Relationship between δD and δ^{18}O in precipitation on north and south of the Tibetan Plateau and moisture recycling

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Abstract The local meteoric water line (MWL) has been established from north to south of the Tibetan Plateau based on the measured results of δD and δ^{18}O in precipitation and river water, and the relationship between MWL and moisture origins discussed. The spatial and seasonal variations of *d* in precipitation and river water on the Tibetan Plateau have been studied. Results show that the spatial and seasonal variations of *d* between north and south of the Tanggula Mountains are related to different moisture origins and water recycling.

Keywords: Tibetan Plateau, MWL, deuterium excess.

Due to parallel fractionation during water cycling, a linear relationship exists between δD and δ^{18}O in precipitation on global scale. Craig[1] defined it as meteoric water line (MWL): $\delta D= 8\delta^{18}O + 10$. The kinetic fractionation process during water evaporation, however, can affect the parallel fractionation, and there exists an excess value in the relationship between δD and δ^{18}O. Dansgaard[2] defined it as deuterium excess (*d*). The average *d* value is about 10 on the global scale.

The *d* value in precipitation is mainly affected by the relative humidity of the area where the moisture came from [3,4]. Moisture from the sea surface evaporation at low latitude is characterized by low *d* precipitation, while moisture from dry area will lead to high *d* in precipitation. Due to the complex of water cycling, the MWL and *d* in precipitation vary temporally and spatially. Based on this knowledge, the variation of *d* in ancient record has been used to retrieve the climate evolution of moisture origins. The variations of *d* in underground water and ice cores in both polar regions provides reliable index to reconstruct the climate condition evolution of moisture origins in ancient time [5—8].

Much attention has been paid to the oxygen isotope in precipitation on the Tibetan Plateau in the past[9—12], but the study of *d* in precipitation is quite limited so far. The knowledge of *d* in precipitation on the Tibetan Plateau can help us to better understand the spatial and temporal variations of moisture sources and moisture recycling on the Tibetan Plateau, as well as the climate condition evolution in moisture source areas. The detailed study of *d* in ancient water on the Tibetan Plateau has the potential to reveal the monsoon evolution during Glacial-Interglacial Age. This paper will focus on the spatial and seasonal variations of *d* in precipitation and its relation with moisture sources from north to south of the Tibetan Plateau.

1 Water sampling and measurement

Precipitation was sampled by each precipitation event at Delingha, Tuotuohe and Lhasa meteorological stations respectively, during the summer of 1996 (at Delingha, the sampling periods lasted from 1993 to 1996). The big rivers along the Qinghai-Tibet Highway were also sampled in 1996, ranging from Germod in the north to Himalayas in the south (table 1). Because there are enough precipitation samples and 1996 is a typical year with annual precipitation close to multi-year average, it is reasonable to study the spatial variation of *d* in precipitation on the Tibetan Plateau based on our observation. The hydrogen isotope was measured at Laboratoire de Modélisation du Climat et de l'Environnement, France. The precision of measured δD was within $\pm$1.5 ‰. The oxygen isotope was measured at Laboratory of Ice Core and Cold Regions Environment, Cold and Arid Regions Environmental and Engineering Research Institute, with a precision of $\pm$0.2 ‰. Part samples were measured for δ^{18}O in both laboratories for comparison and the results were quite agreeable.

Table 1 Precipitation and river water sampling

Station	Beginning date	Ending date	Sample number
Delingha	1993-05-12	1996-05-26	112
Tuotuohe	1996-05-26	1996-08-28	49
Lhasa	1996-05-27	1996-08-23	59
River sample	1996-07-13	1996-07-26	13

2 Results

2.1 MWL on the Tibetan Plateau

Fig. 1 gives the local MWL from north to south on the Tibetan Plateau based on the measured results. There exists a good linear relation between δD and δ^{18}O in precipitation at three sites. However, the regression results at the three sites vary evidently:

Delingha: $\delta D = 8.47\delta^{18}O + 15.2$ ($R^2 = 0.98$),

Tuotuohe: $\delta D = 8.21\delta^{18}O + 17.46$ ($R^2 = 0.967$),

Lhasa: $\delta D = 7.90\delta^{18}O + 6.29$ ($R^2 = 0.97$).

Compared with the GMWL[1] ($\delta D = 8\delta^{18}O + 10$), the local MWL shows substantial spatial variations. At Delingha and Tuotuohe, north of the Tanggula Mountains, the regression slopes are higher than 8 and the intercept is above 15. At Lhasa in the south, the regression slope is lower and the intercept is only 6. This spatial variation reflects different moisture origins and different moisture recycling in different regions.

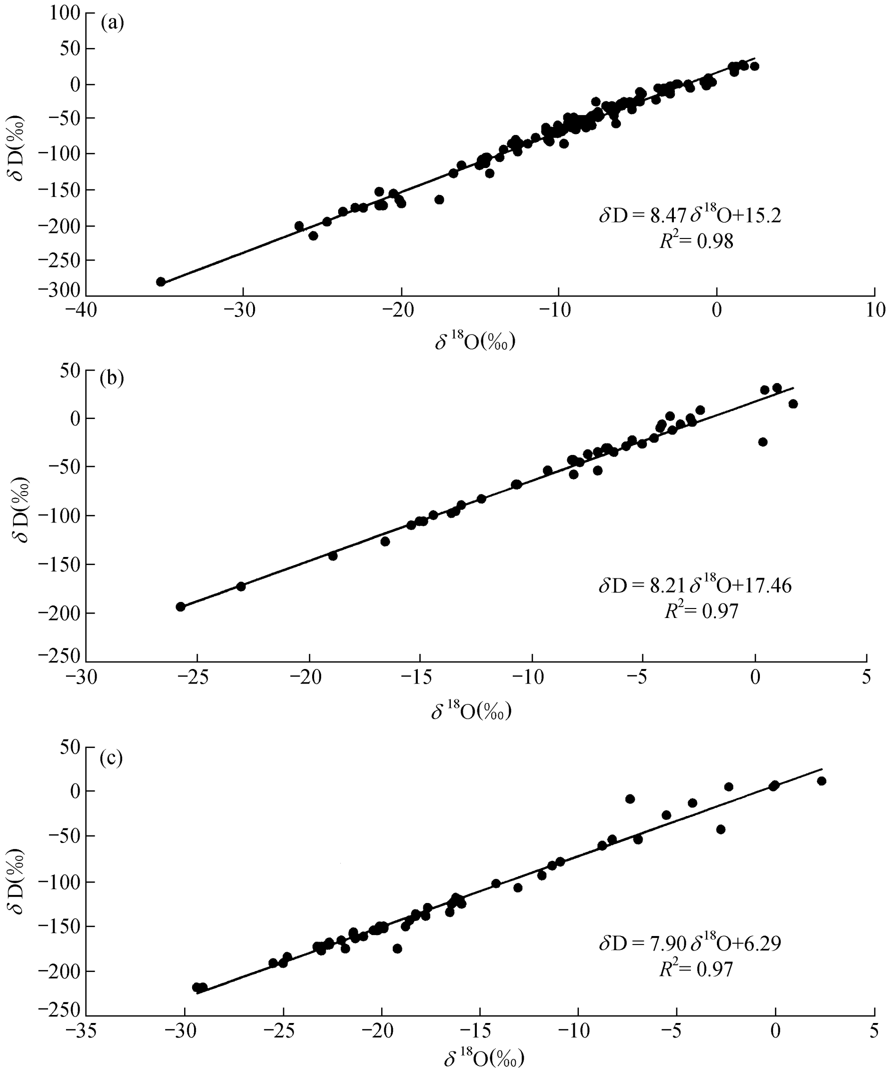

Fig. 1. Local MWL from north to south on the Tibetan Plateau. (a) Delingha, (b) Tuotuohe, (c) Lhasa.

2.2 Seasonal variations of *d* in precipitation on the Tibetan Plateau

Because of the seasonal variations of moisture origins and moisture recycling, *d* in precipitation varies seasonally on the global scale [13]. In eastern China, *d* in precipitation is characterized by high value in winter and low value in summer [14].

Fig. 2 (a) gives the seasonal variation of *d* in precipitation at Delingha, northeast of Tibetan Plateau. Fig. 2 (b) is the seasonal variation of *d* in precipitation at Lhasa, south of the Tibetan Plateau measured by IAEA/ WMO[15]. The *d* value is related to evaporation processes. Besides the water surface evaporation at moisture sources, the evaporation of falling raindrops during precipitation can also affect *d* in precipitation. The second process cannot be ignored especially for precipitation in dry condition. Unlike the monthly average, *d* in individual precipitation event varies

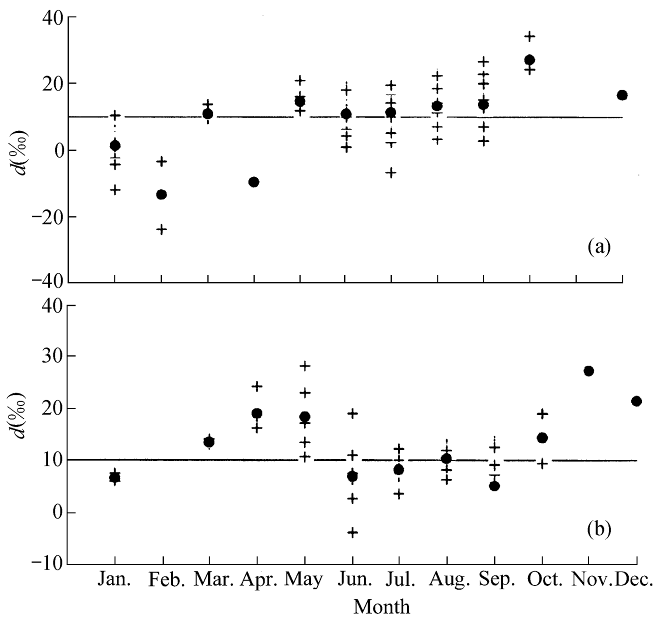

Fig. 2. Seasonal variations of *d* in precipitation at Delingha, northeast of Tibetan Plateau (a) and at Lhasa, south of the Tibetan Plateau (b).

in large magnitude due to different moisture source humidity and precipitation conditions. The measured *d* in precipitation event in Japan can be as high as 70, much higher than the global average [16]. At Delingha, *d* in individual precipitation event varies on seasonable scale, between –25‰ and 35‰. In winter, solid precipitation can effectively prevent the re-evaporation of snow. The extremely low *d* in summer precipitation might result from the re-evaporation of raindrops during precipitation, especially for small long-lasting rain.

At Delingha, precipitation is mainly concentrated in summer. During the observation period, there were only a few precipitation events in some months (for example, March and April), or even no precipitation at all (in November). From the seasonal variation trend of *d* in precipitation at Delingha, *d* in winter and spring (January—April) is relatively lower. From May to October, *d* is higher than in winter months, though it is difficult to exclude the effect of re-evaporation of raindrops in summer rain. At Lhasa, south of the Tibetan Plateau, *d* is of lower value from June to October, but higher value before and after summer. *d* value is also very low in winter in the very few precipitation samples, quite the same as at Delingha.

To compare the seasonal variations of *d* in precipitation at the two stations, it can be seen that the seasonality of *d* variation is distinctive at Lhasa. The low *d* value in summer is in coincidence with monsoon precipitation, representing moisture from sea surface evaporation in high humidity. Before and after summer period, precipitation is affected by continental moisture, resulting in higher *d* in precipitation. The *d* value is very low in the cold January. At Delingha, there is no corresponding low period of *d* in summer precipitation, and *d* is higher than that at Lhasa. This reflects drier moisture origin at Delingha, which is in coincidence with the local moisture recycling in dry climate condition. In winter and spring, *d* varies largely in both stations. Except for the low *d* in January at both stations, *d* is high at Lhasa and low at Delingha during this period.

2.3 Spatial variations of *d* in precipitation on the Tibetan Plateau

Fig.3 (a) shows the spatial variation of *d* in precipitation observed during July and August of 1996 and river water from north to south of the Tibetan Plateau. *d* decreases from north to south of the Tibetan Plateau. At Delingha and Tuotuohe, *d* in precipitation is generally at the same level, varying between 11‰ and 12‰. At Lhasa in the south, *d* in precipitation is as low as 7‰.

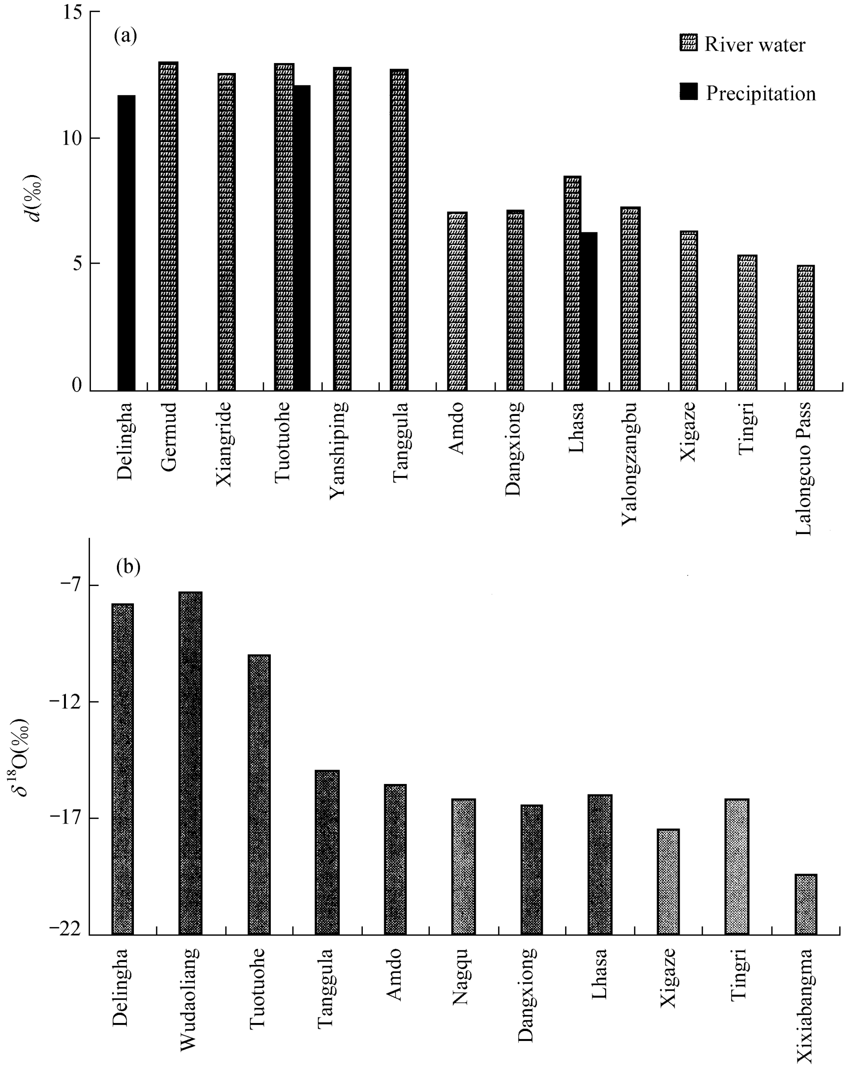

Fig. 3. Spatial variations of *d* in precipitation and river water (a) and δ^{18}O in precipitation (b) on the Tibetan Plateau.

Big river water is an average of the local precipitation, thus the stable isotopes in river water are more stable than that in precipitation. The spatial variation of *d* in big river water on the Tibetan Plateau is remarkable. To the north of the Tanggula Mountains, *d* in river water is higher, varying between 12‰ and 13‰. To the south of the Tanggula Mountains, *d* in river water is lower, varying between 5‰ and 9‰.

The spatial distribution of *d* in precipitation and river water from north to south of the Tibetan Plateau is related to different moisture origins on the plateau. Different moistures between the two sides of the Tanggula Mountains result in obvious spatial distribution of *d* in precipitation.

To the north of the Tanggula Mountains, precipitation is affected by continental air mass. Local evaporation in dry climate condition contributes a lot to precipitation, resulting in higher slope and higher intercept in the local MWL, and higher *d* in precipitation as well. To the south of the Tibetan Plateau, lower *d* in precipitation and river water and low slope in local MWL, indicate that moisture comes from very humid climate condition. While in this area, precipitation is directly affected by summer monsoon precipitation, which origins from the sea surface evaporation in very high relative humidity.

The spatial variations of *d* in precipitation and river water on the Tibetan Plateau agrees with the spatial distribution of δ^{18}O on the plateau, reconfirming that the Tanggula Mountains is an important geographical dividing line. Earlier work shows that the different moistures also lead to different seasonal variation of oxygen stable isotope between the two sides[17]. This spatial difference in moisture origins and water recycling is reflected in spatial distribution of δ^{18}O in precipitation. Fig.3 (b) shows the spatial variation of δ^{18}O in precipitation from north to south of the Tibetan Plateau[12]. The spatial distribution of δ^{18}O between the two sides of the Tanggula Mountains is quite similar to that of the spatial variation of *d*. The higher δ^{18}O in the north of the Tibetan Plateau is also related to the local water recycling in the inland of the continent, while low δ^{18}O in precipitation in the south of the Tibetan Plateau is related to monsoon precipitation originated from marine air mass.

3 Conclusions and discussion

The moisture origins and moisture recycling condition are different between north and south of the Tibetan Plateau. Southwest monsoon bring sea surface evaporated moisture to the southern part of the Tibetan Plateau and results in rich precipitation in this area. For the northern part of the Tibetan Plateau, located in the center of Eurasian, the marine air mass is very difficult to reach directly and much part of precipitation will re-evaporate to the atmosphere from the land surface. In that area, water recycling plays an important role in the hydrological cycle. In winter, north wind controls the whole plateau, and less precipitation occurs.

Different moisture origins and water recycling mechanisms result in the temporal and spatial distribution of isotopes in precipitation on the Tibetan Plateau. Although there is a good linear relation between δ^{18}O and δD, this relation varies between south and north of the plateau. In the northern part of the Tibetan Plateau, continental air mass leads to a higher slope and intercept in the local MWL, while in the northern part of the plateau, the marine air mass leads to a low slope and low intercept in the local MWL.

The seasonal variation of *d* in precipitation has also been affected. The lower *d* in summer in the southern part of the plateau is related to the marine air mass. However, at Delingha, northeast part of the plateau, *d* is higher in summer than in winter and spring. This seasonal variation in dry climate condition can also be found from the ice core record in Mongolia[18], but opposite to the general seasonal variation of *d* in precipitation in the Northern Hemisphere. Winter precipitation is rather limited with low *d* in precipitation samples. This might be due to the long-distance transport of sea surface evaporated moisture. But further work is needed to support this explanation.

Dry climate and intensive inland water recycling in the northern part of the plateau also result in higher *d* in precipitation and river water. In the southern part of the Tibetan Plateau, affected by southeast monsoon precipitation, *d* is of lower value in both precipitation and river water. The spatial variation of *d* is in agreement with that of δ^{18}O in precipitation.

The above is just a preliminary results about *d* in precipitation on the Tibetan Plateau, and more work is needed to better understand the behavior of *d* in precipitation on the plateau. Observations have shown that *d* value in individual precipitation events varies very largely. The variation of *d* in individual precipitation events should be studied in detailed based on the synoptic condition. Though few precipitation events occur in winter on the plateau, the origin of winter precipitation should also be further studied in the future. The mechanism controlling *d* in snow formation at extremely low temperature on high peak of the plateau is also unknown. As the glaciers on the high Tibetan Plateau might bear rich information about the moisture origin evolution, further work is also needed to better understand the variation of *d* with altitude in high mountain area on the plateau.

In the past two decades, ice cores have been drilled in Dunde ice cap at Qilian Mountains, Guliya ice cap at west Kunlun Mountains, Dasuopu Glacier at Xixiabangma. These ice cores can provide continuous, high-resolution information about climatic and environmental changes on the Tibetan Plateau[19—21]. Further study of *d* in the Tibetan Plateau ice cores has the potential to provide information about moisture origin variation, especially the monsoon evolution on the Tibetan Plateau.

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