Environ Geol (2008) 55:1501–1506
DOI 10.1007/s00254-007-1100-4

ORIGINAL ARTICLE

Seasonal deuterium excess in Nagqu precipitation: influence of moisture transport and recycling in the middle of Tibetan Plateau

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Received: 8 August 2007 / Accepted: 18 October 2007 / Published online: 14 November 2007

Abstract A total of 198 precipitation samples were collected at Nagqu on the central Tibetan Plateau in 2000. Based on the isotope data from individual samples, the local meteoric water line was established: $\delta D = 7.7\delta^{18}O–4.6$ ($r^{2\,=}$ 96, $p < 0.0001$). Stable isotope data from precipitation exhibit a seasonal variability in deuterium excess. The study indicated that the influence of moisture transport and recycling on seasonal variation of *d-excess* in precipitation events is potentially significant. During summer precipitation, the lower *d-excess* values are usually related to warm and humid Indian Ocean moisture transport. In spring and winter, due to the cold and dry westerly and northern moisture transport, *d-excess* values in precipitation are usually higher. The *d-excess* in summer precipitation is also influenced by the secondary evaporation between cloud base and ground during precipitation events, as well as the admixture of water vapor from evapotranspiration over the continent along the storm trajectories. The results also suggested that the *d-excess* values in precipitation at Nagqu displayed an obvious transition due to its location on the central Tibetan Plateau.

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Keywords Stable isotope · *d-Excess* · Moisture transport and recycling · Nagqu

Introduction

There is a close relationship between $\delta^{18}O$ and δD in precipitation, which is so-called Meteoric Water Line (MWL) defined by Craig (1961) as $\delta D = 8\delta^{18}O + 10$. Dansgaard (1964) introduced the concept of deuterium excess, which is defined as $d = \delta D\text{-}8\delta^{18}O$. The value of *d-excess* in precipitation is believed to be mainly related to the meteorological conditions (such as relative humidity, temperature, and wind regime) at the source region (Merlivat and Jouzel 1979). Precipitation derived from different water vapor sources can results in a series of MWLs with specific *d-excess* values (Gat 1981). For this reason, the *d-excess* parameter has been used as a diagnostic tool to interpret the contribution of water vapor from different sources to the atmosphere at a specific location. However, it is also documented that *d-excess* values are partially related to the mixing of evapotranspiration water vapor fluxes from continental surfaces occurring along the storm track (Gat et al. 1994). Also, re-evaporation of raindrops below the cloud base during precipitation events in arid areas has been shown to influence *d-excess* values (Gat and Tzur 1967; Stewart 1975; Fritz et al. 1987). Therefore, the seasonal variations of *d-excess* can provide information about moisture sources and the hydrological cycle, as well as local climatic conditions (Tian et al. 2007).

Much isotopic investigation on precipitation and ice cores has been carried out in the Tibetan Plateau in the past and obtained lots of valuable research progress (Zhang et al. 1995; Yao et al. 1999; Tian et al. 2001a, b, 2003). But the study of *d-excess* in precipitation is comparatively limited so far due to lack of hydrogen stable data. This limited study mainly focuses on the southern plateau (Nyalam and Lhasa stations) and northeastern plateau (Delingha and Tuotuohe stations). Recently, Tian et al. (2007) have investigated the *d-excess* in precipitation at Shiquanhe and Gaize of the western plateau and Yushu of the eastern plateau. However, in the middle of the Tibetan Plateau, the behavior of the stable isotope in precipitation is complex owing to the influence of both continental air mass and monsoon precipitation (Tian et al. 2003) and the study of *d-excess* in precipitation is still poor. Based on the previous studies of *d-excess* and isotopic investigation of precipitation at Nagqu station of the central plateau, we make a discussion and analysis for the variation of the *d-excess*. In this study, we aim at using *d-excess* data to identify the influence of moisture source and local hydrologic cycle on precipitation signals in the middle of the Tibetan Plateau.

Sample collection and methods

During 2000, 198 precipitation (rain, sleet, and snow) samples were collected at Nagqu Meteorological Station (92°04′E, 31°29′N, 4507 m) located in the middle of the Tibetan Plateau (Fig. 1). All precipitation samples were event-based. Rainfall samples were collected and sealed in plastic bottles immediately following an event to limit evaporation. Snow and other solid precipitation samples were collected and melted at room temperature and then processed in the same way as rainfall samples. All water samples were also taken back periodically and stored frozen in the laboratory until analysis. Meteorological data (temperature and precipitation amount) were also recorded during the precipitation events.

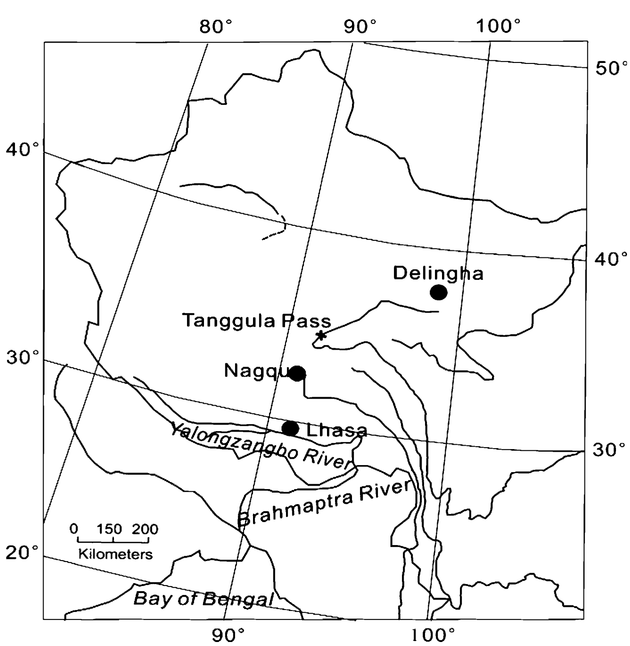

Fig. 1 Sampling site and its surrounding area

Oxygen isotope of water samples was analyzed with MAT-252 mass spectrometer at the Laboratory of Ice Core and Cold Regions Environment, Cold and Arid Regions Environmental and Engineering Research Institute, Lanzhou, China. Hydrogen isotope analysis was performed at Ecological Research Center of Kyoto University, Japan. Determination of oxygen isotope ratios was performed by equilibration of CO_2 with water samples at 25°C (Epstein and Mayeda 1953). Hydrogen isotope ratios were determined using the uranium reduction technique. The method for hydrogen isotopic measurement is introduced in detail by Vaughn et al. (1998). All oxygen and hydrogen isotopic analyses are reported in standard delta (δ) notation versus Vienna Standard Mean Ocean Water (VSMOW) in which $\delta = (R/R_{\text{v-smow}} - 1) \times 1{,}000$ and R and $R_{\text{v-smow}}$ represent either the $^{18}O/^{16}O$ or D/H ratios of the sample and standard, respectively. The uncertainty of the measurement was determined by repeated analysis of international reference materials V-SMOW, GISP, and SLAP as well as lab internal standards ($n = 15$). The analytical precision is ±0.2‰ for $\delta^{18}O$, and ±0.5‰ for δD, respectively.

Statistical tests in this study are carried out with statistical software SPSS 13.0, which show differences/similarities of *d-excess* at Nagqu, Lhasa, and Delingha, as well as those of different seasons for Nagqu.

Results and discussion

Meteoric water line for Nagqu

Based on isotope values in individual precipitation events, the local meteoric water line (LMWL) for Nagqu (Fig. 2) was established as $\delta D = 7.7\delta^{18}O\text{-}4.6$ ($r^2 = 0.96$, $p < 0.0001$, t test).

There is a good correlation between the two isotope parameters that is independent of sample age or season. The slope and the intercept of this line are lower than those of the average global MWL (GMWL) (Craig 1961). It is noticeable that the line is very close to that from Lhasa ($\delta D = 7.9\delta^{18}O\text{-}6.3$, $r^2 = 0.97$) (Tian et al. 2001c). The two stations are located in the south of Tanggula Mountains and similar LMWLs probably reflect roughly same moisture sources and the hydrological cycle.

Deuterium excess in Nagqu precipitation

Figure 3 gives the temporal variation of precipitation amount, $\delta^{18}O$ and *d-excess* in individual precipitation

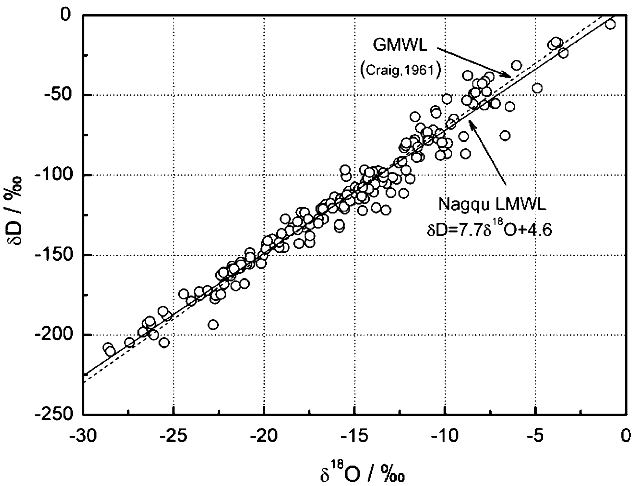

Fig. 2 Correlation betweenδ^{18}O andδD in precipitation events at Nagqu in 2000

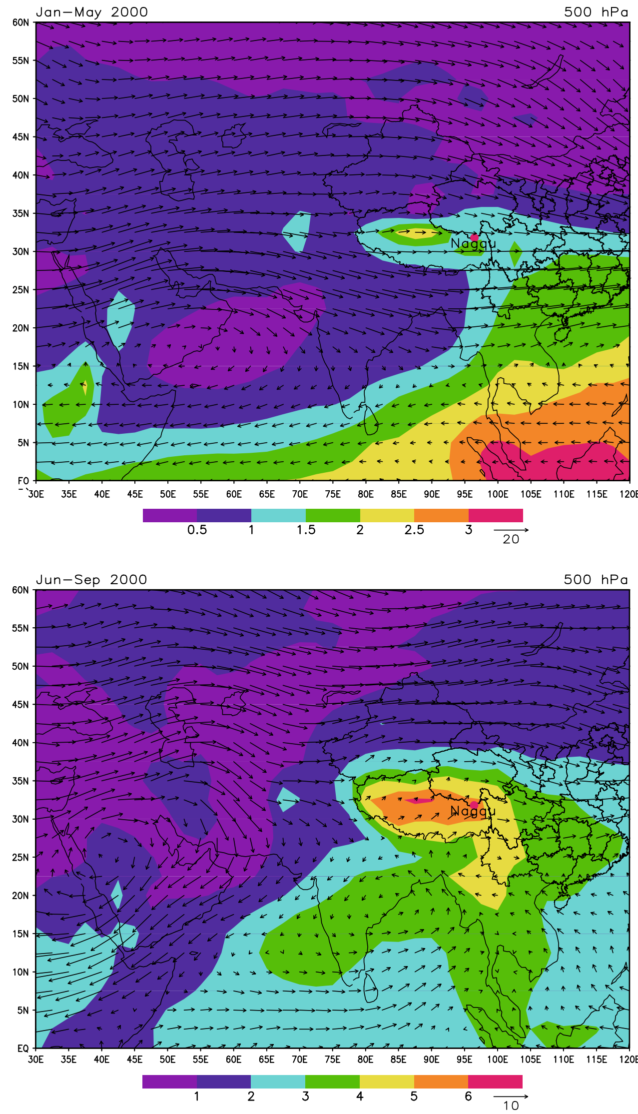

Fig. 4 The mean divergent wind vector field and specific humidity during January–May and June–September at 500 hPa pressure level in central Plateau in 2000

events at Nagqu in 2000. According to Fig. 3, *d-excess* values at Nagqu range from −21.9‰ to 32.3‰, with a weighted average of 13.3‰. δ^{18}O and *d-excess* values display a comparatively distinct seasonal trend at Nagqu, with lower δ^{18}O and *d-excess* values during summer (June–September) and higher values during winter and spring (January–May) (Fig. 3). The same seasonal distribution of δ^{18}O and *d-excess* has been found to occur at Lhasa, of the southern Tibetan Plateau (Tian et al. 2003, 2007). Tian et al. (2007) attributed seasonality in δ^{18}O and *d-excess* at Lhasa to different moisture sources.

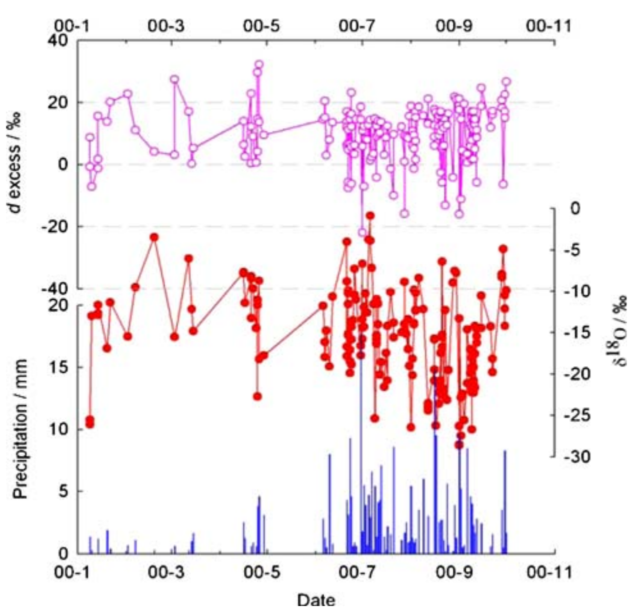

Fig. 3 Seasonal variation ofδ^{18}O, *d-excess* in precipitation events and corresponding precipitation amount at Nagqu in 2000

Deuterium excess and moisture transport

Based on the differences of δ^{18}O in precipitation between summer and winter, Tian et al. (2001b) identified a clear boundary between monsoon precipitation and non-monsoon precipitation in the Tibetan Plateau. The boundary reflects the northward extension of the Indian Ocean monsoon, and is coincident with the Tanggula Mountains. The area investigated is located in the central Tibetan Plateau, south of the Tanggula Mountains. Such a location makes it a transitional area between monsoon and non-monsoon and the atmospheric circulation pattern is very complex. Figure 4 exhibits the mean wind vector field and specific humidity at 500 hPa pressure level around the region investigated in 2000 from the monthly mean NCAR/NCEP reanalysis data. It can be seen from Fig. 4 that the westerly wind mainly dominates this area during winter and spring period from January to May, and westerly winds and southwest monsoon intersect in this area during summer. Thus, the isotopic variations of precipitation in Nagqu are of obvious complexity (2001a).

The seasonal differences of *d-excess* in precipitation at Nagqu can be explained by the different moisture sources. In summer, humid marine air mass from the Indian Ocean can reach this region along two different paths (Lin and Wu 1990), one moving along the Brahmaputra–Yalongzangbo River and the other over the Indian peninsula crossing the Himalaya Mountains. The humid moisture not only provides a large quantity of precipitation (90%, 2000) but also results in low $\delta^{18}O$ in precipitation due to increasing depletion of ^{18}O by rainout along the transport trajectory and crossing the Himalaya Mountains (Fig. 3). Accordingly, the lower *d-excess* values occur in summertime, which mainly result from warm and humid surroundings of the Indian Ocean. During winter and spring, however, the continental air mass from the north and west dominates this area, which brings less moisture and provides little precipitation. Due to the very dry overlying air mass, $\delta^{18}O$ and *d-excess* in precipitation is higher.

The relationships between *d-excess* in precipitation over the Tibetan Plateau and moisture sources have been discussed previously. Tian et al. (2001c) revealed the influence of moisture transport on variation of *d-excess* in precipitation on the southern and northern Tibetan Plateau using isotope data for Lhasa and Delingha. Figure 5 shows a comparison of the seasonal variations of *d-excess* in precipitation among Delingha, Nagqu, and Lhasa. It can be seen from Fig. 5, *d-excess* values in precipitation at Nagqu are different from those at Delingha and Lhasa, which display an obvious transitional feature. Based on an analysis of variance, different stations have significant influence ($p < 0.05$) (least significant difference test following ANOVA) on *d-excess* values in precipitation. From the data of the whole year, there are no obvious differences in *d-excess* at three stations, however the seasonal differences of *d-excess* among them is comparative remarkable, especially between Lhasa and Delingha, with a statistical difference at $p < 0.01$ level. This is because moisture forming precipitation at Lhasa and at Delingha come from different sources during summer season. *d-excess* values in Lhasa precipitation are lower due to moisture deriving from the warm and humid Indian Ocean, however, *d-excess* values in Delingha precipitation are higher due to moisture forming precipitation originating from the dry continent rather than the humid ocean. Comparing to Lhasa and Delingha, *d-excess* values in Nagqu precipitation are inclined to be medial as a result of its location of the central Tibetan Plateau, which makes precipitation at Nagqu affected by both continental air mass and ocean air mass. At the ending of summer, *d-excess* values at the three locations increase abruptly, which may be affected by moisture coming from dry area. In spring, influenced by the local moisture recycling, *d-excess* values are higher at Lhasa and Nagqu than at Delingha. In winter, *d-excess* values at the three locations all have a large variational scope, and except for the lower *d-excess* occurring to the three locations in January, *d-excess* values at Lhasa and Nagqu are higher than those at Delingha during other months. The seasonal differences of *d-excess* in Nagqu precipitation (no significance) are not more obvious than those in Lhasa precipitation ($p < 0.05$), which also reflects the influence of continental moisture on summer precipitation at Nagqu. However, the deficiency of isotope data in May, November, and December (no precipitation in 2000) may be an important reason that the seasonal differences of *d-excess* in Nagqu precipitation statistically fail to the significance test.

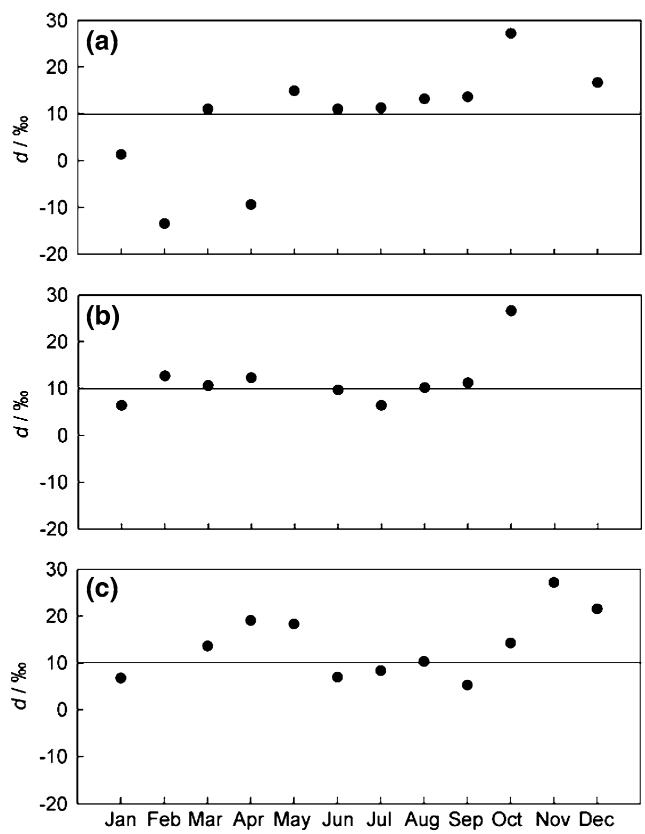

Fig. 5 A comparison in seasonal variation of monthly weighted average *d-excess* in precipitation among **a** Delingha, **b** Nagqu, and **c** Lhasa

Table 1 Average temperature, relative humidity and amount-weighted average *d-excess* values and the corresponding local meteoric water line of individual precipitation samples collected at Nagqu for different precipitation amount ranges

Amount (mm)	Ave. *t* (°c)	Ave. *rh* (‰)	*d-excess* (‰)	LMWL	r^2	*n*
0–1	8.7	72.7	5.8	$\delta D = 7.3\delta^{18}O - 6.4$	0.94	60
1–2	7.4	77.2	13.2	$\delta D = 7.9\delta^{18}O + 11.4$	0.98	31
2–5	7.5	76.7	14.3	$\delta D = 8.0\delta^{18}O + 14.1$	0.99	36
5–10	7.0	77.8	12.9	$\delta D = 7.7\delta^{18}O + 6.6$	0.99	17
10–20	8.7	78.0	17.3	$\delta D = 7.4\delta^{18}O + 6.6$	0.99	3

Local influence on deuterium excess values

Several possible explanations that involve local-scale process may account for the seasonal variability of *d-excess* in precipitation at Nagqu. In summer, the lower humidity and higher temperatures at Naqgu facilitate increased secondary evaporation of raindrops during their descent from the cloud base to the ground, which in turn decreases the *d-excess* value for the precipitation events (Dansgaard 1964). Table 1 gives an influence of secondary evaporation between cloud base and ground on *d-excess* in precipitation at Nagqu in summer. According to the table, when precipitation amount is between 2 and 5 mm, the slope of the LMWL is 8.0, indicating the raindrops are almost not affected by secondary evaporation. For small amount events (<1 mm), secondary evaporation has an intense effect on the raindrops. When precipitation amount is above 5 mm, secondary evaporation has a comparative effect on the raindrops. From the table we can also see secondary evaporation results in a significant decrease of *d-excess* values for small precipitation events.

Additionally, an admixture of water vapor from evapotranspiration over the continents along the storm paths may influence *d-excess* values in precipitation in summer. Yang et al. (2004) investigated the moisture sources forming precipitation of this area and determined that approximate 21.8% moisture forming precipitation coming from the transportation of the monsoon circulation to the evaporative vapor on the way. It can also been seen from Table 1, when the precipitation amount is between 5 and 20 mm, the slope of the LMWL is above 7.4, but the *d-excess* values in precipitation are higher, which indicates *d-excess* in precipitation may be influenced by the mixing water vapor originating from inland evaporation and plant transpiration during the monsoon moisture moving over continental areas.

Summary

The data and interpretations presented here highlight the complexity of isotopic variation in precipitation on the central Tibetan Plateau. Based on the isotope values in precipitation events, the LMWL is $\delta D = 7.7\delta^{18}O + 4.6$, and *d-excess* values range from −21.9‰ to 32.3‰, with a weighted average of 13.3‰. The *d-excess* values from precipitation events at Nagqu indicate that the contribution of moisture transport and moisture recycling is potentially significant. In summer, the lower *d-excess* values in precipitation usually result from southern moisture transport, which is mainly derived from the hot and humid Indian Ocean. In spring and winter, due to this area dominated by westerly and northern air mass, which is cool and dry, *d-excess* values in precipitation are usually higher. The variations of *d-excess* in summer precipitation are to a large extent influenced by the secondary evaporation between cloud base and ground during precipitation events, as well as the admixture of water vapor from evapotranspiration over the continent along the storm trajectories. Our results also suggest that the *d-excess* values in precipitation at Nagqu exhibit an obvious transition due to its location of the central Tibetan Plateau.

Acknowledgments This research is supported by National Natural Science Foundation of China (grant 40671043, 40771048 and 40571039), the National Basic Research Program of China (grant 2005CB422002), the Innovation Program of Chinese Academy of Sciences (KZCX3-SW-339). We give thanks to Nagqu meteorological station for collecting precipitation samples. We are grateful to Nagqu meteorological station and China Meteorological Administration for providing Meteorological data. We also thank engineer Sun Weizhen for helping in the measurement of $\delta^{18}O$ and Ecological Research Center of Kyoto University, Japan for helping in the measurement of δD.

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