Comment on "Origin of water in the Badain Jaran Desert, China: new insight from isotopes" by Wu et al. (2017)

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Abstract

Precipitation isotope data were used to determine the origin of groundwater in the Badain Jaran Desert (BJD) in the study of Wu et al. (2017). Both precipitation and its isotope composition vary seasonally, so arithmetic averages of precipitation isotope values poorly represent the isotope composition of meteoric water. Their finding that the BJD groundwater is recharged by modern meteoric water from local areas including the southeastern adjacent mountains was based on arithmetic averaging. However, this conclusion is not supported by the corrected mean precipitation isotope values, which are weighted by the precipitation rate. Indeed, the available isotopic evidence shows that modern precipitation on the Qilian Mountains is more likely to be the main source of the groundwater and lake water in the BJD, as found by Chen et al. (2004).

1 Introduction

The Badain Jaran Desert (BJD) is characterized by a unique landscape that contains a large number of lakes and the world's largest stationary sand dunes maintained by groundwater. However, the origin of the groundwater remains uncertain (Dong et al., 2013). Using stable and radioactive environmental isotopes, Wu et al. (2017) investigated the connection between lakes and groundwater, and the origin of groundwater in the southeastern desert area. They suggested that the BJD groundwater is derived primarily from modern meteoric water from local areas, including the southeastern adjacent small mountains. Based on isotopic evidence, the authors ruled out other hypotheses on the groundwater source, including fossil groundwater (Gates et al., 2008; Ma and Edmunds, 2006; Wang et al., 2015; Yang et al., 2010) and snowmelt from the Qilian Mountains, 500 km (center-to-center distance) southwest of the desert (Chen et al., 2004; 2006).

The authors argued that the ^{14}C dating over-estimated the age (~10 ka) of the BJD groundwater due to interference by additional dead carbon input from ancient carbonates. We have conducted work related to the ^{14}C dating and found the same problem with overestimation of the groundwater edge (Chen et al., 2014; Wang and Chen, 2018). They reasoned that the average age of groundwater in the BJD should be much younger, since it includes modern meteoric water as indicated by tritium levels (Gates et al., 2008; Wu et al., 2017). They presented many evidences and discussions for their conclusion of groundwater recharged by modern precipitation from local areas. However, their averaging of the precipitation isotope data did not account for seasonality of precipitation amount, which led to a misconception of the real groundwater origin.

2 Source water identification based on weighted mean precipitation isotope values

The determination of mean precipitation isotope values is of great significance for assessing the contribution of precipitation as a water source to regional hydrological systems and for assessing interactions among different hydrological components. To examine the relationship between the BJD groundwater and local precipitation, the historical precipitation isotope data from a nearby GNIP (Global Network of Isotopes in Precipitation, https://nucleus.iaea.org/wiser/index.aspx) station in Zhangye (1986–2003) were used by Wu et al. (2017). The GNIP database provides data on monthly precipitation isotopes as well as monthly rainfall for the Zhangye station. As shown in Figure 1a and Figure 1b, the monthly δD and $\delta^{18}O$ values in the study area exhibit large seasonal variations, which are mainly controlled by temperature (Zhan et al., 2017). The isotopic seasonality pattern of precipitation is similar in different years. During the summer half year when temperature is higher, the rainfall is more enriched in heavier isotopes.

According to the GNIP data, the mean annual precipitation is about 130 mm, with more than 60% of the total annual rainfall occurring from June to August during which the isotope values are the highest (Figure 1b). Since the annual precipitation is seasonal, the monthly precipitation isotope data should be weighted by the monthly precipitation amount to calculate the annual mean for representing the isotope composition of local precipitation as a potential source of the BJD groundwater. The weighted mean isotopic values $\overline{\delta_w}$ can be calculated using the following equation:

$$\overline{\delta_w} = \frac{\sum_{j=Jan}^{Dec} \overline{\delta_j} \cdot \overline{P_j}}{\sum_{j=Jan}^{Dec} \overline{P_j}} \qquad (1)$$

where $\overline{\delta_j}$ and $\overline{P_j}$ are the averaged isotopic values and averaged rainfall amount of month j during the GNIP observation years, respectively. $\overline{\delta_j}$ and $\overline{P_j}$ can be calculated as follows:

$$\overline{\delta_j} = \frac{\sum_i \delta_{i,j}}{n} \tag{2}$$

$$\overline{P_j} = \frac{\sum_i P_{i,j}}{n} \tag{3}$$

where $\delta_{i,j}$ and $P_{i,j}$ are the isotopic value (δD or δ^{18}O) and rainfall amount of month j in year i from the available dataset of GNIP database, respectively; and n is the corresponding number of data available years.

Based on the dataset from the GNIP database, the calculated weighted mean values for δD and δ^{18}O of Zhangye's precipitation are -40.9‰ and -5.50‰, respectively (Figure 1c). Using arithmetic average values, Wu et al. (2017) determined δD and δ^{18}O values around -74‰ and -10.5‰, respectively. When plotted on the δ^{18}O-δD graph (Figure 1c), the arithmetic average values are close to the intersection of the evaporation line EL1 (for groundwater and lake water in the desert) and the GMWL (Global Meteoric Water Line), which led Wu et al. (2017) to conclude that groundwater and lake water in the BJD originates from modern meteoric precipitation in local areas including the adjacent small mountains. However, if the weighted mean values are used, this conclusion no longer holds. The source water recharging the BJD groundwater and lakes is much more depleted in D and ^{18}O, compared with the isotope composition of local precipitation.

3 Reanalysis on the origin of groundwater in the BJD

Using available data from literature, we reanalyzed the possible origin of groundwater in the BJD. We focus on the BJD southern margin area where the desert lakes are mostly concentrated. The isotope data of the groundwater and lake water (Figure 2a) lie on the evaporation line EL2 (δD = 4.6δ^{18}O – 29.8, r^2 = 0.94), which is reasonably similar to EL1 in Wu et al. (2017). Here only data from groundwater and lake water samples within the BJD area were used for determining the EL2. The weighted mean isotope values of precipitation in the regions close to the BJD (blue circles) show a decreasing trend with increasing elevation from 1382 to 2569 m a.s.l., reflecting the effect of elevation on isotope fractionation (Poage and Chamberlain, 2001). The intersection of EL2 and GMWL (δD = -83.6‰, $\delta^{18}O$ = -11.7‰), which represents the mean isotope composition of the recharge source for BJD groundwater, is clearly outside the range of precipitation in the local and adjacent regions, indicating another different source water with more depleted isotope composition.

Together with the statistical isotopic values of precipitation in the BJD and the Qilian Mountains (rainfall and snowmelt) from literature data, a significant inverse correlation of δD and $\delta^{18}O$ values with elevations of the precipitation can be established (Figure 2b, c). The altitude gradients for δD and $\delta^{18}O$ are -2.0‰/100m and -0.26‰/100m, respectively, which are close to the global mean levels (Poage and Chamberlain, 2001). Based on these gradients, the location of water associated with the intersection of EL2 and GMWL corresponds to an average elevation of 3914 m a.s.l. (3920 m estimated by δD and 3908 m by $\delta^{18}O$). Therefore, the recharge region for groundwater and lake water in the BJD is likely to include areas of elevations higher than 3914 m a.s.l. to produce source water of more depleted isotope composition.

The closest region that could meet this elevation requirement is the Qilian Mountains (average elevation between 4000 and 5000 m a.s.l.), northeast of the Qinghai-Tibet Plateau (Figure 3a). Nineteen snowmelt and rainfall water samples from 3540 to 5010 m a.s.l. in the glacier zone of the Qilian Mountains were collected by Ren (1999). The statistical isotope compositions of these samples are close to that given by the GMWL-EL2 intersection (Figure 2a). Therefore, the isotope evidence points to the Qilian Mountains as a main source region for groundwater and lake water in the BJD, as observed previously (Chen et al., 2004).

In the study of Wu et al. (2017), they ruled out the Qilian Mountains as a recharge area for groundwater in the BJD based on the large isotopic difference between the GMWL-EL2 intersection and data of water samples mainly collected from the Shiyang River watershed (Li et al., 2016), which is located in the eastern lower area of the Qilian Mountains. The mean elevation of the Shiyang River watershed is only 2487 m a.s.l. (Bourque and Hassan, 2009), lower than even the mean level of the entire mountain. Therefore, their argument for excluding the Qilian Mountains as a recharge region is questionable. Water samples collected from rivers on the northern slope of the Qilian Mountains are characterized by large variations of isotope compositions (Figure 2a), with the lowest isotopic values found by Ren (1999) from a river in the upstream glacier zone. Scattered data between the plots of snowmelt on the mountain and rainfall in lower regions indicated that most of these river samples are likely to be mixtures of snowmelt water and piedmont precipitation. Isotope signatures show little connection between these rivers on the northern slope and the groundwater in the BJD.

The relationship between d-excess and $\delta^{18}O$ was also discussed in Wu et al. (2017). The d-excess value (d-excess = $\delta D - 8\delta^{18}O < 0$) indicates the deviation from the GMWL, reflecting the degree of evaporation, to which the water has been subjected to. Wu et al. (2017) noted the difference in the d-excess value between the Qilian-sourced water (sampled from the northern slope rivers of the Qilian Mountains region) and BJD groundwater, and argued that the Qilian Mountains cannot be the origin of the latter because no evaporation could occur to water underground. Located in the northeastern margin of the Qinghai-Tibet Plateau, the Qilian Mountains area consists of many northwest–southeast parallel mountain ranges and valleys (Qiu et al., 2016). Although little evidence of evaporation was found in sampled river water from the northern slope area, water in other near-surface water systems (like lakes, wetlands, and soil water reservoir) of longer residence time within the wide Qilian Mountains region would have been subjected to more intense evaporation and produced isotopic signature similar to that of the BJD groundwater. The d-excess results cannot exclude the Qilian Mountains as a recharge region either.

Groundwater in the BJD has also been postulated to be sourced from the Yabulai Mountain region (Figure 3a). The highest mountain there is 1938 m a.s.l., which is unlikely to provide rainfall input with depleted heavy isotopes as shown in Figure 2. In a recent groundwater resource development project, eight wells were drilled (depths of 135 to 260 m) in the southeastern part of the BJD. The static groundwater levels in these wells show a decreasing trend from southwest to northeast (Figure 3b), indicating an overall movement of groundwater along this direction. The groundwater flow direction is consistent with our opinion of groundwater originating from Qilian Mountains, which is located to the southwest of the BJD. Researchers have also examined the chemistry of lake water and groundwater in the study area and surrounding areas. For example, Yang and Williams (2003) investigated the ion chemistry of lake water and groundwater from the BJD and its periphery, and ruled out the possibility of recharge from recent local rainfall to the lakes and groundwater. In a previous study (Chen et al., 2012), the hydrochemical and isotopic results also supported our remote recharge hypothesis.

We agree with the concern of Wu et al. (2017) about the accuracy of ^{14}C dating for the BJD groundwater, which provided estimates of very old ages. In a recently published paper (Wang and Chen, 2018), we found considerable overestimation of the groundwater age by the ^{14}C dating method due to neglect of dead carbon brought by deep CO_2 emission. In contrast to the fossil groundwater hypothesis, the detectable tritium activities as shown in their study and many others (Chen et al., 2006; Gates et al., 2008; Yang and Williams, 2003) indicate a modern precipitation source of the BJD groundwater. This suggests that the groundwater flows through hundreds of kilometers over only tens of years. Due to geological activities, various southwest–northeast deep fault systems have developed between the Qilian Mountains and the desert (Chen et al., 2006). Based on the geological conditions and geochemical evidences (helium results), these large deep fault systems are hypothesized to act as a quick passage for the groundwater (Chen et al., 2006, 2004, 2012), which explains the detectable tritium in the groundwater.

The reanalysis above suggests that groundwater in the BJD mainly originates from the modern precipitation of Qilian Mountains. We hypothesize that near-surface water in the Qilian Mountains, subjected to evaporation, infiltrates and recharges groundwater, which is then delivered to the BJD through the deep interconnected faults. This hypothesis of course still needs to be further verified and studied. It should also be noted that, the higher average elevation (4000 to 5000 m a.s.l.) of the Qilian Mountains than the mean recharge elevation (3914 m a.s.l.) estimated in this study, as well as the large variation of isotope composition of groundwater in the BJD, may imply a mixture of the Qilian-sourced water (of more depleted isotope compositions from 4000 to 5000 m a.s.l) with precipitation from other lower areas. Groundwater might have mixed with rainwater from low-elevation areas on its pathway.

4 Concluding remarks

We reanalyzed the precipitation isotope data of the Zhangye station to determine the original source of the groundwater in the Badain Jaran Desert. These data were averaged arithmetically in the recent study of Wu et al. (2017), whereas weighted averaging is more appropriate. The reanalysis does not support the conclusion of Wu et al. (2017) that the BJD groundwater is sourced from local meteoric water. Indeed, the reanalysis suggests a mean recharge elevation of about 3914 m a.s.l. for the BJD groundwater, which indicates that the precipitation in the Qilian Mountains region is more likely to be a main source of the BJD groundwater, as initially hypothesized by Chen et al. (2004).

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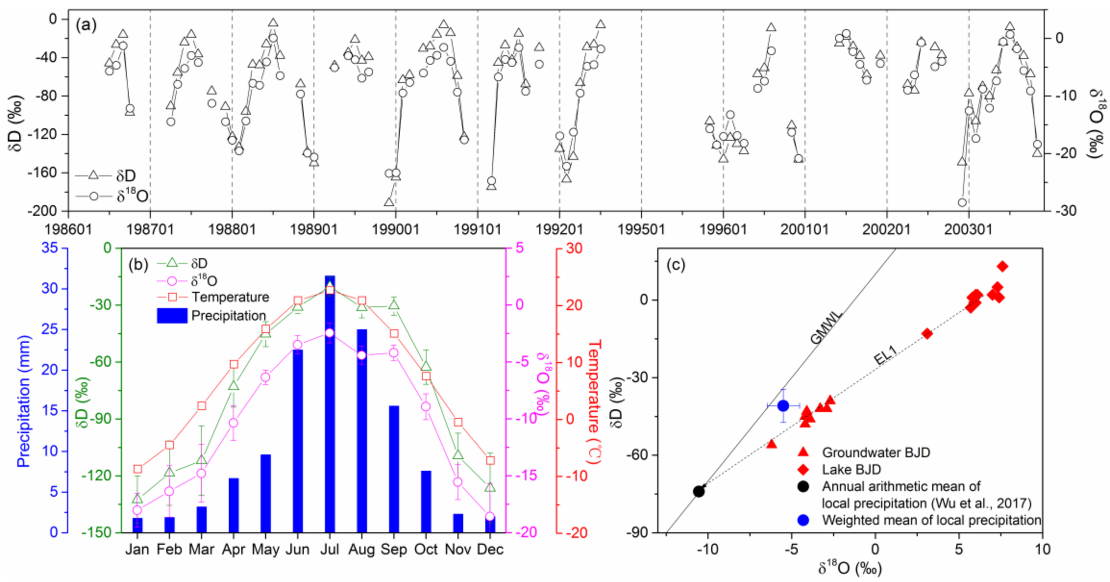

Figure 1. Isotope composition of monthly precipitation of the GNIP station Zhangye (all available dataset **(a)** and monthly mean values **(b)**), and δD-δ^{18}O plots of groundwater, lake water and annual precipitation in the study area (based on data from Zhangye station) **(c)**. Data in **(a)** and **(b)** are sourced from the GNIP database while plot **(c)** is modified from Wu et al. (2017). Statistical mean values are shown together with standard errors where feasible.

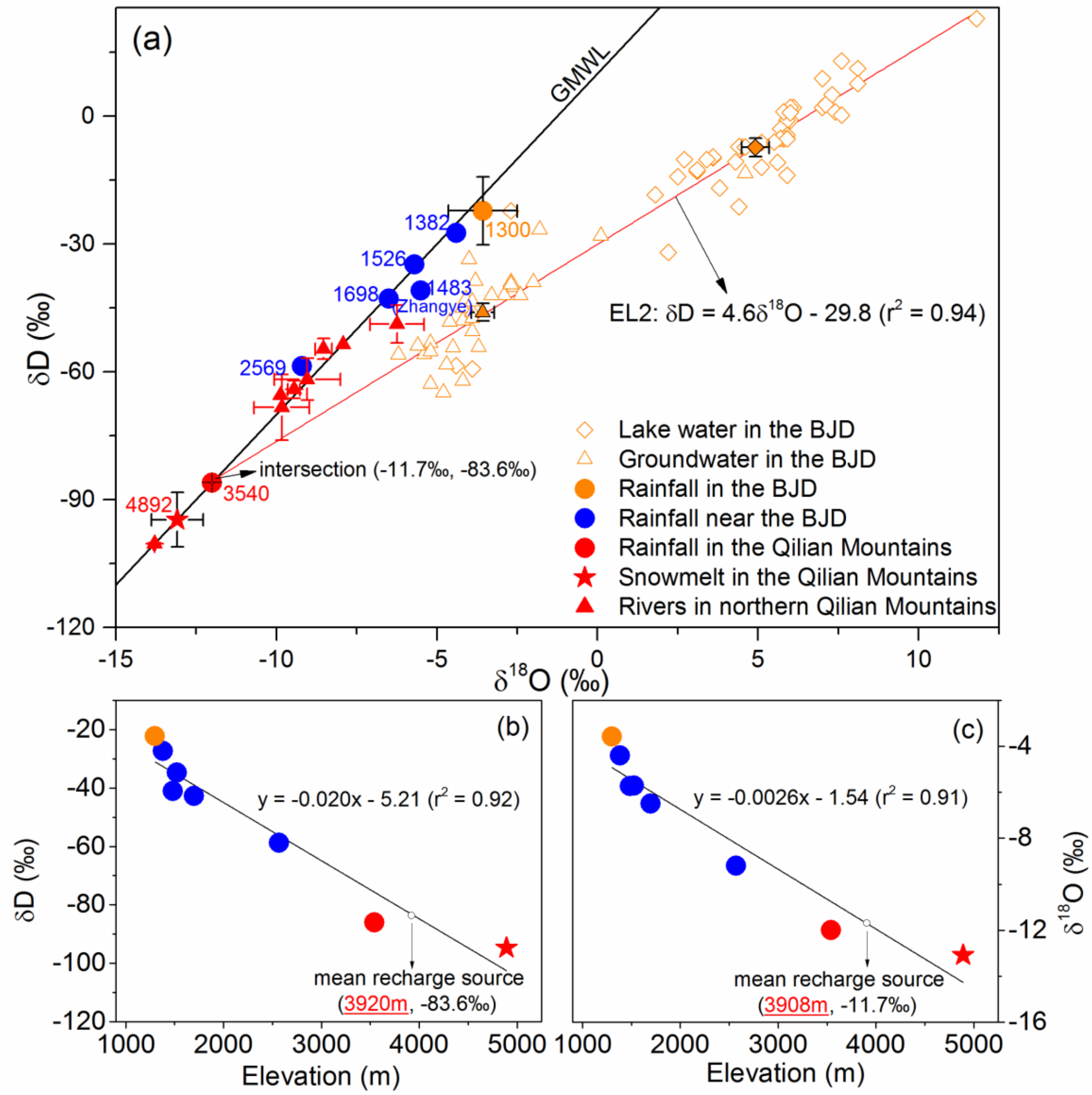

Figure 2. δD vs. δ^{18}O plot of water related to the BJD groundwater origin **(a)**, and altitude gradients of related precipitation isotopes **(b, c)**. For precipitation (rainfall and snowmelt), the corresponding sampling elevations (m a.s.l.) are also shown. Statistical mean values are shown together with standard errors where feasible. The weighted means of local rainfall (blue circles) are from Wu et al. (2010) and the GNIP database. Rainfall (yellow circle), lake water (yellow square; 47 samples) and groundwater (yellow triangle; 31 samples) in within the BJD area are based on data from Wu et al. (2017), Ma and Edmunds (2006), Zhao et al. (2012), Gates et al. (2008), Chen et al. (2012) and Yang et al. (2010). Summer rainfall (red circle; 4 samples) and snowmelt (red pentagram; 15 samples) in the Qilian Mountains are based on data from Ren (1999). Isotopic data for various rivers (red triangles) on the northern slope of the Qilian Mountain are collected from Chen et al. (2012), Li et al. (2016), Zhu, Su, and Feng (2008) and Ren (1999).

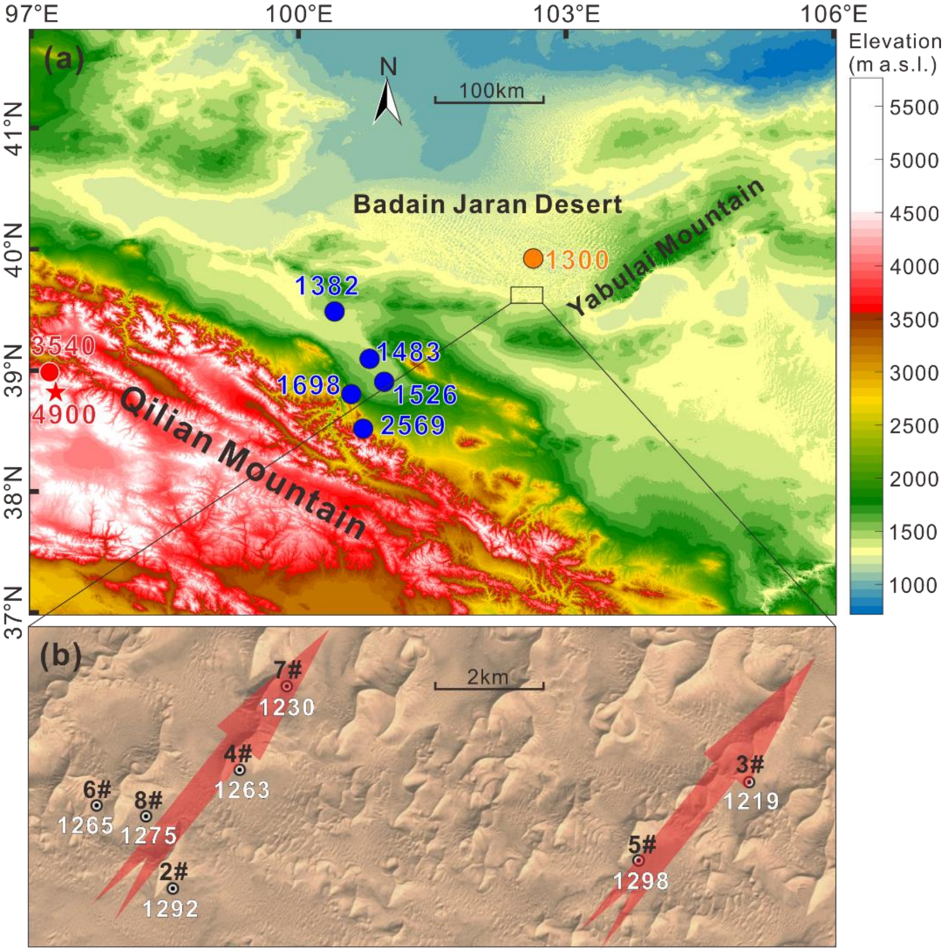

Figure 3. Elevation map of the study area **(a)** and groundwater wells drilled in the BJD **(b)**. Locations for precipitation sampling in different areas are also shown in **(a)**, as well as the elevation (m a.s.l.). The elevations of static groundwater levels in seven of the extraction wells (well #1 is far away from these wells and hence not shown) are indicated by white text in **(b)**. Arrows in **(b)** show the estimated groundwater flow direction (based on groundwater elevation).