δD of precipitation and daily temperature, especially the $\delta^{18}O$. This indicated that there was temperature effect in precipitation isotope values. The Yushugou River basin is located in the northwest arid area of China, with strong evaporation, when the isotope fractionation is mainly controlled by kinetic fractionation. Due to the different kinetic energy between hydrogen and oxygen molecules in a phase shift, which caused imbalanced evaporation, the $\delta^{18}O$ value was concentrated more remarkably than the δD value in residual water vapor. The degree of enrichment is proportional to the evaporation intensity. Enrichment causes oxygen isotopic values to be more sensitive to temperature than is deuterium. Therefore, $\delta^{18}O$ is more significant than δD for indicating temperature, and more suitable for studying the mechanism of water environmental isotopic change.

The mean precipitation isotope composition is a function of air humidity, and the difference is mainly caused by the cloud condensation followed by Rayleigh fractionation (Dansgaard, 1964). As a result, there is a certain relationship between the isotopic composition of rainwater and the local precipitation. Because of the low humidity of the air in arid areas (Liu and Zhou, 1985, 2009), during the precipitation process, the rainwater is easily influenced by evaporation before reached the ground, and isotope kinetic fractionation effect occurs, so a precipitation effect usually exist in the precipitation $\delta^{18}O$ value (Jacob and Sonntag, 1991). Precipitation effect refers to the inverse correlation between the δD and $\delta^{18}O$ values and precipitation. The correlation between the stable isotopes and precipitation yields the relationships (Fig. 5).

$$\delta^{18}O = -0.32P - 3.73\left(r = -0.33\right),$$

$$\delta D = -1.88P - 27.37(r = -0.28).$$

As can be seen from the negative correlation coefficients, the precipitation effect between the hydrogen and oxygen isotopic variation and precipitation is not very obvious. This may be because the Yushugou River basin is located in an extreme continental region. The local water vapor cycle in the river basin resulted in almost no relationship between δD and $\delta^{18}O$ values and precipitation in rainfall events during the wet season. There is a certain relationship between the difference in δ value of the stable isotopes in precipitation and moisture sources. In addition, during this period the precipitation is large while the temperature is higher. Higher temperature leads to isotope fractionation during evaporation, so the isotope δ value in precipitation is not significantly reduced.

Analysis shows that the temperature effect is greater than the precipitation effect during the wet season in the Yushugou River basin. This phenomenon is consistent with the classical isotope theory that precipitation effect is usually not significant in inland areas (Yurtsever and Gat, 1981), and the $\delta^{18}O$ value is more greatly

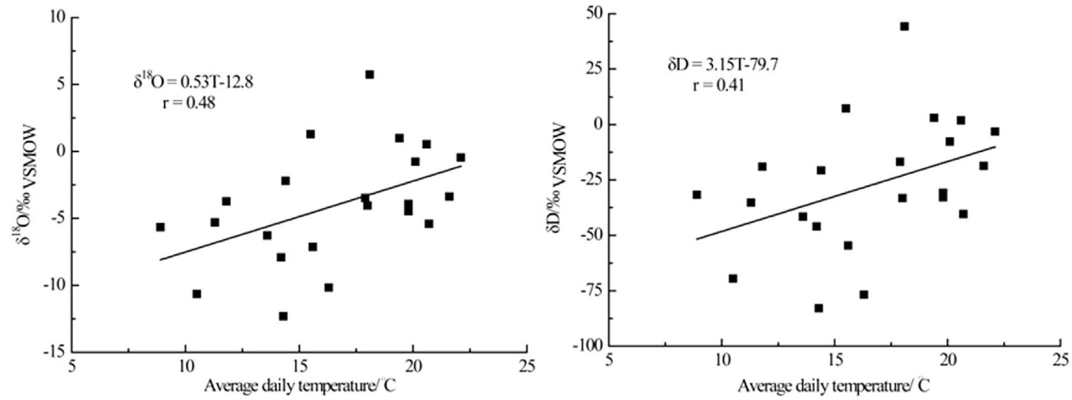

Fig. 4. The relationship between $\delta^{18}O$ and δD and average daily temperature.

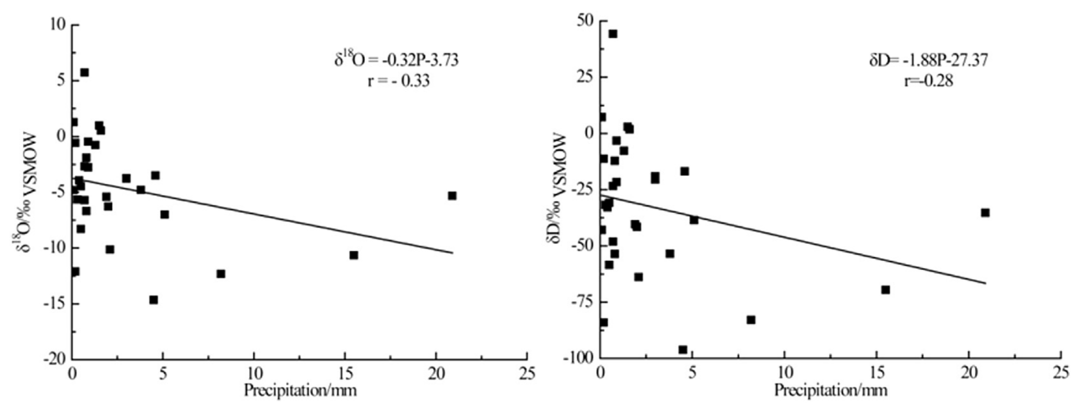

Fig. 5. The relationship between $\delta^{18}O$ and δD and precipitation amount.

influenced by temperature in continental interior regions of middle and high latitudes (Kohn et al., 2005; Yu et al., 2008). The temperature effect dominated the precipitation effect in Yushugou River basin. The entire region showed a continental climate characteristic of middle and high latitudes, and reflected the regional special natural geographical and meteorological conditions.

To further determine the influence of regional special natural geographical and meteorological conditions, we compared our results with Urumuqi River basin, Fukang, Linze, and Lhasa (Table 2). Temperature effects exist in Yushugou River basin, Urumuqi River basin, Fukang, and Linze. The water sources of the four stations resulted predominantly from westerly air masses (Zhao et al., 2011; Yao et al., 2013). The correlation coefficient between $\delta^{18}O$ and temperature is negative at Lhasa. This agrees with the finding that in the westerly domain shows the best positive correlation between $\delta^{18}O$ and temperature (Yao et al., 2013). However, the temperature effect in Yushugou River basin ($r = 0.48$) is weaker than those in Urumuqi River basin ($r = 0.86$), Fukang ($r = 0.89$) and Linze ($r = 0.91$). Such differences may be due to the regional characteristics of the Yushugou River basin. In the observation periods, owing to the high temperature, local convection was remarkable in spring and summer. Water vapor from different underlying surfaces carries different $\delta^{18}O$ (Yao et al., 2000). The precipitation produced by local convective gustiness accounts for a high proportion, which destroyed the original relationship between atmospheric precipitation $\delta^{18}O$ and temperature (Yao et al., 2000). Therefore, the intense local convective precipitation caused the decreased relationship between a single precipitation event $\delta^{18}O$ and temperature.

Table 2
Statistics of correlations between $\delta^{18}O$ values and temperature ($r_{\delta\text{-}T}$) and precipitation amount ($r_{\delta\text{-}P}$) of Yushugou River basin and other regions.

Station	Latitude	Longitude	Altitude/m	Observation period	P[a]/mm	T[a]/°C	$r_{\delta-T}$	$r_{\delta-P}$	Source
Yushugou River basin	43°05′N	93°57′E	1670	May 2013–Aug 2013	94.3	18.6	0.48	−0.33	Present work
Urumuqi River basin (Houxia)	43°13′N	87°07′E	2130	May 2006–Aug 2007	450	1.4	0.86	−0.33	Feng, 2011
Fukang	44°17′N	87°58′E	460	2005–2010	167	7.5	0.89	0.31	Liu et al., 2014
Linze	39°21′N	100°08′E	1375	2005–2010	127	7.8	0.91	0.35	Liu et al., 2014
Lhasa	29°42′N	91°08′E	3658	1994–2007	417	6.3	−0.16	−0.26	Yao et al., 2013

[a] Mean precipitation (P) and temperature (T) values during respective observation periods.

There is a negative correlation between $\delta^{18}O$ and precipitation at Lhasa. This is associated with the large scale Indian monsoon flow undergoing intense convection in tropical storms where an ensemble of physical and microphysical processes functions in the convective system (Risi et al., 2008). Although the precipitation effect for Yushugou River basin and Urumuqi River basin are not very obvious, there are weak precipitation effects compared with

Fukang and Linze. This suggests that the precipitation effect in mountain is greater than that of the plain because of the significant local convection. This may be caused by the extreme complexity of the isotopic turnover in convective rain. In the processes of convective rain, the air mass moves in a vertical direction and the condensate formed at any stage falls through all the foregoing ones. Thereby, it is mixed with the droplets and takes up new vapour at lower stages. Additionally, further complications are added by the process of exchange in the clouds (Dansgaard, 1964). During our observation period, rain and heat typically occur together and evaporation from the surface is strong. Therefore, as the droplets fall to the ground, processes of exchange and evaporation further complicate the amount effect (Liu et al., 2014).

In this study, there is weak precipitation effect in the Yushugou River basin. Precipitation during the observation period accounted for nearly 85% of annual precipitation in 2013. Therefore, the correlation coefficient between $\delta^{18}O$ and precipitation of our result can reflect the characteristic of precipitation effect in Yushugou River basin. The correlation coefficient between precipitation $\delta^{18}O$ and temperature is 0.48. During the observation period, the temperature was relatively high. Therefore, the correlation coefficient between precipitation $\delta^{18}O$ and temperature in this study can only represent spring and summer. Longer time scale research can better reflect the relationship between precipitation $\delta^{18}O$ and temperature in this basin.

4.4. Correlations between $\delta^{18}O$ and d-excess values in precipitation and moisture sources analysis

Environmental isotopes of precipitation, at different scales, are useful in tracing moisture sources of precipitation and air mass motion path (Welker, 2000; Ichiyanagi and Yamanaka, 2005; He et al., 2006; Longinelli et al., 2006; Yu et al., 2008; Zhao et al., 2011). The d-excess values for the precipitation are related to kinetic fractionation during evaporation, and are influenced by air temperature and relative humidity during evaporation (Merlivat and Jouzel, 1979; Jouzel et al., 1982, 1997). The d-excess value is considered to be a most important parameter representing regional water vapor sources. By combining the $\delta^{18}O$ and d-excess trace method with the NCEP/NCAR reanalysis datasets, we can propose origins of the moisture entering the Yushugou River basin.

The NCEP/NCAR reanalysis datasets were used to investigate atmospheric water vapor sources for the mountainous area of the Yushugou River basin. Based on the NCEP/NCAR reanalysis datasets, we calculated the wind and humidity fields at 500 hPa in May 2013 and June to August 2013 over the Yushugou River basin and adjacent regions (Fig. 6), which represent the moisture transport paths and the possible moisture sources during spring and summer seasons. In both seasons, water in the Yushugou River basin and adjacent regions originated predominantly from westerly air masses.

In order to more precisely determine the origin of the moistures entering the research basin, we compared the seasonal variations of precipitation $\delta^{18}O$ and d-excess with the air mass trajectory model. By employing the HYSPLIT4.0 air mass trajectory model provided by NOAA and combined with Global Reanalysis1 datasets from the National Center for Environmental Prediction (NCEP), we calculated the air mass trajectories of moisture sources for every precipitation event before 96 h. All the calculated results were expressed in an air mass trajectory chart and were started at 500, 2000, and 3500 m above the ground level (AGL) at $2.5° \times 2.5°$ resolution. From doing this, we can further verify the moisture origin of Yushugou River basin. As some air mass trajectory charts of precipitation events are very similar, only eight air mass trajectory charts are shown (Fig. 7).

May is categorized as the spring season in the study area. In this season, precipitation $\delta^{18}O$ value was lower and that of d-excess was higher (Fig. 2). This was due to the heavy isotopes being separated from water vapor first. The δ value was gradually depleted along with the moisture migration. The moisture of precipitation mainly originated from Europe and western Russia, and occasionally was influenced by moisture from the Arctic Ocean (Fig. 7). Moisture was mainly controlled by westerly air masses and accidentally affected by drier polar air masses during the spring. Moreover, in this season the temperature was relatively lower and evaporation was less. Less water vapor was added. Therefore, the precipitation $\delta^{18}O$ value was relatively lower and the d-excess value appeared higher.

From June to August, the summer for the basin, precipitation $\delta^{18}O$ shows enrichment and d-excess was relatively lower (Fig. 2). The precipitation moisture was mainly derived from Europe, Central Asia, Western Russia, Mediterranean, and Black Sea (Fig. 7). The moisture was derived from the westerly air masses in summer. After long range transmission, most water vapor isotopes were lost, but because the basin is located in arid Northwestern China, characterized by low humidity and less precipitation, a large amount of water vapor for precipitation in the basin was derived from local evaporation. The surface water $\delta^{18}O$ in arid regions was high, so the

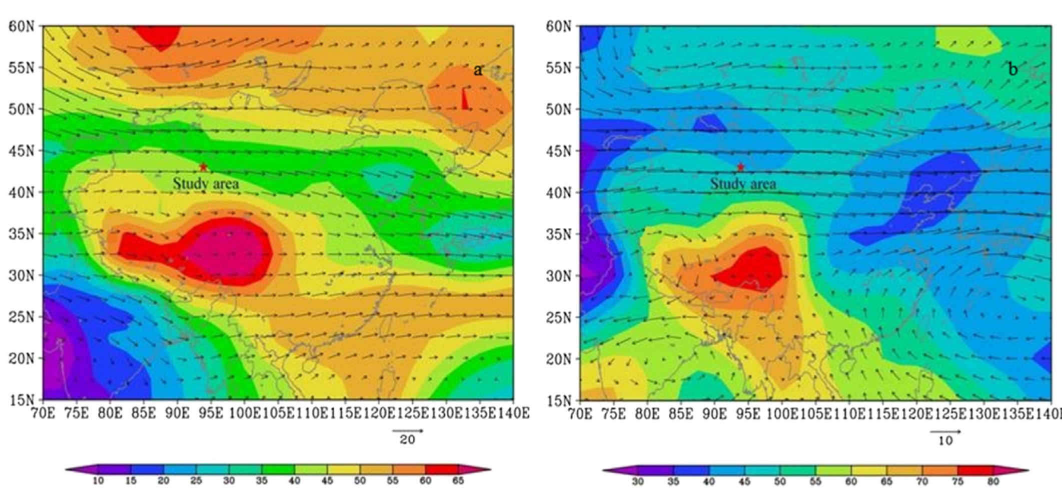

Fig. 6. Spatial distributions of wind fields (arrows) and humidity fields (color) at 500 hPa during spring 2013 (May) (a) and summer 2013 (June to August) (b) over China and adjacent regions. Arrows indicate wind direction and colors represent humidity (g/kg). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

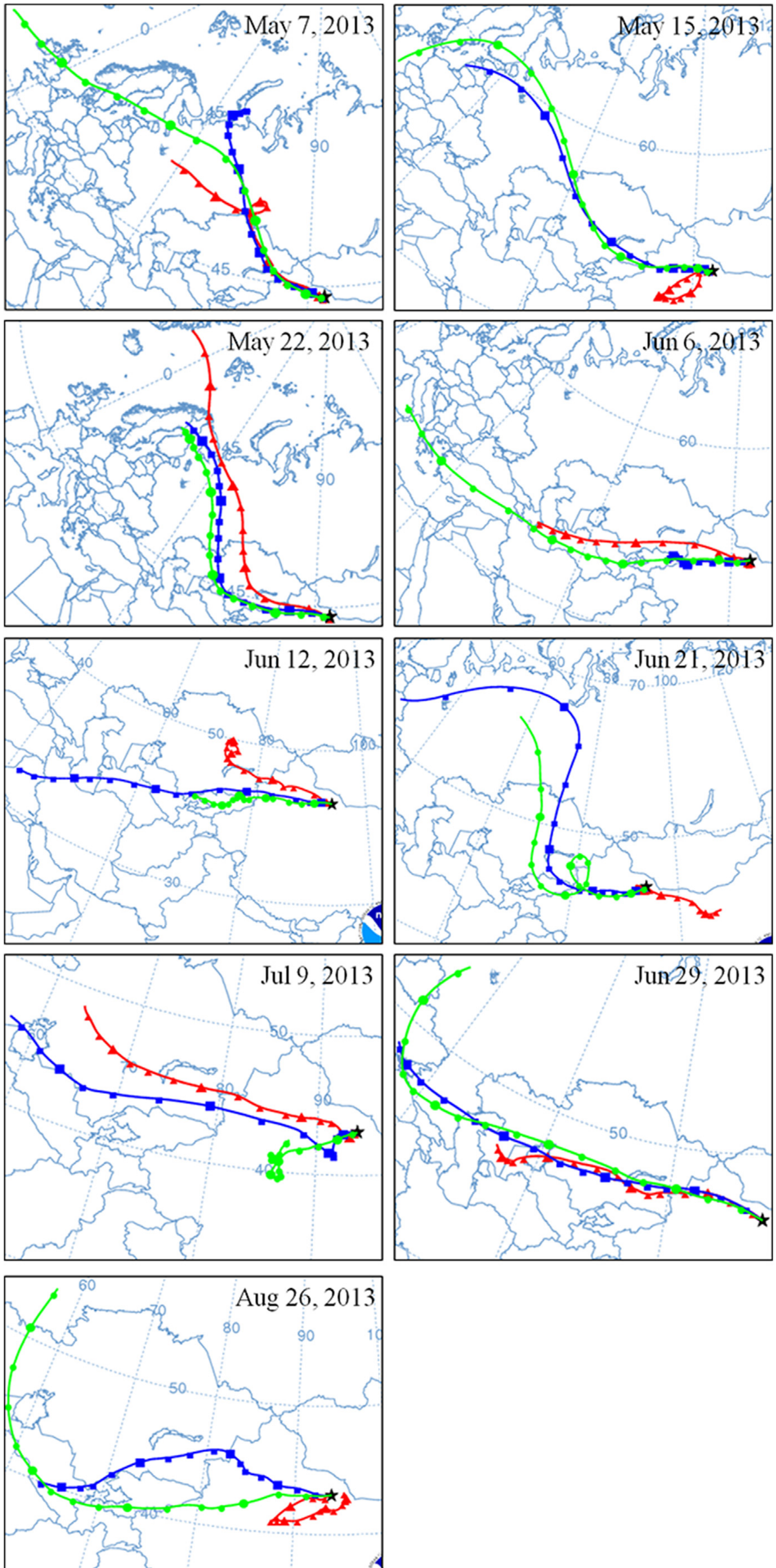

Fig. 7. HYSPLIT reverse-calculated 96-hr trajectories ended at Yushugou Hydrometric Station. For each trajectory model, the red, blue, and green lines in map view represent the path of air parcels terminating at 500, 2000, and 3500 m AGL for the 96-hr period prior to the specified date. Vertical motion for each air parcel as calculated by HYSPLIT is shown in each map. (Source site ★ at 43.08N, 93.95E) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

evaporation water vapor ^{18}O is also high. Moreover, due to evaporation in dry climates raindrops condition, heavy isotopes were enriched in summer. The precipitation $\delta^{18}O$ value was relatively higher while the d-excess value was relatively lower.

The highest precipitation $\delta^{18}O$ value (5.74‰) occurred on June 12, while the d-excess value (1.69‰) was the lowest. The water vapor from the Central Asia Area and areas near Mediterranean Sea experienced a long-distance transportation (Fig. 7). But the precipitation was very small, only 0.7 mm. The average daily temperature was 18.1 °C, which caused strong local convective activity. Combined with enrichment due to evaporation of raindrops during precipitation, the highest $\delta^{18}O$ and low d-excess values emerged. The $\delta^{18}O$ value of the second precipitation on June 21 was the lowest during the observation period. From the air mass trajectory chart, water vapor for this precipitation event came from western Russia and local evaporation from northwest China. This precipitation event should be classified as being formed by continental air mass. During long-distance transport from western Russia, the water vapor was depleted in $\delta^{18}O$. On that day, precipitation happened at three times (7:00–7:30am, 8:30–9:05am, 14:45–15:05pm Beijing Time). The lowest $\delta^{18}O$ value occurred during the second precipitation event, and so the fractionation degree of oxygen stable isotopes in the cloud was higher. The precipitation event at 8:30–9:05am Beijing Time happened when the local convection was relatively weaker. As a result, the extremely low $\delta^{18}O$ value (−14.65‰) and the highest d-excess value (21‰) occurred in this precipitation event.

5. Discussion

To more precisely determine the origin of the moisture, we compared the variation of $\delta^{18}O$ and d-excess in precipitation of the Yushugou River basin with results of Lhasa (affected by southwest monsoon air mass), Urumqi, and Zhangye (affected by westerly air mass) from May to August. We found similar temporal variations in $\delta^{18}O$ and d-excess for our study area and Urumqi (Fig. 8), with more positive $\delta^{18}O$ values in summer and more negative $\delta^{18}O$ values in spring and the opposite pattern for d-excess. Such variation is consistent with variations in moisture source evaporation conditions. The similar seasonal variations in precipitation $\delta^{18}O$ of the Yushugou River basin and of the westerly zone (Yao et al., 2009), and the dissimilarity with the variations in Lhasa, reveal that the moisture input to the Yushugou River basin was derived predominantly from the westerlies and the polar air masses. More negative precipitation $\delta^{18}O$ and higher d-excess for the Yushugou River basin than that of Urumqi suggest that $\delta^{18}O$ depletion in the water was caused by rainfall during long-distance transport (Siegenthaler and Oeschger, 1980). Moreover, the high precipitation d-excess values suggest that recycled water derived from local sources contributes to precipitation significantly (Araguás-Araguás et al., 1998). This shows intensive water vapor recycling in the Yushugou River basin. In spring and summer, precipitation $\delta^{18}O$ values for our study area and Urumqi were more negative than those for Zhangye, and d-excess for Zhangye was lower. The much lower d-excess values of Zhangye compared to the Yushugou River basin (Fig. 4b), suggest stronger re-evaporation of raindrops during precipitation in Zhangye (Jouzel et al., 1997; Tian et al., 2001a).

In summer, precipitation $\delta^{18}O$ values of the Yushugou River basin, Urumqi, and Zhangye were more positive than those of the Lhasa. Extremely low $\delta^{18}O$ values were related to intensive monsoon transport, and high $\delta^{18}O$ values resulted from westerly air masses and local water circulation (Tian et al., 2001b; Yu et al., 2006; Yao et al., 2013). Thus, the more positive precipitation $\delta^{18}O$ indicated that water vapor from the summer monsoon had no effect on precipitation in the Yushugou River basin in the summer.

6. Conclusions

During the wet season, the $\delta^{18}O$ and δD values in precipitation samples collected in the Yushugou River basin varied significantly, from −14.65‰ to 5.74‰ and from −96.2‰ to 44.23‰, respectively. The seasonal variation of $\delta^{18}O$ in precipitation was obvious, with high values in summer and low values in spring. The slope and intercept of LMWL at Yushugou were smaller than the GMWL and the China LMWL. Therefore, the Yushugou LMWL can better reflect the status of the natural geographical and meteorological conditions. There was a temperature effect in precipitation isotope values, whereas a precipitation effect between the hydrogen and oxygen isotopic variation and precipitation was not very obvious. The temperature effect was greater than the precipitation effect in the Yushugou River basin. Although the precipitation effect for Yushugou River basin and Urumuqi River basin were not very obvious, there were weak precipitation effects compared with Fukang and Linze. The precipitation effect in mountain areas was greater than that of the plain because of the significant local convection. Results also showed that the d-excess values displayed a seasonal fluctuation. The d-excess was relatively higher in spring and lower in summer. The variation was related to the moisture origin and local relative humidity. Based on the NCEP/NCAR reanalysis data and three-dimensional isentropic back-trajectories in

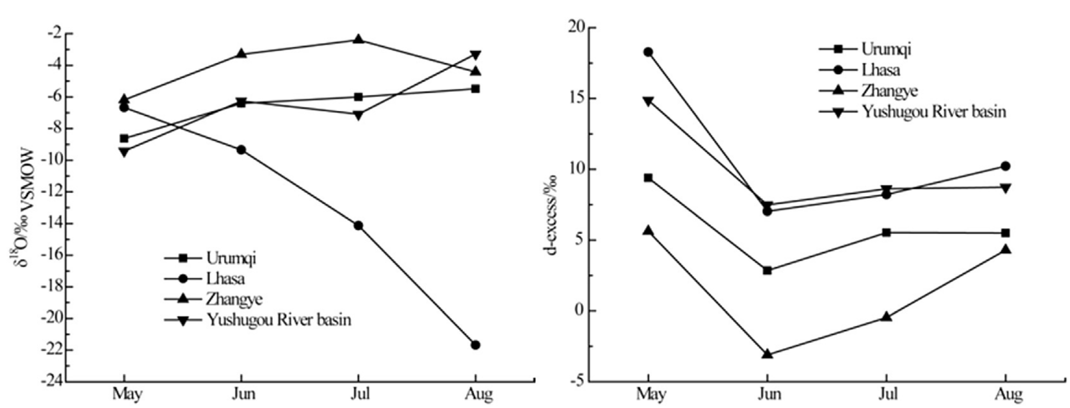

Fig. 8. Comparison of variations in precipitation $\delta^{18}O$ and d-excess among the Yushugou River basin and Urumqi, Zhangye, and Lhasa. The precipitation $\delta^{18}O$ and d-excess values for Urumqi, Zhangye, and Lhasa are from the IAEA database (http://nds121.iaea.org/wiser).

HYSPLIT model, and compared to other stations in westerly domain and monsoon domain, this study indicated that the moisture was mainly controlled by westerly air mass and less affected by the drier polar air mass during the spring, and the moisture was derived from westerly air masses in summer.

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