Stable Isotope Variations in Precipitation and Moisture Trajectories on the Western Tibetan Plateau, China

Authors: Wusheng Yu, Tandong Yao, Lide Tian, Yaoming Ma, Naoyuki Kurita, et. al.

Source: Arctic, Antarctic, and Alpine Research, 39(4) : 688-693

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(07-511)[YU]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 39, No. 4, 2007, pp. 688–693

Stable Isotope Variations in Precipitation and Moisture Trajectories on the Western Tibetan Plateau, China

Wusheng Yu†§*
Tandong Yao†*
Lide Tian†*
Yaoming Ma†*
Naoyuki Kurita‡
Kimpei Ichiyanagi‡
Yu Wang† and
Weizhen Sun†

*Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China
†State Key Laboratory of Cryospheric Science, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China
‡Institute of Observational Research for Global Change, Yokosuka, Japan
§Corresponding author: yuws@itpcas.ac.cn

Abstract

Observations at the Shiquanhe and Gaize meteorological stations provide data for analysis of $\delta^{18}O$ and δD variations in precipitation for the Ngari (Ali) region, western Tibetan Plateau. Temperature controls $\delta^{18}O$ in precipitation in this area. $\delta^{18}O$ in precipitation positively correlates with air temperature at the Shiquanhe and Gaize stations, especially for precipitation weighted monthly mean $\delta^{18}O$. The $\delta^{18}O$ – T correlation gradually strengthens from south to north across the western Tibetan Plateau and adjacent regions, with gradual weakening of southwest monsoon activity. The strongest correlation is found at Hetian. There is a poor correlation between $\delta^{18}O$ and air temperature in the south at New Delhi because the moisture derives predominantly from the Indian Ocean in summer. The Ngari region exhibits a close relation between δD and $\delta^{18}O$ in precipitation samples, similar to stations in adjacent regions and the global meteoric water line. The summer seasonal averaged deuterium excess (*d*) values increase gradually from south to north across western Tibetan and adjacent areas, resulting from southwest monsoon activity gradually weakening to the north.

Introduction

Numerous researchers (Johnsen et al., 1989, 1995; Cuffey et al., 1994; Thompson et al., 2000) have used stable isotopes to reconstruct paleoclimate variations represented in polar and Tibetan ice-core records. However, the interpretation of stable isotope records in ice cores must be based on knowledge of temporal and spatial variations of stable isotopes in precipitation and their relations with meteorological conditions. The stable isotopes in precipitation relate not only to the condensation temperature, but also to the initial conditions of moisture origin and transport mechanisms (Dansgaard, 1964; Merlivat et al., 1979; Rozanski et al., 1982, 1992; Jouzel et al., 1987, 1997).

The Tibetan Plateau is the largest and highest plateau in the world. Due to its unique geographic position and topography, the origins of moisture over the Plateau are complex. The interactions among different moisture sources impact the spatial and temporal variation of stable isotopes in precipitation. Studies show a very poor correlation between $\delta^{18}O$ and temperature on the southern Tibetan Plateau—strong southwest monsoon activity in this area results in high precipitation rates and low $\delta^{18}O$ values. Accordingly, stable isotopes in precipitation show an apparent precipitation "amount effect" (Araguás-Araguás et al., 1998; Tian et al., 2001a, 2001b). The effects of the monsoon diminish in the middle of the Tibetan Plateau, but continue to cause a reduced correlation between $\delta^{18}O$ and temperature at the annual scale (Tian et al., 2001a, 2001b, 2003). On the northern Tibetan Plateau beyond the extent of monsoon precipitation, a good linear relationship exists between $\delta^{18}O$ in precipitation and temperature. Here the temperature effect controls $\delta^{18}O$ in precipitation (Zhang et al., 1995; Yao et al., 1999; Tian et al., 2003). The spatial variation of the $\delta^{18}O$ – T relationship from south to north on the Tibetan Plateau shows a gradually decreasing impact of monsoon precipitation.

Understanding stable isotope variations in precipitation over this extensive region can provide insight and a theoretical basis for interpreting observations of stable isotopes in ice cores. In recent decades, a number of studies have focused on stable isotopes in precipitation from south to north on the Tibetan Plateau (Yao et al., 1995, 1996, 1999; Zhang et al., 1995; Thompson, 2000; Thompson et al., 2000; Tian et al., 2001a, 2001b, 2001c, 2003). There remains, however, a gap in understanding of stable isotopes in the western Tibetan Plateau. In this paper, we discuss the variations of stable isotopes in precipitation, the local meteoric water line (MWL), the relationship between the MWL and moisture origins, and the variation of the *d* values based on the observation of stable isotopes at the Shiquanhe and Gaize meteorological stations (in the Ngari region, western Tibetan Plateau).

Methods and Materials

STUDY AREA

The Ngari region study area lies in the western Tibetan Plateau (Fig. 1). It borders on the Nagqu (Nakchu) region, west of the Tanggula Mountains, and stretches to the western portion of the Himalayas in the west and southwest. It joins the middle section of the Kangdese (Gangdise) Mountains, and ends on the southern side of the Kunlun Mountains in the north. This region

1523-0430/07 $7.00

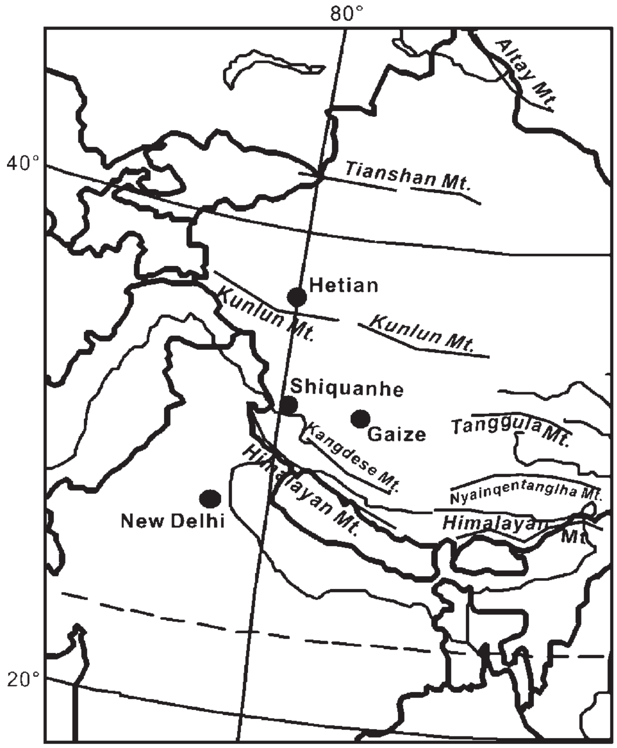

FIGURE 1. Map of the precipitation sampling sites in the western Tibetan Plateau and adjacent regions.

has an annual average temperature of 0°C to 2°C, and an average annual rainfall of 73 mm. About 80% of the annual precipitation falls in the summer season from June to September. Rainfall also varies spatially across the region, decreasing gradually from east to west (Ye and Gao, 1979); northwestern Ngari region has an average annual rainfall less than 50 mm.

The meteorological stations of Gaize (Gertse, Gertze) and Shiquanhe (Senge Khabab) are located, respectively, in the east and the west of Ngari region. Shiquanhe lies in a narrow river basin. The climate is dry with an annual precipitation of about 75 mm. Gaize lies on the southeastern Changtang (Changthang, Qiangtang) Plateau, with some lakes and marshland in the vicinity. The precipitation at Gaize exceeds that at Shiquanhe, averaging nearly 190 mm per annum.

SAMPLING AND DATA COLLECTION

The Gaize meteorological station launched a program to monitor stable isotopes in precipitation in 1998. Sample collection in 1999 was incomplete. The Shiquanhe station collected precipitation samples from 1999 to 2002 (Table 1). Both stations sampled each precipitation event. Rainfall samples were collected and immediately sealed in plastic bottles. Snow and other solid precipitation were collected on clean porcelain plates, put into clean plastic bags, and sealed. After the samples melted at room temperature, they were processed in the same manner as rainfall. All the samples were stored frozen in a cold laboratory until analyzed. The Frontier Observational Research System for Global Change, Japan, made the deuterium measurements, with an analytical precision of 1.0‰. The State Key Laboratory of Cryosphere and Environment, Chinese Academy of Sciences, Lanzhou, China, measured oxygen isotope compositions of all the precipitation samples using a MAT-252 mass spectrometer with a precision of 0.2‰. Both laboratories measured $\delta^{18}O$ in some samples from both sampling stations for comparison and the results agreed quite well. In addition, we use isotopic data from Hetian (Hotan) and New Delhi. These stations were established as part of the International Atomic Energy Agency/World Meteorological Agency (IAEA/WMO) Global Network of Isotopes in Precipitation (GNIP), whose measurements include $\delta^{18}O$, δD, temperature, and precipitation. The records at Hetian (station number 5182800) are from 1988 to 1992, and at New Delhi (station number 4218200) are from 1961 to 2001 (available at http://isohis.iaea.org). Precipitation was collected in monthly amalgamated samples, and analyzed at the IAEA laboratory in Vienna, Austria, for both $\delta^{18}O$ and δD, with an analytical precision of 0.1‰ and 1.0‰, respectively (Araguás-Araguás et al., 1998).

TABLE 1

Characteristics of the sampling sites and of the water sampling.

	Hetian	Shiquanhe	Gaize	New Delhi
Latitude	37°05′N	32°30′N	32°18′N	28°35′N
Longitude	79°34′E	80°05′E	84°01′E	77°12′E
Altitude (m)	1375	4278	4430	212
Observation period	1988–1992	1999–2002	1998–2002	1961–2001
Number of samples	47	65	191	452
Annual rainfall (mm)	36	75	190	740

The precipitation sampling program recorded the duration of each precipitation event, air temperature on the ground (recorded by a bimetallic thermograph), precipitation amount, and other relevant meteorological data (before and after each precipitation event).

Results and Discussion

TEMPERATURE DEPENDENCE OF $\delta^{18}O$ IN PRECIPITATION

Figure 2 shows the relationships between $\delta^{18}O$ in precipitation and air temperature (the "air temperature" is the averaged value of the temperature at the start and end of an event) in recent precipitation events at the Shiquanhe and Gaize meteorological stations. The correlation coefficient between $\delta^{18}O$ in precipitation and temperature at Shiquanhe is 0.43, within a 0.01 confidence limit. The correlation coefficient at Gaize is much poorer, only 0.22, also within a 0.01 confidence limit.

We find better correlations between monthly precipitation-weighted means of $\delta^{18}O$ and monthly temperatures (Fig. 3) than those for individual precipitation events (Fig. 2). Results from a linear regression least squares fit using weighted monthly means of the data can be expressed as follows:

$$\text{Shiquanhe}: \ \delta^{18}O = 0.63\bar{T} - 16.12 \quad (r = 0.65, P < 0.01) \quad (1)$$

$$\text{Gaize}: \ \delta^{18}O = 0.37\bar{T} - 12.22 \quad (r = 0.56, P < 0.01) \quad (2)$$

Clearly, weighted monthly means of $\delta^{18}O$ in precipitation and air temperatures on the western Tibetan Plateau produce better least squares fits and closer $\delta^{18}O$ – T correlations. This suggests that a temperature effect on $\delta^{18}O$ in precipitation over the sampling period exists due to seasonal variations at the two stations.

To illustrate the spatial variation (north to south) of the $\delta^{18}O$ – T relationship near the western Tibetan Plateau, Figure 3 also shows data from adjacent regions. The Hetian meteorological station lies to the north, and the New Delhi station lies to the south (Fig. 1, Table 1). The correlation between $\delta^{18}O$ in precipitation and air temperature at Hetian is strongest ($r = 0.86$, $P < 0.01$). At the

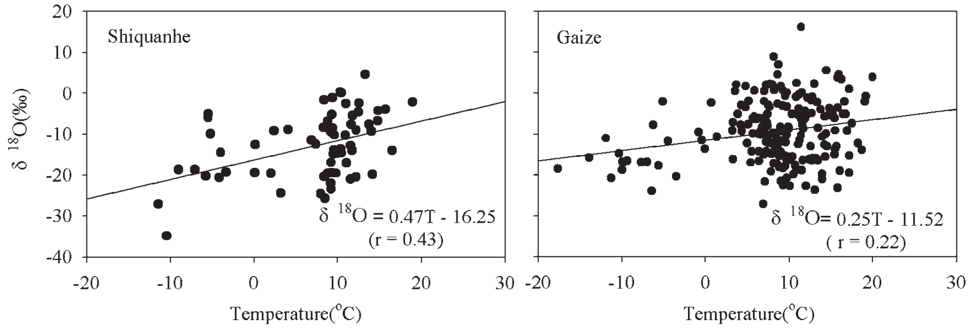

FIGURE 2. Relationship between $\delta^{18}O$ and temperature in recent precipitation events at Shiquanhe and Gaize.

other extreme, the oxygen isotopic compositions of precipitation at New Delhi show essentially no correlation with air temperature. Together the data show a decrease from north to south across the western Tibetan Plateau and adjacent regions in the significance of the linear regression least squares fit between $\delta^{18}O$ and T.

Monsoon precipitation patterns can largely explain the spatial variations of the $\delta^{18}O$ – T relationship. With the attenuation of monsoon precipitation from south to north, the correlation of $\delta^{18}O$ – T gradually becomes stronger. The southwest monsoon conditions are very strong at New Delhi, and $\delta^{18}O$ is low during summer monsoon precipitation, while summer temperatures remain high (Fig. 4d). In contrast, Hetian lies to the north of the Plateau, beyond the influence of the monsoon rains. Without the southwest monsoon control, $\delta^{18}O$ in precipitation shows a very strong temperature dependence. The $\delta^{18}O$ values and temperature are both very high in summer and low in winter (Fig. 4a). At Gaize and Shiquanhe, however, the $\delta^{18}O$ values increase from January to June with the gradually increasing air temperature, but then appear to decrease at the end of July or early August until the end of the rainy season (Fig. 4c, 4b). This deviation in the $\delta^{18}O$ – T correlation at the two stations coincides with the southwest monsoon reaching the western Tibetan Plateau for a short period in summer each year.

Araguás-Araguás et al. (1998) discussed the spatial variations of oxygen isotope responses in southeast Asia (Fig. 5). A curve sketched on Figure 5 separates different regimes of $\delta^{18}O$ response. North of the curve, $\delta^{18}O$ in precipitation shows strong temperature dependence. South of the boundary, however, $\delta^{18}O$ in precipitation is controlled more by the effect of strong monsoon activity. The mechanism of this control is described as a precipitation "amount effect." Hetian lies in the "temperature effect" region and New Delhi lies in the "amount effect" region, which agrees with the positive correlation between $\delta^{18}O$ in precipitation and temperature at Hetian and lack of correlation between $\delta^{18}O$ in precipitation and temperature at New Delhi. On the other hand, the Ngari region, mid-way between Hetian and New Delhi, lies in the transition belt between "temperature effect" regions in the north and precipitation "amount effect" regions in the south (Fig. 5). The duration of the southwest monsoon activity in the Ngari region is not as long as that at New Delhi; as a result, the $\delta^{18}O$ – T correlation at the Gaize and Shiquanhe stations is better than that at New Delhi. That is, temperature remains the dominant factor that controls the variations of $\delta^{18}O$ in the Nagri region. But, the southwest monsoon precipitation results in the low $\delta^{18}O$ values in late summer, weakening the relationship of $\delta^{18}O$ in precipitation and air temperature (Yu et al., 2004). The $\delta^{18}O$ – T correlation gets stronger with increasing latitude from south to north, corresponding directly with the monsoon impact.

The weaker $\delta^{18}O$ – T correlation at Gaize than at Shiquanhe (Fig. 2) may correspond to southwest monsoon activity at Gaize being stronger and more frequent than at Shiquanhe. Gaize is closer to the Bay of Bengal, resulting in higher summer precipitation, and the southwest monsoon reaches Gaize earlier. In addition, the vegetation at Gaize is more abundant than that at

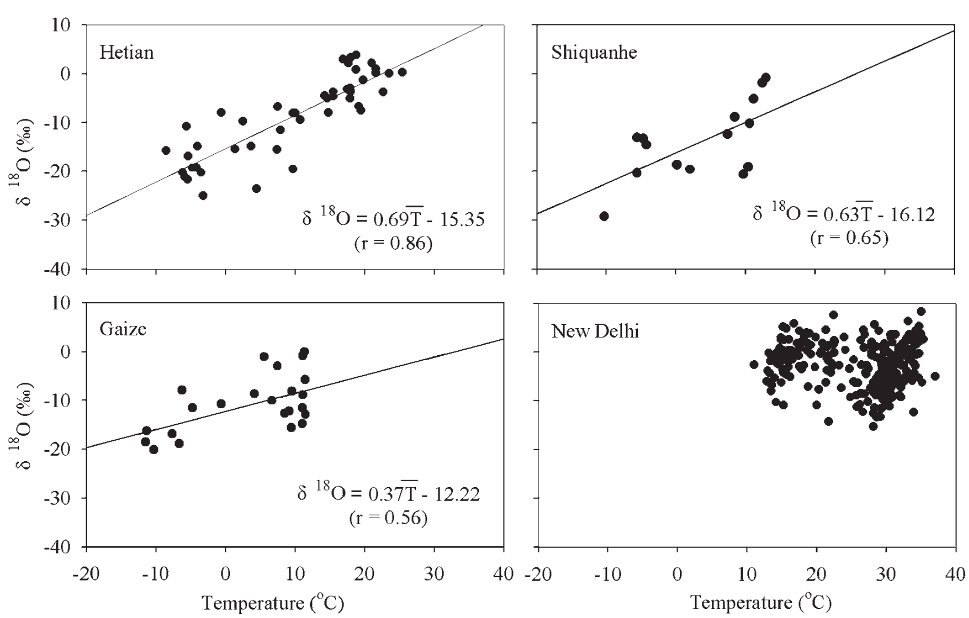

FIGURE 3. The variations of precipitation-weighted monthly $\delta^{18}O$ and monthly mean temperature at four stations (Hetian, Shiquanhe, Gaize, and New Delhi).

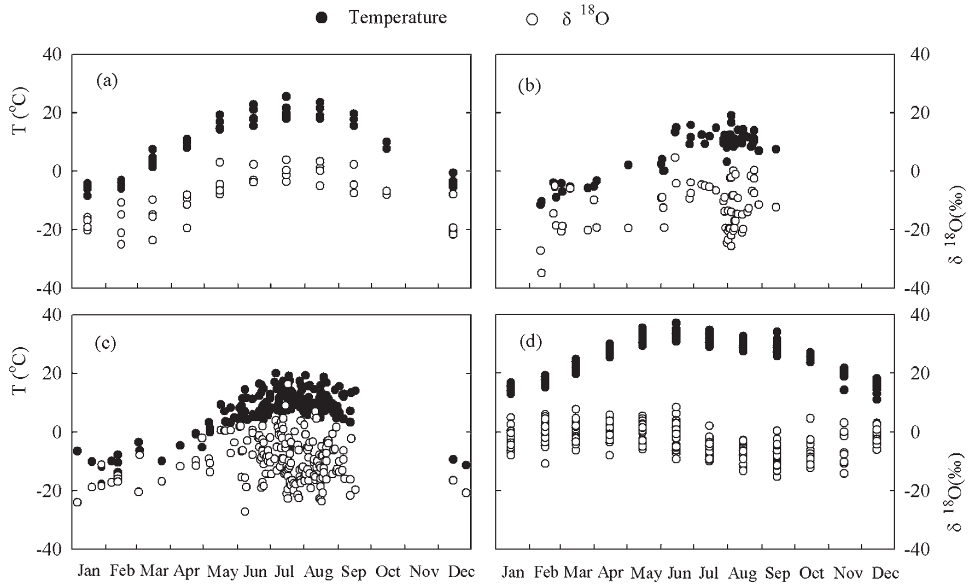

FIGURE 4. Comparison of temperatures and $\delta^{18}O$ trends in precipitation over the annual cycle at four meteorological stations: a–Hetian; b–Shiquanhe; c–Gaize; d–New Delhi. Plots for Hetian and New Delhi show monthly mean values, while for Shiquanhe and Gaize show event values.

Shiquanhe and there are small lakes and marshland in the region. Hence, the local evaporation intensity at Gaize is greater than at Shiquanhe. Accordingly, the precipitation resulting from local convection contributes a larger proportion of the rainfall so as to weaken the $\delta^{18}O$ – T relationship. All these factors result in making the correlation between $\delta^{18}O$ in precipitation and air temperature at Gaize weaker than at Shiquanhe.

LOCAL MWL IN WESTERN TIBETAN PLATEAU AND ADJACENT REGIONS

Due to parallel fractionation during water cycling, δD and $\delta^{18}O$ relate linearly in precipitation on a global scale. Craig (1961) first summarized and related these data, and defined the meteoric water line (MWL). The global MWL is $\delta D = 8.0\ \delta^{18}O + 10$ for continental precipitation unaffected by evaporation.

The local meteoric water lines were calculated from individual precipitation events at the four stations in this study. The following regressions are based on samples for δD collected at Shiquanhe in 1999–2002 and at Gaize in 2000–2002. There exists a good linear relation between δD and $\delta^{18}O$ in precipitation at all four stations, as follows:

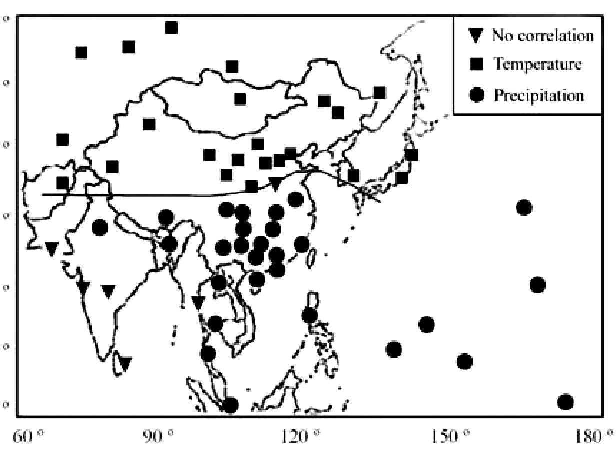

FIGURE 5. Areas of Southeast Asia with different δD and $\delta^{18}O$ responses to changes of surface air temperature and amount of precipitation, based on the long-term monthly means of isotopic and meteorological data (adapted from Araguás-Araguás et al., 1998). The sketched curve separates different regimes of $\delta^{18}O$ response.

Hetian:

$$\delta D = 8.40\delta^{18}O + 11.41 \quad (r = 0.995, n = 47, P < 0.01) \tag{3}$$

Shiquanhe:

$$\delta D = 8.09\delta^{18}O + 7.96 \quad (r = 0.985, n = 65, P < 0.01) \tag{4}$$

Gaize:

$$\delta D = 8.29\delta^{18}O + 11.62 \quad (r = 0.981, n = 172, P < 0.01) \tag{5}$$

New Delhi:

$$\delta D = 7.16\delta^{18}O + 4.14 \quad (r = 0.978, n = 256, P < 0.01) \tag{6}$$

The local MWLs show substantial spatial variation. At New Delhi, the regression slope (7.16) is lower than 8 and the intercept (4.14) is far below 10. In contrast, at the other three stations, the slopes and intercepts are close to those for the global MWL. In brief, in the south of the study region, the local MWL is shallower and offset below the global MWL, and in the middle and the north of the study region the local MWLs are close to the global line. In addition, the correlation between δD and $\delta^{18}O$ in precipitation strengthens gradually (the correlation coefficient (r) increased gradually) from south to north across the western Tibetan Plateau and adjacent regions, resulting from the gradually decreasing impact of monsoon precipitation.

SEASONAL AND SPATIAL VARIATIONS OF DEUTERIUM EXCESS (d) *IN PRECIPITATION*

Kinetic effects influence the effective fractionation factors, and there exists an excess value in the relationship between δD and $\delta^{18}O$. This deuterium excess (d), defined by Dansgaard (1964) as $d = \delta D - 8.0\ \delta^{18}O$, is used as an index for nonequilibrium conditions. The d value in precipitation reflects the evaporation conditions at the source of the moisture (Merlivat and Jouzel, 1979; Jouzel and Merlivat, 1984; Armengaud et al., 1998).

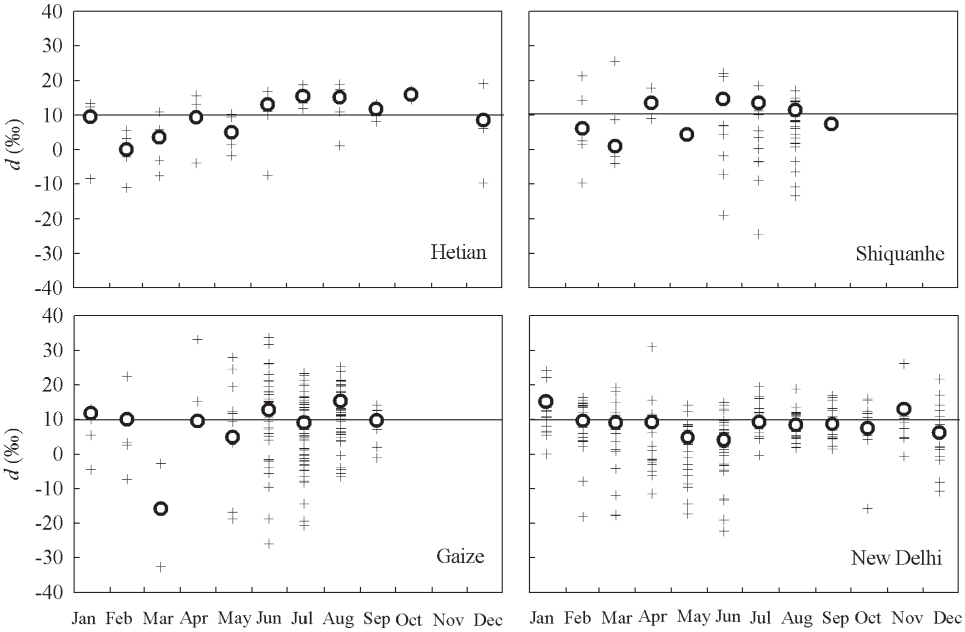

FIGURE 6. Seasonal variations of deuterium excess (*d*), in precipitation at four stations in the western Tibetan Plateau and adjacent regions. The crosses and open circles stand for individual data and weighted monthly means, respectively.

Precipitation derived from sea surface evaporation at low latitude is characterized by low *d* values (<10‰). Under dry climate condition, the kinetic fractionation will be intensified during evaporation, and the *d* value in the subsequent precipitation will be high (>10‰). In contrast, under humid climate condition, the kinetic fractionation in evaporation will be weakened, resulting in low *d* (<10‰) in the subsequent precipitation (Merlivat and Jouzel, 1979; Clark and Fritz, 1997).

The *d* values in precipitation from the Shiquanhe and Gaize stations were calculated based on simultaneous measurements of δD and $\delta^{18}O$. In addition, we use records of *d* in precipitation at New Delhi and Hetian provided by GNIP. These results show obvious spatial and temporal variations in the western Tibetan Plateau and its surroundings (Fig. 6). The *d* values from individual precipitation events (crosses) at the four stations vary substantially, unlike those from the precipitation weighted monthly means (open circles). This results from the varying moisture sources and humidity during precipitation events.

Due to the very sparse precipitation in winter, we would mainly compare the *d* values in summer at the four stations. The weighted average monthly *d* values at New Delhi are low, except for January and November, especially from May to October. The low *d* values in summer coincide with monsoon precipitation, representing moisture from surface evaporation of the Indian Ocean in high humidity. Southwest monsoon precipitation, representing moisture from the Indian Ocean, also causes low *d* values at Gaize in July.

Because southwest monsoon storms in summer at Shiquanhe are not as intensive as at Gaize, the weighted average monthly *d* values in summer at Shiquanhe are higher than those at Gaize, especially in June and July. Summer precipitation at Hetian displays no corresponding period of low *d* values, and the *d* values are the highest of the four stations. This reflects moisture coming from a drier source, beyond the influence of the southwest monsoon. This coincides with the local moisture recycling in dry climate conditions and westerlies precipitation.

From south to north, in summer, the southwest monsoon activity gradually weakens, resulting in decreasing humidity, and at Hetian the moisture origins are controlled by the westerlies and local moisture recycling. On the other hand, the westerlies gradually weaken from north to south through this region, such that they have little impact at New Delhi. At Shiquanhe and Gaize, the westerlies and monsoon interweave, with the southwest monsoon dominating in summer. That is, the western Tibetan Plateau is a transition zone between the regions dominated by the monsoon and the regions dominated by the westerlies. Accordingly, from south to north across our study regions, the summertime averaged *d* values (weighted annual means) gradually increase with the humidity decreasing (Fig. 7).

Conclusions

Stable isotopes in precipitation depend on many factors such as the origins of the moisture and precipitation processes. In this paper, we discuss variations of $\delta^{18}O$ in precipitation in the western Tibetan Plateau (the Shiquanhe and Gaize meteorological stations) and adjacent regions, and analyze the relationships between δD and $\delta^{18}O$ at four stations (New Delhi, Gaize, Shiquanhe, and Hetian).

At Shiquanhe and Gaize, the variations of $\delta^{18}O$ in precipitation relate closely to temperature variations. However, southwest monsoon precipitation in summer weakens the relationship between $\delta^{18}O$ and temperature. The $\delta^{18}O$ – T correlation at Gaize is not as significant as that at Shiquanhe. This corresponds to stronger and more frequent monsoon activities at Gaize than at Shiquanhe. Moreover, the more abundant ground vegetation and

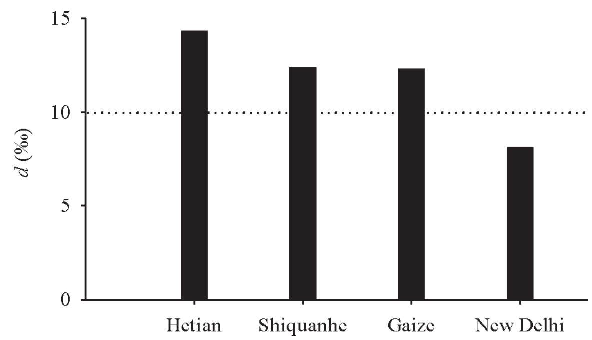

FIGURE 7. Spatial variations of mean *d* in summer precipitation (June–August) over the years of observation at four stations across the western Tibetan Plateau and adjacent regions.

proximity of small lakes and marshlands increase the local evaporation intensity at Gaize.

As the influence of monsoon precipitation weakens from south to north across the western Tibetan Plateau and adjacent regions, the $\delta^{18}O$ – T correlation gradually becomes stronger.

δD and $\delta^{18}O$ in precipitation samples relate closely in the Ngari region, as they do at stations in the nearby regions. With increasing latitude from south to north, southwest monsoon activity gradually weakens in summer. Accordingly, the seasonal averaged deuterium excess values in summer increase gradually from south to north across the western Tibetan Plateau and adjacent regions, with decreasing humidity.

Acknowledgments

This work was supported by the Collective Innovation of the National Natural Science Foundation of China (40121101), the Ministry of Science and Technology of the People's Republic of China (2005CB422004), the National Natural Science Foundation of China (40571039, 40701037, 40671043), and the CEOP project. The authors gratefully acknowledge the support of K. C. Wong Education Foundation, Hong Kong. We are greatly indebted to Dr. Suzanne P. Anderson for helpful suggestions during reviewing. We also thank Dr. Cindy Cooley and Tingjun Zhang for their great help. Especial thanks are given to the two anonymous reviews for very constructive comments. Some isotopic data used in this paper are from the IAEA/WMO Global Network of Isotopes in Precipitation.

References Cited

Araguás-Araguás, L., Froehlich, K., and Rozanski, K., 1998: Stable isotope composition of precipitation over southeast Asia. *Journal of Geophysical Research*, 103(D22): 28,721–28,742.

Armengaud, A., Koster, R. D., Jouzel, J., and Ciais, P., 1998: Deuterium excess in Greenland snow: Analysis with simple and complex models. *Journal of Geophysical Research*, 103(D8): 8947–8954.

Clark, I., and Fritz, P., 1997: *Environmental Isotopes in Hydrogeology*. Boca Raton: Lewis Publishers, 328 pp.

Craig, H., 1961: Isotopic variations in meteoric water. *Science*, 133: 1702–1903.

Cuffey, K. M., Alley, R. B., Grootes, P. M., Bolzan, J. F., and Anandakrishnan, S., 1994: Calibration of the $\delta^{18}O$ isotopic paleothermometer for central Greenland, using borehole temperature. *Journal of Glaciology*, 40(135): 341–349.

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

Johnsen, S. J., Dansgaard, W., and White, J. W. C., 1989: The origins of Arctic precipitation under present and glacial conditions. *Tellus, Series B*, 41: 452–468.

Johnsen, S. J., Dahl-Jensen, D., Dansgaard, W., and Gundestrup, N., 1995: Greenland palaeotemperatures derived from GRIP bore hole temperature and ice core isotope profiles. *Tellus, Series B*, 47: 624–629.

Jouzel, J., and Merlivat, L., 1984: Deuterium and oxygen-18 in precipitation: modeling of the isotope effects during snow formation. *Journal of Geophysical Research*, 89(D7): 11,749–11,757.

Jouzel, J., Russell, G. L., Suozzo, R. J., Koster, R. D., White, J. W. C., and Broecker, W. S., 1987: Simulations of HDO and $H_2{}^{18}O$ atmospheric cycles using the NASA/GISS general circulation model: The seasonal cycle for present-day conditions. *Journal of Geophysical Research*, 92(D12): 14,739–14,760.

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

Merlivat, L., and Jouzel, J., 1979: Global climatic interpretation of the deuterium-oxygen 18 relationship for precipitation. *Journal of Geophysical Research*, 84(C8): 5029–5033.

Rozanski, K., Sonntag, C., and Munnich, K. O., 1982: Factors controlling stable isotope composition of European precipitation. *Tellus*, 34(2): 142–150.

Rozanski, K., Araguás-Araguás, L., and Gonfiantini, R., 1992: Relation between long-term trends of oxygen-18 isotope composition of precipitation and climate. *Science*, 258: 981–985.

Thompson, L. G., 2000: Ice core evidence for climate change in the Tropics: implications for our future. *Quaternary Science Reviews*, 19: 19–35.

Thompson, L. G., Yao, T. D., Mosley-Thompson, E., Davis, M. E., Henderson, K. A., and Lin, P.-N., 2000: A high-resolution millennial record of the South Asian Monsoon from Himalayan ice cores. *Science*, 289(5486): 1916–1919.

Tian, L. D., Yao, T. D., Numaguti, A., and Sun, W. Z., 2001a: Stable Isotope Variations in monsoon precipitation on the Tibetan Plateau. *Journal of the Meteorological Society of Japan*, 79(5): 959–966.

Tian, L. D., Masson-Delmotte, V., Stievenard, M., Yao, T. D., and Jouzel, J., 2001b: Tibetan plateau summer monsoon northward extent revealed by measurements of water stable isotopes. *Journal of Geophysical Research*, 106(D22): 28,081–28,088.

Tian, L. D., Yao, T. D., Sun, W. Z., Stievenard, M., and Jouzel, J., 2001c: Relationship between δD and $\delta^{18}O$ in precipitation on north and south of the Tibetan Plateau and moisture recycling. *Science in China, Series D*, 44(9): 789–796.

Tian, L. D., Yao, T. D., Schuster, P. F., White, J. W. C., Ichiyanagi, K., Pendall, E., Pu, J. C., and Yu, W. S., 2003: Oxygen-18 concentrations in recent precipitation and ice cores on the Tibetan Plateau. *Journal of Geophysical Research*, 108(D9): ACH 16-1–ACH 16-10.

Yao, T. D., Thompson, L. G., Jiao, K. Q., Mosley-Thompson, E., and Yang, Z. H., 1995: Recent warming as recorded in the Qinghai-Tibetan cryosphere. *Annals of Glaciology*, 21: 196–200.

Yao, T. D., Thompson, L. G., Mosley-Thompson, E., Yang, Z. H., Zhang, X. P., and Lin, P.-N., 1996: Climatological significance of $\delta^{18}O$ in north Tibetan ice cores. *Journal of Geophysical Research*, 101(D23): 29,531–29,538.

Yao, T. D., Masson, V., Jouzel, J., Stievenard, M., Sun, W. Z., and Jiao, K. Q., 1999: Relationships between $\delta^{18}O$ in precipitation and surface air temperature in the Urumqi River Basin, east Tianshan Mountains, China. *Geophysical Research Letters*, 26(23): 3473–3476.

Ye, D. Z., and Gao, Y. X., 1979: *Meteorology of the Tibetan Plateau*. Beijing: Science Press, 202–212. (In Chinese).

Yu, W. S., Yao, T. D., Tian, L. D., Wang, Y., and Sun, W. Z., 2004: Variation of $\delta^{18}O$ in precipitation in the western Tibetan Plateau. *Journal of Glaciology and Geocryology*, 26(2): 146–152. (In Chinese with English abstract).

Zhang, X. P., Shi, Y. F., and Yao, T. D., 1995: Variational features of precipitation $\delta^{18}O$ in Northeast Qinghai-Tibet Plateau. *Science in China, Series B*, 38(7): 854–864.

Ms accepted June 2007