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Enhanced Recent Local Moisture Recycling on the Northwestern Tibetan Plateau Deduced From Ice Core Deuterium Excess Records

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Key Points:

- The local moisture recycling ratios were estimated for the northwestern Tibetan Plateau over the past decades
- The local moisture recycling contributes close to half of the regional precipitation
- The local moisture recycling has enhanced in recent decades, and this may be related to changes of regional climate, environment conditions

Supporting Information:

- Supporting Information S1

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Enhanced Recent Local Moisture Recycling on the Northwestern Tibetan Plateau Deduced From Ice Core Deuterium Excess Records

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Abstract Local moisture recycling plays an essential role in maintaining an active hydrological cycle of the Tibetan Plateau (TP). Previous studies were largely limited to the seasonal time scale due to short and sparse observations, especially for the northwestern TP. In this study, we used a two-component mixing model to estimate local moisture recycling over the past decades from the deuterium excess records of two ice cores (i.e., Chongce and Zangser Kangri) from the northwestern TP. The results show that on average almost half of the precipitation on the northwestern TP is provided by local moisture recycling. In addition, the local moisture recycling ratio has increased evidently on the northwestern TP, suggesting an enhanced hydrological cycle. This recent increase could be due to the climatic and environmental changes on the TP in the past decades. Rapid increases in temperature and precipitation have enhanced evaporation. Changes of land surface of plateau have significantly increased evapotranspiration. All of these have intensified local moisture recycling. However, the mixing model used in this study only includes a limited number of climate factors. Some of the extreme values of moisture recycling ratio could be caused by large-scale atmospheric circulation and other climatic and weather events. Moreover, the potential mechanisms for the increase in local recycling need to be further examined, since the numeric simulations from climate models did not reproduce the increased contribution of local moisture recycling in precipitation.

1. Introduction

Known as the "water tower of Asia," the Tibetan Plateau (TP) has played an important role in the water cycle of Asia (Bothe, Fraedrich, & Zhu, 2010; Immerzeel, Beek, & Bierkens, 2010). The transport of moisture on the TP is essential for the sustainable water supplies in the downstream regions of many major rivers originated from the plateau (Chen et al., 2012; Curio, Maussion, & Scherer, 2015; Feng & Zhou, 2012; Yu et al., 2007). Previous studies have indicated three major moisture transport pathways for the TP, i.e., the Asian monsoon systems, the midlatitude westerlies, and the local moisture recycling (e.g., Curio et al., 2015). However, the existing water cycle could be profoundly affected by the significant climate changes observed over the TP during the past decades (Lu et al., 2014; Wu et al., 2015; Yang et al., 2011; Yang et al., 2014). Therefore, it is necessary to understand these changes in the water cycle, especially at the decadal time scale. Most existing studies on moisture transport focus on the northeastern, central, and southern parts of the TP (Cui & Li, 2015; Tian et al., 2001; Wu et al., 2015; Yang et al., 2007), largely because of the lack of observations on the northwestern TP due to its harsh environment (Yu et al., 2006; Yu et al., 2007). However, the northwestern TP is an important link between the Asian monsoon and midlatitude regions (Watanabe & Yamazaki, 2012). Therefore, the knowledge of the moisture transport over this region is crucial for better understanding the hydrological cycle on the TP.

Stable water isotopic compositions ($\delta^{18}O$ and δD) of precipitation and the deuterium excess (d excess) have great potential to investigate the hydrologic cycle at local to global scales (Aemisegger et al., 2014; Froehlich, Gibson, & Aggarwal, 2002; Kreutz et al., 2003; Pfahl & Sodemann, 2014; Vuille et al., 2005). The deuterium

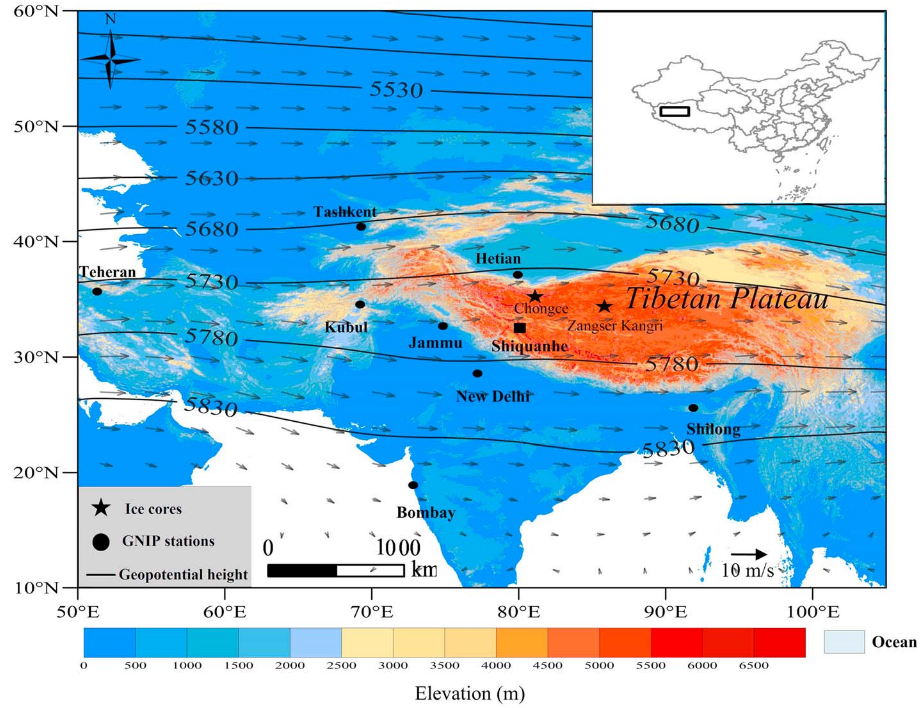

Figure 1. Study region map showing the location of Chongce and Zangser Kangri ice core sites (black stars), and GNIP stations along the westerlies and Indian summer monsoon (black solid dots). The stable water isotope data of Shiquanhe (square) are also used in this study, which is from the observation of Yu et al. (2007). The black contour lines and arrows indicate the annual mean geopotential height (m) and wind field (m/s), respectively, at the 500 hPa, averaged from 1961 to 2015. The black box in the top-right corner indicates the target region (81–86°E, 32–36°N).

excess ($d = \delta D - 8\delta^{18}O$) is a second-order parameter reflecting nonequilibrium fractionation during initial evaporation from the ocean, reevaporation at land surface, or reevaporation and/or mixing along the air mass trajectory (Merlivat & Jouzel, 1979). It has been widely used to trace atmospheric circulation and moisture sources (Bershaw, Penny, & Garzione, 2012; Liu et al., 2008; Yao et al., 2013; Yu et al., 2007). However, the study of d excess in precipitation is often limited to seasonal scale, and studies over longer time scales are rare due to short observation periods. The d excess records in ice cores on the TP could be used to complement precipitation sampling for high elevations (Yao et al., 2013) and have been used to distinguish the contribution of different atmospheric circulation and regional recycled moisture from local moisture during different periods on the central TP (Joswiak et al., 2013; Pang et al., 2012; Tian et al., 2001, 2005; Zhao et al., 2012). Pang et al. (2012) found that the abnormally high d excess values in East Rongbuk Glacier on the Himalayas were linked with the strengthening of winter westelies, whereas low values were associated with the intensification of Indian summer monsoon. The d excess series in the ice cores from the Tanggula Mountains, central TP, has been used to investigate the long-term variation in the relative contribution of westerlies moisture and local moisture recycling (Joswiak et al., 2013).

The interactions between land and atmosphere play an important role in the water cycle on the TP (Yang et al., 2011). The importance of local moisture recycling on maintaining an active hydrological cycle has been studied on the TP and surrounding areas (Curio et al., 2015; Hua, Zhong, & Ke, 2016; Kong, Pang, & Froehlich, 2013; Kurita & Yamada, 2008; Liu et al., 2008; van der Ent, 2009; Xu et al., 2011; Zhang, Tang, & Chen, 2017). However, no work has been attempted to evaluate the changes of local moisture recycling from d excess records in ice cores. In this study, based on a two-component mixing model, we try to calculate the changes of local moisture recycling ratio over the past decades using two d excess series from the northwestern TP (i.e., Chongce, 35°14′N, 81°07′E, 6,010 m above sea level (asl); Zangser Kangri, 34°18′N, 85°51′E, 6226 m asl; Figure 1). To verify our results, we use an atmospheric general circulation model with an embedded moisture-tracing module (Community Atmosphere Model version 3) to track source regions supplying moisture to the northwestern TP and to quantify their respective contributions to total precipitation. This model has been tested and used for climate simulations and paleoclimate studies (Pausata et al., 2011; Sturm, Zhang, & Noone, 2010), as well as the moisture tracing in other regions (Salih et al., 2016). The relatively long period covered in this study, from 1961 to 2012, allows for a robust analysis of historical trend as well as the interannual variability of local moisture recycling, and its relationship with moisture transport and other impact factors, such as sea surface temperature and the natural variability of the climate system.

2. Data

2.1. Ice Core Data

The Chongce and Zangser Kangri ice cores were drilled from two glaciers located at the northwestern Kunlun Mountains on the northwestern TP (Figure 1). The Chongce glacier is located at western Kunlun, covering an area of 163.06 km^2 with a volume of 38.16 km^3 (Shi et al., 2008). The snowline altitude is about 5,900 m asl. Three ice cores (with length of 133.83 m, 135.81 m, and 58.82 m respectively) were recovered in October 2012 from a southwest leaning flat-topped glacier at the southern slope of Chongce (35°14′N, 81°07′E, 6010 m asl; Figure S1 in the supporting information). These ice cores were kept frozen and transported to the Key Laboratory of Coast and Island development of Ministry of Education, Nanjing University. This study is based on the 58.82 m core, which was split axially into two halves. One half was stored for archive, and the other half was cut into 1,956 samples with intervals of 2–3 cm in a cold room (−20°C) for analyses of stable isotopes and β-activity. The $\delta^{18}O$ and δD were measured using a Picarro Wavelength Scanned Cavity Ring-Down Spectrometer (WS-CRDS, model: L 2120-i, precision at ±0.1‰). The detailed dating was presented in An, Hou, Zhang, Wu, et al. (2016). The ice core was drilled in October, but the precipitation amount is usually little in November and December in this region. Therefore, the 2012 layer was also included to make best use of the data in present study, and the analysis period of Chongce ice core is from 1953 to 2012.

The Zangser Kangri glacier is located in the Qangtang Plateau, northwest part of the TP (Figure 1), with an area of 337.98 km^2 and a volume of 41.70 km^3 (Shi et al., 2008). The snowline is about 5,700–5,940 m asl. The glacier temperature ranged from −15.2°C to −9.2°C, with a mean temperature of −11.7°C, −12.4°C at the 10 m depth and a basal temperature of −9.2°C. The ice cores were drilled at a south-leaning flat-topped glacier at the southern slope of Zangser Kangri (Figure S1). Two ice cores to bedrock (127.7 m for Core 1 and 126.7 m for Core 2) were recovered from the glacier (34°18′05.8″N, 85°51′14.2″E, 6,226 m asl; Figure 1) in April 2009, and this study was based upon the analysis of Core 1. These two ice cores were kept frozen and transported to the State Key Laboratory of Cryospheric Sciences, the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences for processing. A total of 2,884 samples were taken from Core 1 at a resolution of 4–6 cm. The outer ~2 cm of each sample was removed for stable oxygen isotope analysis. The inner portion of the ice core was collected in precleaned polyethylene sample containers for chemical and dust particle analyses. The $\delta^{18}O$ and δD were measured using a Picarro Wavelength Scanned Cavity Ring-Down Spectrometer (WS-CRDS, model: L 2120-i, precision at ±0.1‰). The detailed dating was presented in a previous study (An, Hou, Zhang, Wang, et al., 2016). In present study, the analysis period of Zangser Kangri ice core is from 1951 to 2008.

2.2. Reanalysis Data and Moisture Trajectory Modeling

The target region in this study is defined by a minimum rectangle encompassing both ice cores (32–36°N, 81–86°E). There is only one meteorological station in this region, i.e., the Gêrzê station (Qin et al., 2009). In order to evaluate the results derived from the ice core d excess series and the model calculation, we used the ERA-Interim reanalysis (European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis) data (Dee et al., 2011) of 0.75° × 0.75° spatial resolution, because it has better performance than other reanalysis data sets in simulating atmospheric water budget over the TP (Gao, Lan, & Zhang, 2014; Zhang et al., 2017). The gridded temperature and relative humidity (calculated from ERA-Interim temperature and dew point temperature) were extracted from the ERA-Interim for the period of 1979–2015 to calculate the local moisture recycling of Chongce and Zangser Kangri. In addition, such climate variables as monthly wind speed and direction, geopotential height, precipitation, and evaporation were also used.

Monthly sea surface temperature (SST) data from the Hadley Center (Rayner et al., 2003) was used to drive the general circulation model, the Community Atmosphere Model version 3 (CAM3) (Collins et al., 2006), with an embedded water-tagging module (Pausata et al., 2011). We also applied the Hybrid Single-Particle

Lagrangian Integrated Trajectory Model 4 (HYSPLIT4) to investigate the influence of atmospheric circulation on extreme values of d excess in ice cores during different seasons. For comparison, the HYSPLIT4 model was run based on two alternative data sets: the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research, USA, reanalysis data and ERA-Interim data.

In addition, the digital elevation model (DEM) data were used to show the three-dimensional terrain for the ice cores sites. The DEM data were from Advanced Spaceborne Thermal Emission and Reflection Radiometer global DEM version 2 with 30 m resolution, available at http://www.jspacesystems.or.jp/ersdac/GDEM/E/4.html.

2.3. Meteorological Data

To further evaluate the model results, climate data from three meteorological stations on the northwestern TP (i.e., Shiquanhe, Gêrzê, and Xainza) were also used. Shiquanhe is the closest meteorological station (32°30′N, 80°05′E, 4,278 m asl, 1961–2012) to the Chongce glacier (Figure 1), and its annual temperature and relative humidity data were used to calculate the local moisture recycling of Chongce. For Zangser Kangri, the average annual temperature and relative humidity of the nearby station Gêrzê (32°09′, 84°25′, 4,414.9 m asl, 1973–2008) and Xainza (30°57′, 88°38′, 4,800 m asl, 1961–2008) were used (An, Hou, Zhang, Wu, et al., 2016; An, Hou, Zhang, Wang, et al., 2016). It is worth noting that Shiquanhe and Xainza stations, although the closest, are still quite far away from the ice core drilling sites. Shiquanhe is about 320 km from Chongce, and Xainza is about 500 km from Zangser Kangri. Therefore, both Shiquanhe and Xainza stations were not included in calculating climatic changes in the target region. The moisture recycling fraction calculated based on data from these stations was only for comparison purposes. The stable water isotope data of Shiquanhe is from Yu et al. (2007).

In addition, we extracted the 2.5° × 2.5° gridded precipitation data from the Global Precipitation Climatology Project (GPCP 2.2 data set) to examine the spatial pattern of precipitation trend (Adler et al., 2003). Previous studies show that this data set is able to capture the precipitation variations over the TP and surrounding areas (Yao et al., 2012).

2.4. GNIP Data

In addition to the stable water isotopes in the ice cores, we also used the precipitation stable water isotope data from Global Network of Isotopes in Precipitation (GNIP). GNIP data are collected by the International Atomic Energy Agency and the World Meteorological Organization since 1961. The GNIP stations used in the present study include Teheran, Tashkent, Kubul, Jammu, Hetian, New Delhi, Bombay, and Shillong (Figure 1).

3. Two-Component Mixing Model

The two-component mixing model has been used to evaluate the fraction of local moisture recycling on the TP and surrounding areas in previous studies (Cui & Li, 2015; Kong et al., 2013; Kurita & Yamada, 2008; Xu et al., 2011). This model assumes that precipitation is formed from the mixture of advected vapor and local moisture recycled by evaporation (Froehlich et al., 2008; Kong et al., 2013). The mixing equation is as follows:

$$f_c = \frac{\mathrm{d}_c - \mathrm{d}_{\mathrm{adv}}}{\mathrm{d}_{\mathrm{evap}} - \mathrm{d}_{\mathrm{adv}}} \quad (1)$$

where f_c is the fraction of precipitation from local evaporation, d_c is the corrected d excess of local precipitation at cloud base, $\mathrm{d}_{\mathrm{adv}}$ and $\mathrm{d}_{\mathrm{evap}}$ are d excess of advected moisture and locally evaporated water. Several factors could affect the d excess of precipitation. It could be increased by moisture recycling due to the kinetic isotope fractionation during evaporation, but decreased by the local effect of subcloud evaporation of precipitation (Froehlich et al., 2008). However, it has been suggested that both the distance between cloud base and ground and the saturation deficit are lower at high altitude, and thus, the impact of subcloud evaporation is negligible at high mountains (Froehlich et al., 2008). Cui and Li (2015) found that in regions above that 3,700 m asl, the precipitation d excess is almost free of the subcloud evaporation effect in summer in the northeastern TP. Both Chongce and Zangser Kangri are higher than 6,000 m asl. Therefore, the annual mean values of d excess from the ice core at each site were used to represent the d excess of local precipitation d_c.

The d excess of advected moisture ($\mathrm{d}_{\mathrm{adv}}$) was difficult to obtain. The study region is dominated by the westerlies, but the moisture from the Indian Ocean could still reach this region in during the summer monsoon season (Figure S2). Based on the method used in previous studies on the TP (Cui & Li, 2015), the annual d excess of advected moisture (d_{adv}) was calculated as the averages of d excess values of precipitation at all upwind locations—Teheran, Tashkent, Kubul, Jammu, Hetian, and Shiquanhe stations (previous October to May) along the westerly transport trajectory, as well as the New Delhi, Bombay, and Shillong stations (June to September) along the Indian monsoon trajectory (Figures 1 and S2). The d excess values of all upwind stations range from 8.0‰ to 18.6‰, and we use the average d excess value of all these stations (11.85‰) as a reasonable estimate for d_{adv}. The d excess of locally evaporated moisture (d_{evap}) is calculated based on following equations (2) to (6):

$$R_{\mathrm{evap}} = \frac{\frac{R_W}{\alpha} - hR_A}{(1-h)\alpha_K} \tag{2}$$

where R represents the isotopic ratio ($R_i = 1 + \delta_i$). The subscript evap, W, and A indicate evaporated moisture, evaporating water, and atmospheric vapor. Based on equations (2) to (6), R_{evap} is calculated, and the value of δ_{evap} (i.e., δD_{evap} and $\delta^{18}O_{evap}$) can be calculated as $\delta_{evap} = R_{evap} - 1$. With values of δD_{evap} and $\delta^{18}O_{evap}$, the d excess of evaporated moisture (d_{evap}) can be calculated accordingly. The annual values of $\delta^{18}O$ and δD in ice cores are used to calculate the isotopic ratio of the evaporating water R_W for ^{18}O and ^2H. The h indicates the relative humidity. The α is the liquid-vapor equilibrium fraction factor for deuterium and oxygen-18, estimated from empirical relations derived by Majoube (1971). The α_k is the kinetic fraction factor ($^2\alpha_k$ for deuterium and $^{18}\alpha_k$ oxygen-18). We adopted the empirical equations used by Froehlich et al. (2008) to calculate α and α_k:

$$^{18}\alpha = e^{1.137T^{-2}\times 10^3 - 0.4156T^{-1} - 2.0667\times 10^{-3}} \tag{3}$$

$$^{2}\alpha = e^{24.844T^{-2}\times 10^3 - 76.248T^{-1} + 52.612\times 10^{-3}} \tag{4}$$

$$^{18}\alpha_K = 1 + 0.0289 \cdot n \tag{5}$$

$$^{2}\alpha_K = 1 + 0.024 \cdot n \tag{6}$$

where T is the temperature (K). In order to get a more accurate T at the ice core drilling site, the instrumental temperature records, collected at adjacent meteorological stations at lower elevations (Figure 1), were adjusted based on the lapse rate of 6 K/km derived from Y. Li, Zeng, et al. (2015). The value 0.58 was adopted for n (Stewart, 1975).

R_A is very difficult to measure directly because of the dynamic nature of the atmosphere and strong seasonality. In this study, the stable isotopic composition (R_A) of the vapor was determined using the precipitation-equilibrium assumption (Gibson, Birks, & Edwards, 2008). The $\delta^{18}O$ and δD of atmospheric vapor (δ_A) was calculated based on equation (7):

$$R_A = \left(\left(\delta_p \text{-} \alpha + 1\right)/\alpha\right) + 1 \tag{7}$$

where δ_P is the mean stable water isotopic composition of precipitation, and in this study it is approximated by the isotopic values of the ice cores. The calculated mean d excess value of atmospheric vapor is about 24.9‰ for both Chongce (1979 to 2012) and 24.3‰ for Zangser Kangri (1979 to 2008). This calculation of moisture recycling fraction is not exact because of limited meteorological records, but it is a reasonable first approximation to help understand the relatively long-term contribution of moisture recycling to local precipitation on the northwestern TP.

4. Results

4.1. The d Excess Variations of the Chongce and Zangser Kangri Ice Cores

The Chongce ice core has the $\delta^{18}O$ values ranging from −15.8‰ to −6.5‰ and the δD values between −111.6‰ and −29.1‰ during the period of 1953–2012. For the Zangser Kangri ice core, the $\delta^{18}O$ values range from −15.3‰ to −6.6‰, and the δD values between −105.6‰ and −30.9‰. The isotopic values of

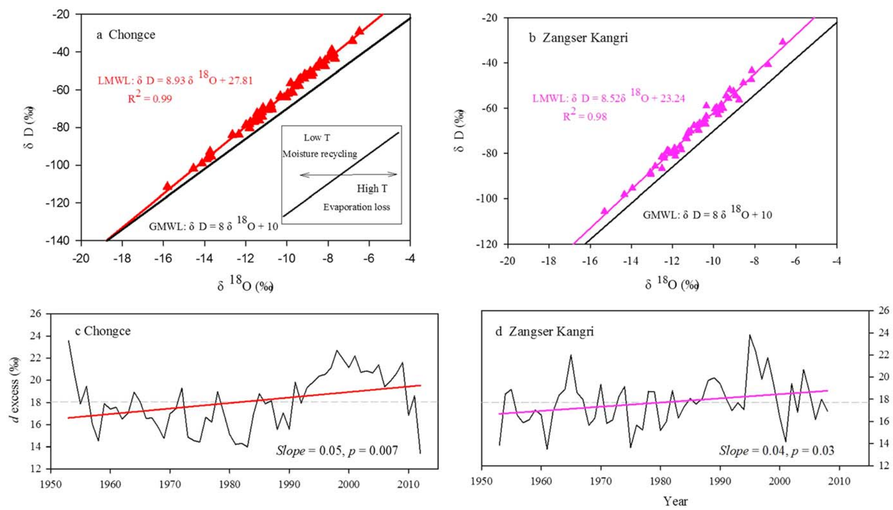

Figure 2. The relationship between $\delta^{18}O$ and δD of the ice core from (a) Chongce and (b) Zangser Kangri with the Local Meteoric Water Line (LMWL) and the Global Meteoric Water Line (GMWL), and the d excess annual series (black lines) in the ice core from (c) Chongce and (d) Zangser Kangri with the linear trends (red lines).

the ice cores for Chongce and Zangser Kangri are plotted mostly above and to the left of the Global Meteoric Water Line (GMWL) (Figures 2a and 2b). This $\delta^{18}O$-δD relationship is consistent with the meteoric water lines derived from precipitation in the adjacent Shiquanhe and Gêrzê station (Yu et al., 2007), as well as those from isotopic values of ice cores in the central TP (Joswiak et al., 2013). The slope and intercept of δD-$\delta^{18}O$ relationship are generally influenced by either subcloud evaporation or local moisture recycling. Since the subcloud evaporation under low relative humidity is negligible for high mountains, the steep slope and large intercept could result from local moisture recycling, which causes nonequilibrium condensation of the isotopes (Bershaw et al., 2012; Tian et al., 2001; Yuan et al., 2011).

The interannual variations of d excess for Chongce (from 1953 to 2012) and Zangser Kangri (from 1953 to 2008) are shown in Figures 2c and 2d. The long-term mean d excess value of Chongce is 18.1‰, ranging from 14.0‰ to 23.6‰ with a standard deviation of 2.5‰ over the whole period from 1953 to 2012. The d excess values of Zangser Kangri range from 13.5‰ to 23.9‰ between 1953 and 2008 (Figures 2c and 2d), with an average of 17.7‰ and a standard deviation of 2.1‰. Both time series show an increasing trend since the end of 1980s. For Chongce, the d excess series shows a mean value of 20.7‰ from 1988 to 2009, 3.9‰ higher than the average from 1953 to 1988. Meanwhile, the d excess values of Zangser Kangri show a higher mean value of 19.4‰ from 1995 to 2005, 2.0‰ higher than the average from 1953 to 1994.

Values of d excess are controlled mainly by relative humidity and temperature over the evaporating surface, and wind speed at the source region of atmospheric moisture (Froehlich et al., 2002; Merlivat & Jouzel, 1979)). Based on the equation developed by Merlivat and Jouzel (1979): $d = -58.1\,h + 57.33$, d excess depends on the mean relative humidity (h) of the air masses above the ocean surface. The combined average mean surface relative humidity over the Arabian Sea (~10°–20°N, ~50°–70° E) and the Bay of Bengal (~10°–20°N, ~80°–100°E) during the summer season (June to September) over the period of 1951–2012 ranges from 77.4% to 80.3%, resulting in d excess values between 10.7‰ and 12.4‰. The average mean surface relative humidity over the Atlantic (~0°–60°N, ~100°W–20°E, previous October to current May) over the period of 1951–2012 ranges from 83% to 85.4%, leading to d excess values between 7.7‰ and 9.1‰. These results suggest that the high d excess values in the ice cores cannot be explained only by the relative humidity and SSTs of the moisture source regions upstream the westerly and Indian monsoon circulations.

The isotopic composition of precipitation is a result of a mixing of advected and recycled moisture of a given region (Kong et al., 2013). The d excess values greater than 10‰ often indicate the existence of the recycled water derived from local evaporated vapor (Bowen et al., 2012; Gat, Bowser, & Kendall, 1994). Because of nonequilibrium fractionation that occurs during evaporation, the d excess value of evaporated moisture becomes larger than that of land surface water (Gat & Matsui, 1991; Henderson-Sellers et al., 2004). Thus, high d excess values may reflect the contribution of local evaporation from a land surface to precipitation in this region.

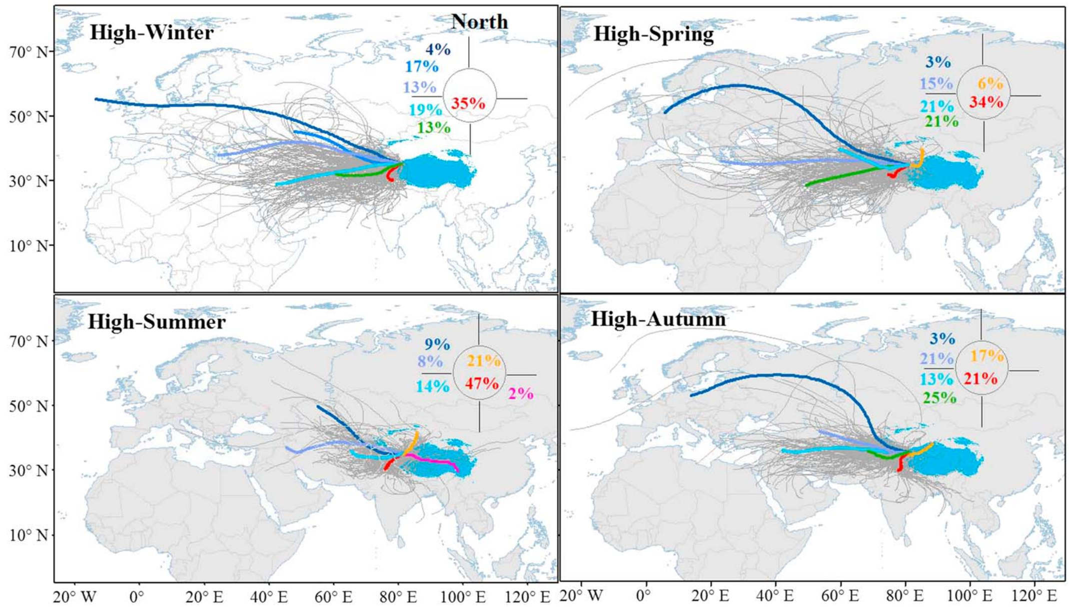

Figure 3. Backward trajectories calculated by NOAA HYSPLIT (based on NCEP reanalysis data) at 1840 m above ground level over Chongce for winter (December–February), spring (March–May), summer (June–August), and autumn (September–November) during the years with high d excess (1998, 1999, and 2001). The numbers indicate the percentage of the air mass transported from different directions (the color of the number corresponds to the color the trajectory), and the numbers in the circle indicate the air mass from local region.

4.2. Influence of Atmospheric Trajectories on Extreme d Excess Values of Ice Cores

The variations of the precipitation $\delta^{18}O$ (or δD) values and d excess are influenced by moisture from different sources carried by various atmospheric trajectories (Steen-Larsen et al., 2013; Yu et al., 2016). In this study, the NOAA HYSPLIT model was exploited to calculate the daily 120 h of back trajectories of air parcels above the Chongce (Figures 3 and 4) and Zangser Kangri (Figures S3 and S4) ice core sites for the years with three highest (higher than mean value $+1.0\sigma$) and three lowest (lower than mean value -1.0σ) d excess values, respectively. With k-means clustering algorithm (Alsabti, Ranka, & Singh, 1997), six clusters are mapped out from the daily trajectories for each season, based on which possible moisture source regions can be identified. The six clusters include the northern and southern trajectories of the westerlies, the northern and southern local trajectories, the Indian summer monsoon, and the polar trajectories.

The HYSPLIT results driven by NCEP and ERA data show similar moisture trajectories for Chongce and Zangser Kangri area, although the ERA-driven trajectories show more information of local region with very short local trajectories. The majority of trajectories for Chongce and Zangser Kangri area are different for years with high and low d excess values. The moisture in this region is generally controlled by the combined effects of the westerlies and local moisture recycling. In general, more moisture comes from the TP and surrounding area in years with high d excess values than in years with low d excess values, especially in summer and spring seasons (Figures 3, S3, and S7). The ERA-driven results show very short northern and southern local trajectories for Chongce area, which could have contributed to the high d excess values (Figures S5 and S6). The NCEP-driven results show significant moisture contribution from the Indian monsoon in the summer for Chongce during years with low d excess values (Figure 4), whereas such contribution is largely absent during the years with high d excess values (Figure 3). The HYSPLIT model results also indicate that the Indian monsoon contributes more moisture to precipitation in the eastern part of the northwestern TP (e.g., Zangser Kangri) than the western part (e.g., Chongce) (Figures S4 and S8). Therefore, the low d excess values may be caused by this contribution of the Indian monsoon, hence less contribution of local moisture, whereas the high d excess values could be related to the more contribution from local moisture recycling.

4.3. The Estimated Recycling Fraction of Local Moisture

Based on the two-component mixing model, we calculated the annual moisture recycling fraction values for Chongce and Zangser Kangri. The local moisture recycling fraction derived from ERA-Interim and station data

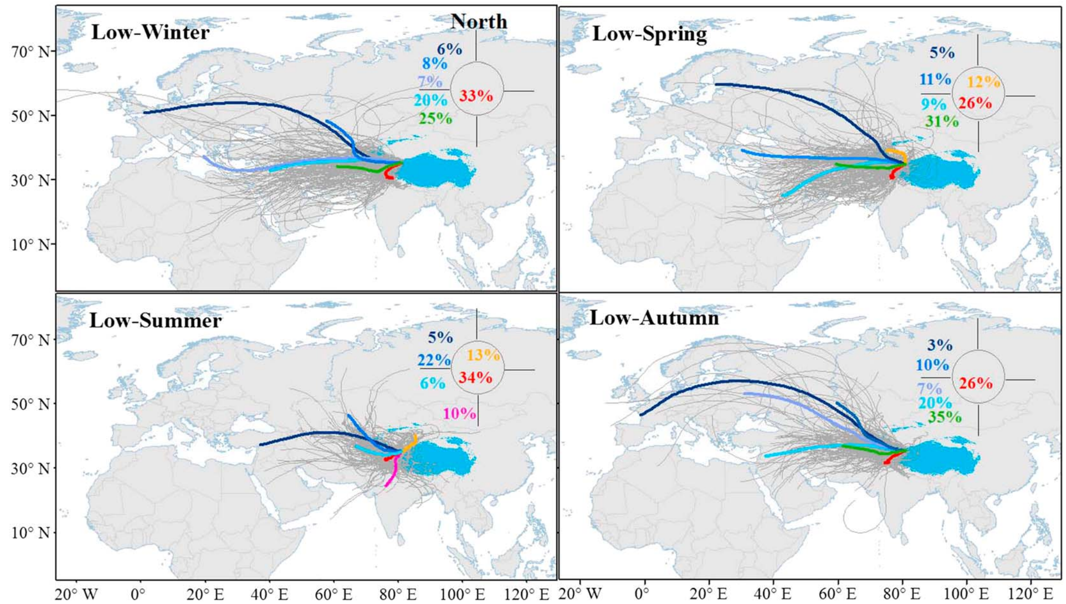

Figure 4. Same as Figure 3, for the years with low d excess (1981, 1983, and 2012).

show identical values and temporal trends (Figures 5a and 5d). Based on climate variables from ERA-Interim data, the mean fraction of local moisture is 53.2 ± 18.0% for Chongce (1979–2012) and 52.9 ± 12.6% for Zangser Kangri (1979–2008). The interannual variation for the local moisture recycling is large, ranging from 15.0% to 82.6% for Chongce and 24.7% to 81.6% for Zangser Kangri. Meanwhile, the mean fraction of local moisture calculated from station data is 49.4 ± 17.1% for Chongce (1961–2012) and 48.4 ± 13.8% for Zangser Kangri (1961–2008), and the interannual variation for the local moisture recycling is large ranges from 15.3% to 82.7% for Chongce and 16.8% to 81.0% for Zangser Kangri. The large annual variations for the local moisture recycling ratio estimations may be caused by the anomalous isotopic values of annual stable water isotopic compositions in ice cores, which could be influenced by single and transient weather events. The Chongce and Zangser Kangri results show similar temporal patterns in both the local moisture recycling (Figures 5a and 5d) and d excess (Figures 2c and 2d). Moreover, the local moisture recycling ratio has a similar significant increasing trend for both sites during the past decades (Figures 5a and 5d). The ratio is relatively low from 1960s to the end of 1980s and begins to increase significantly after 1990s, especially for Chongce. At the same time, the regional temperature from the nearest meteorological stations Shiquanhe, Gêrzê, and Xiainza shows an evident increasing trend from since 1960s (Figures 5b and 5e), whereas the relative humidity shows great interannual and decadal variability with no discernible trend (Figures 5c and 5f). The increasing temperature could lead to an increase in the regional evaporation on the northwestern TP, and thus enhance local moisture recycling.

The local moisture recycling ratios are sensitive to the isotopic values of evaporating water (d_{evap}, i.e., R_W for ^{18}O and ^{2}H). The annual d_{evap} is derived from the values of annual isotopic values of Chongce and Zangser Kangri ice cores ($\delta^{18}O$ and δD), which have large intra-annual variations. We evaluate the uncertainty range of the local moisture recycling ratio by estimating it using the annual maximum and minimum, in addition to annual isotopic values of ice cores. The resulting differences in the moisture recycling ratios are relatively small, and the time series show very similar temporal patterns (Figure S9 and Table S1 in the supporting information). This suggests that the local moisture recycling ratios derived from the annual mean isotopic values of ice cores are reasonably stable and robust.

The d excess of advected moisture (d_{adv}) is an important component for calculating local moisture recycling. Based on equation (1), the d_{adv} should be less than d_c and d_{evap}. The minimum value of d_c is 13.4‰ for Chongce and 13.5‰ for Zangser Kangri ice core. The minimum value of d_{evap} is 21.8‰ for Chongce and 21.1‰ for Zangser Kangri ice core. Based on the isopotic data, the d_{adv} ranges from 8.0‰ to 18.6‰. However, for calculating *f* from equation (1), the maximum d_{adv} value that applies is the minimum of d_c

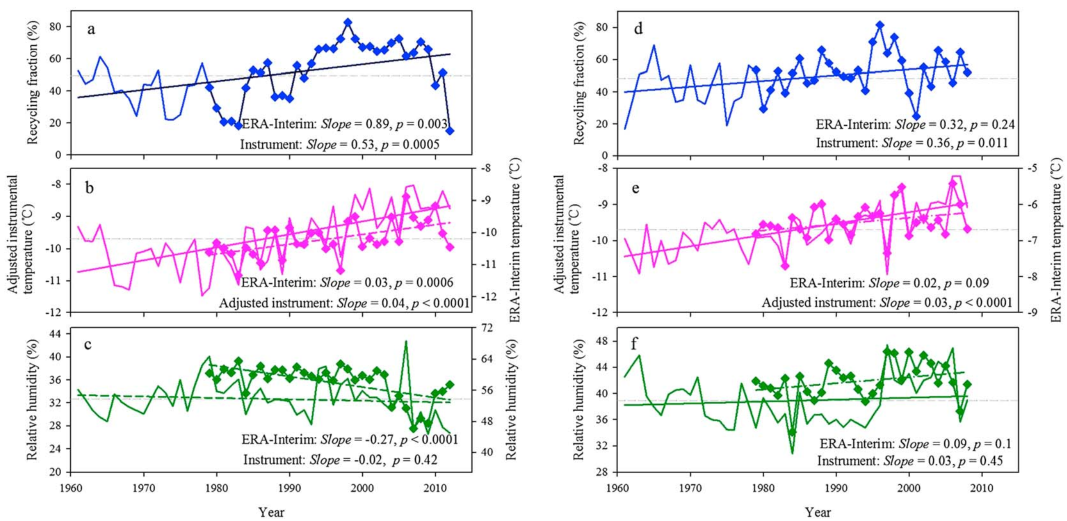

Figure 5. The annual series of local moisture recycling fraction calculated for (a) Chongce and (d) Zangser Kangri based on station data (smooth lines) and ERA-Interim (lines with diamonds); (b) mean annual temperature and (c) relative humidity derived from ERA-Interim at Chongce (lines with diamonds) and nearby stations: Shiquanhe station (simple lines); (e) mean annual temperature and (f) relative humidity derived from ERA-Interim at Zangser Kangri (lines with diamonds) and nearby Gêrzê and Xainza stations (simple lines). The station temperature data in Figures 5b and 5e are adjusted for elevation based on the lapse rate of 6 K/km derived from Y. Li, Zeng, et al. (2015). The solid and dashed lines indicate the linear trends for the ERA-Interim and instrumental data, respectively.

and $d_{evap.}$ Based on this, we estimated the uncertainty range of the local moisture recycling ratio by using the maximum (13.4‰ and 13.5‰, for Chongce and Zangser Kangri ice cores, respectively) and minimum (8.0‰) values, as well as the average (11.85‰) for d_{adv} to calculate the range of *f*. The resulting local moisture recycling fractions are 64.4%, 53.2%, and 46.3% for maximum, average, and minimum $d_{adv.}$ Despite such differences, the three time series show very similar temporal patterns over the past decades (Figure S10). The mean value of 11.85‰ is chosen as the value of d_{evap} for subsequent calculations.

4.4. Simulated Contribution of Local Moisture Recycling

In order to evaluate the results from the two-component mixing model, and further explore the dynamical processes involved, we use CAM3 climate model with water-tagged module to trace the moisture sources and each of their individual contribution to precipitation in our study area. The water-tagging technique in the model can trace the moisture that forms the local precipitation back to previously tagged region. The simulation covers a period from 1951 to 2015. The CAM3 model has a horizontal resolution of 2.8° × 2.8°, with 26 vertical levels and a model top at 3.5 hPa. We tagged 10 specific moisture source regions for precipitation over the study area (Figure S11). The selected regions cover almost all the possible moisture sources of the northwestern TP and are also consistent with the dynamical features of the atmospheric circulation, which influences the northwestern TP.

The CAM3 simulation shows that the most important moisture source region for the northwestern TP is the Indian Ocean, contributing of 40.5% of total moisture during the period 1951–2015 (Figure S12). The local moisture recycling is the second largest moisture contributor for the area, accounting for 14.6% of annual total moisture. In particular, the contribution of local moisture could increase to 27.5% in summer season (June–August; Figure 6). These values are lower than the moisture recycling ratios derived from the two-component mixing model for the two ice core sites. Moreover, the CAM3 model shows no trend in the contribution of local moisture recycling from 1951 to 2015 for annual values, and only a weak increasing trend in spring and winter (Figure 6).

5. Discussion

5.1. Comparisons With Previous Local Moisture Recycling Ratio Estimations

It has been suggested that regional moisture recycling is a major source of precipitation for the TP as topographic features make it difficult for moisture to leave the region (van der Ent, 2009). Studies over

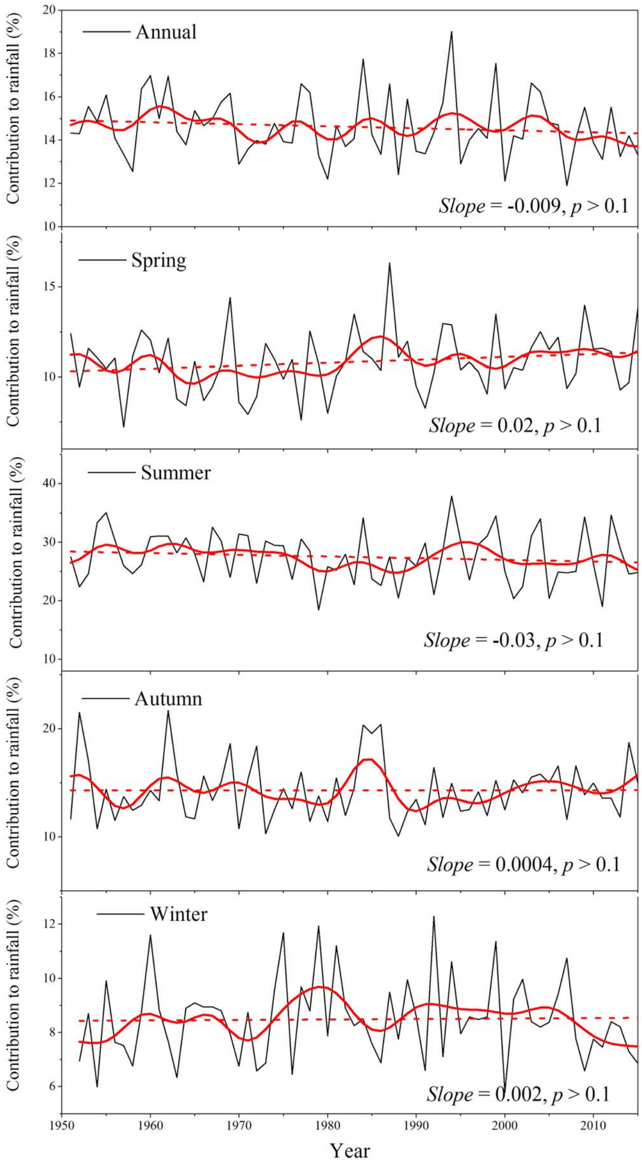

Figure 6. The model simulated contribution of local moisture to precipitation on the northwestern TP (averaged over the area 32–36°N, 81–86°E) in annual average, spring, summer, autumn, and winter from 1961 to 2015. The red solid line represents the FFT smoothed values, and the red dashed line indicates the linear trend over the period 1951–2015.

the northwestern TP have drawn similar conclusions (Yang, Ye, & Wu, 1992; Yu et al., 2016). Meanwhile, previous studies have shown a wide range of values of moisture recycling rates for the TP. For example, using the same two-component mixing model, Cui and Li (2015) found that the annual contribution of local recycling was about 23.4% in the Qinghai Lake Basin of the northeastern TP and Xu et al. (2011) estimated that the average contribution of evaporation from the Lake Nam Co in the central TP to local atmospheric vapor has varied from 28.4% to 31.1% during the summer season (Table 1). Kurita and Yamada (2008) found that local recycling ratio ranged from 30% to 80% over the middle of the Tibetan Plateau during the monsoon season (Table 1). These values are relatively lower but within the ranges of the estimated local moisture recycling ratios in our study (15.3%–82.7% for Chongce and 16.8%–81.0% for Zangser Kangri). The great uncertainties in estimating this particular aspect of the hydrological processes may be caused by the influence of local climate or transient weather events. Even in present study, the annual local moisture recycling ratio series also showed discrepancies for Chongce and Zangser Kangri in interannual scale, despite the similar enhancing trend over the past decades. The differences could be attributed to the differences in local climate or hydrological processes. For example, the local moisture recycling ratio for Chongce showed low values since mid-2000s, which was accompanied by the decreasing trend of regional relative humidity (Figure 5c). By contrast, the local moisture recycling ratios for Zangser Kangri in recent years were relatively stable, and the regional relative humidity values were also stable and high since mid-2000s (Figure 5f); the stable regional relative humidity may have provided more evaporating water and thus led to relatively stable local moisture recycling. Moreover, the Zangser Kangri is located more eastern and affected by more moisture from Indian monsoon, which also can cause some differences in the final local moisture recycling ratios.

In addition, the use of different data sets with varied data sources and compilation methods could also lead to large differences in the estimated local moisture recycling of existing studies. For example, based on the ERA-Interim and NCEP data sets, Zhang et al. (2017) reported that local moisture may have contributed about 18% of the total precipitation for the west central TP during the period of 1979–2013. However, based on the analysis of 12 year high-resolution climatology data set, Curio et al. (2015) found that 63.2% of the precipitation for the TP is provided by local moisture recycling from 2000 to 2012. In contrast, the calculations using two-component mixing model in this study are based on the measured stable water isotopic compositions in ice cores and instrumental records, while the CAM3 simulation used Hadley SSTs. The different data sets may have caused differences in the values of local moisture recycling ratios.

Table 1
Comparison of Recycled Moisture Fraction Estimates From Similar Studies Using Stable Water Isotopes

Contribution (%)	Study region	Study period	Data source
30.0–80.0	Naqu, central TP	August 2004	Kurita and Yamada (2008)
28.4–31.1	Nam Co Basin, central TP	Summer 2005–2006	Xu et al. (2011)
23.4	Qinghai Lake Basin, northeastern TP	Annual average of July 2009 to June 2010	Cui and Li (2015)
15.0–82.6	Chongce, northwestern TP	1979–2012	This study
24.7–81.6	Zangser Kangri, northwestern TP	1979–2008	This study

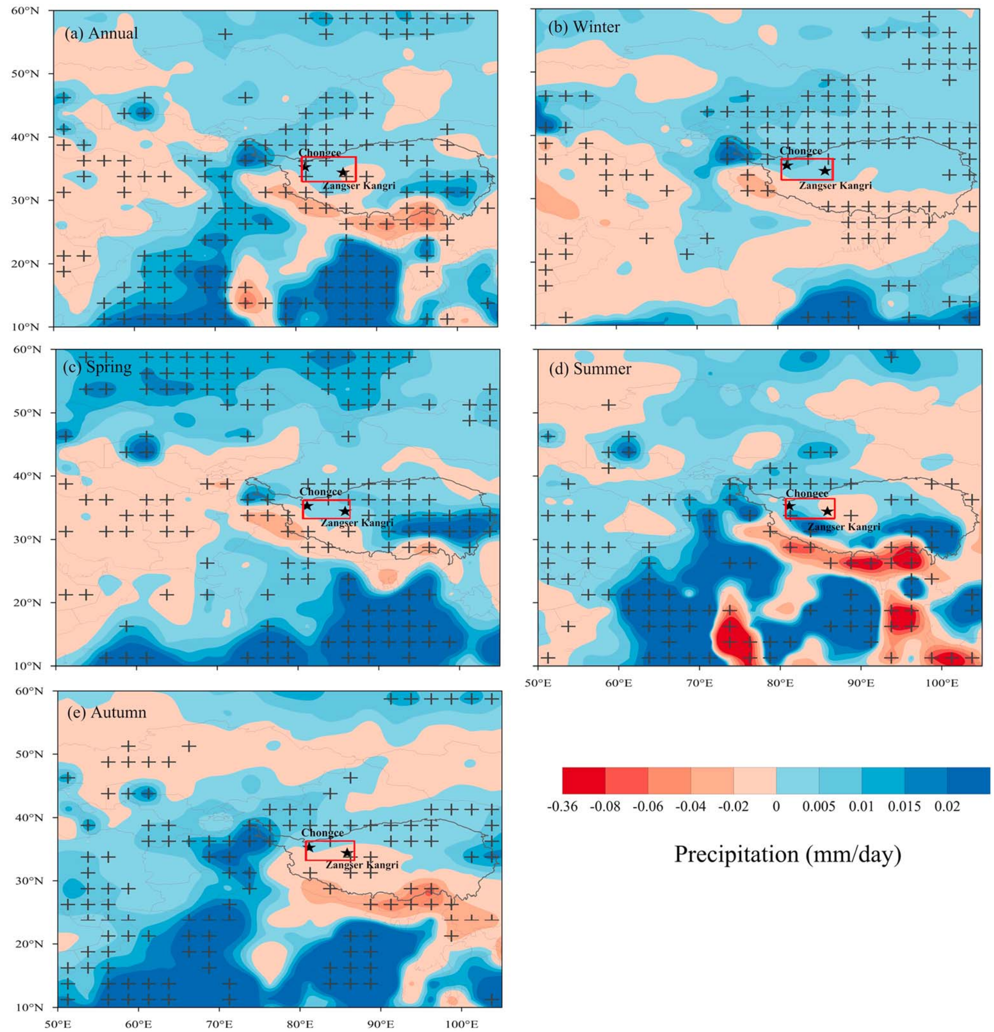

Figure 7. Precipitation trends for 1979–2015 from the GPCP in (a) annual, (b) winter, (c) spring, (d) summer, (e) autumn time series. The stars indicate the ice core sites (Chongce and Zangser Kangri). The crosses represent trends significant at the 95% confidence level. The red box in each panel indicates the target region (81–86°E, 32–36°N).

Despite these discrepancies, our estimations show that the contribution from local moisture recycling has increased since 1990s on the northwestern TP, which is consistent with the study of Zhang et al. (2017), who also found that the hydrological cycle has intensified and the precipitation recycling ratio on the TP has increased significantly in recent decades. The CAM3 simulation in this study also suggested that the local moisture recycling was a major (the second largest) moisture source for the northwestern TP, although the contribution of local moisture recycling to regional precipitation was relatively stable, especially in summer season.

5.2. The Enhanced Local Moisture Recycling on the Northwestern TP Over the Past Decades

The enhanced local recycling may be attributed to several climatic and environmental changes of the TP in the past decades, which are discussed below in more details. First, local moisture recycling can be enhanced by increasing precipitation and evaporation resulted from the fast warming of the region. Many studies have reported evident climate changes on the TP over the last few decades characterized by significant increase of temperature and precipitation (van der Velde et al., 2014; Wu et al., 2015 Yang et al., 2011, 2014]. Our analysis of climate data also confirms these changes. Figure 7 shows the annual and seasonal precipitation trends from GPCP data over the northwestern TP and surrounding areas (Figures 7a–7e) over the period of 1979–2015. Annual precipitation has increased over most of the northwestern TP (Figure 7a). This trend is

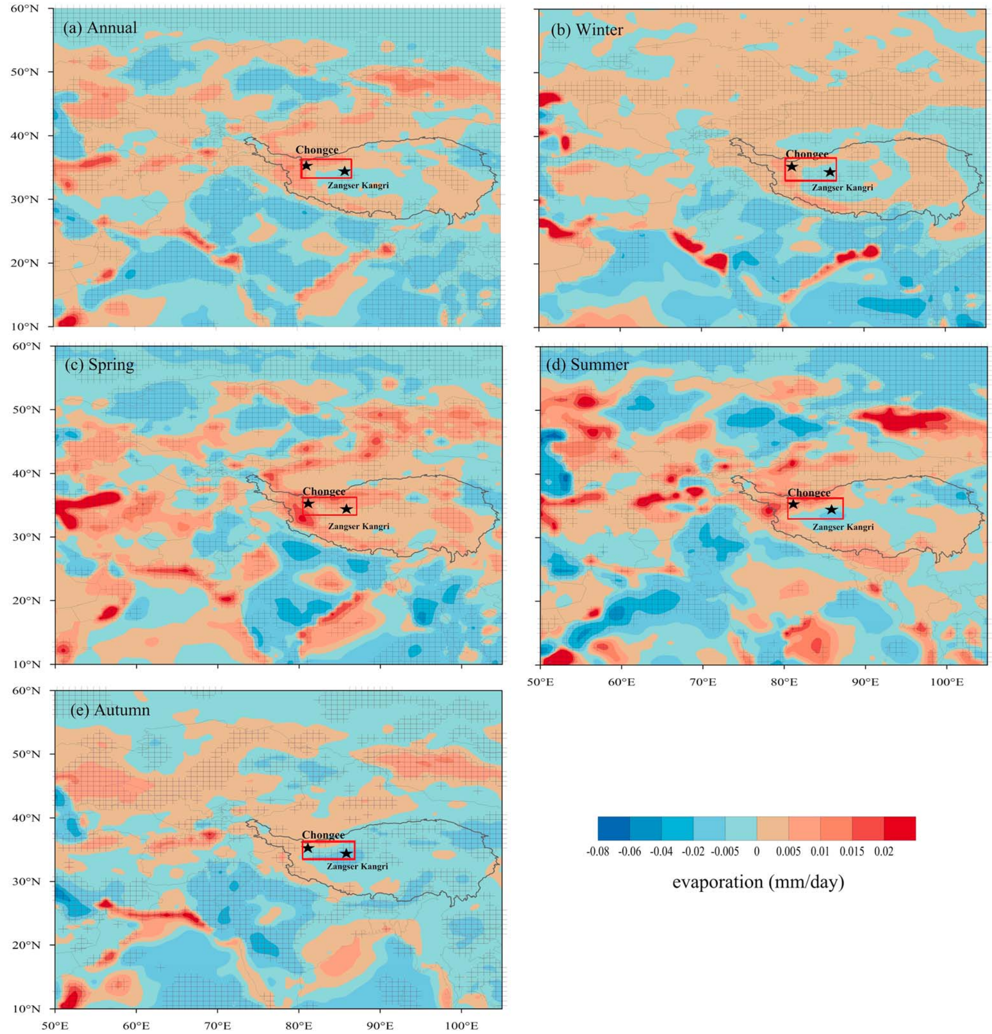

Figure 8. Evaporation trends for 1979–2015 from the ERA-Interim in (a) annual, (b) winter, (c) spring, (d) summer, and (e) autumn time series. The stars indicate the ice core sites (Chongce and Zangser Kangri). The crosses represent trends significant at the 95% confidence level. The red box in each panel indicates the target region (81–86°E, 32–36°N).

statistically significant for winter (Figure 7b), spring (Figure 7c), and summer (Figure 7d) seasons. However, the GPCP data show a decreasing trend in the Zangser Kangri site. This might be due to the fact that the site is more influenced by the Indian monsoon, and it has weakened in recent decades (Yao et al., 2012). Precipitation processes on the TP are extremely heterogeneous, with the influence from topography, local convective activity, and large-scale circulation (Feng & Zhou, 2012). Therefore, the precipitation could have large spatial variations. Our result is largely consistent with previous studies based on different data sets. For example, using a new gridded daily precipitation data set with the spatial resolution of 0.25° × 0.25° (CN05.1, covering the period of 1961–2012 (Wu & Gao, 2013), Wang, Pang, & Yang, 2017 find that precipitation has increased over the most parts of the TP from 1961 to 2012, including the northwestern TP.

The increase in precipitation and temperature could increase local evaporation. We further evaluate changes in evaporation over the TP and the surrounding areas. The gridded annual evaporation data from ERA-Interim show increasing trend from 1970 to 2015 over the western edges of the TP, eastern TP, and the Himalayas (Figures 8a–8d). The increase in evaporation is not significant over the northwestern part of the TP (Figures 8a–8e). The largest increase in evaporation occurs in spring, covering the entire northwestern TP (Figure 8c). Evaporation serves to transport both water and energy from the land surface to the atmosphere (Yang et al., 2007). Therefore, its increase could serve to enhance the local atmospheric circulation, hence the local moisture recycling. It is worth noting that whereas precipitation increases for most of the northwestern TP (Figure 7), evaporation only increases in a part of the northwestern TP (Figure 8). This could be caused by the differences in land surface condition and atmospheric circulation patterns that lead to different responses in local moisture recycling for the northeastern and northwestern TP.

Second, local moisture recycling can also be enhanced by land surface changes, such as increase of surface water and vegetation. Previous studies found that the accelerated glacier melting and permafrost degradation have caused the expansion and deepening of the lakes in the interior TP since the late 1990s (Li et al., 2011; W. Li, Zhao, et al., 2015; Zhang et al., 2013; Zhu, Xie, & Wu, 2010). As a result, permanent surface water has increased significantly on the TP (Pekel et al., 2016). The northwestern TP have much higher glacier coverage compared with other regions of the TP. Recent study found that the lake levels exhibit dramatic increases during both warm and cold season on the northwestern TP, and the glacier mass loss is potentially an important contributor to the dramatic lake level rise in this region (Lei et al., 2017). The increased evaporation from large lakes, soil moisture, the active layer of permafrost, snowmelt and glacier runoff could increase the ratio of local moisture in precipitation, hence increase the d excess values (Bowen et al., 2012; Froehlich et al., 2008; Xu et al., 2011). The TP has been greening in recent decades under the climate change (Zhang et al., 2013; Zhu et al., 2016) with enhanced evapotranspiration in the past three decades (Shen et al., 2015). The d excess has similar values for plant-transpired vapor and evaporated land surface moisture. It has been suggested that transpiration is by far the largest water flux from Earth's continents, and the contributing fraction of transpiration to local precipitation is much larger than evaporation (Jasechko et al., 2013). Therefore, the greening of the TP can also contribute to more local moisture content in precipitation on the northwestern TP.

Finally, local moisture recycling could also be enhanced by increase of soil moisture in the TP. Some recent studies suggest that soil is becoming wetter in the arid and semiarid regions of the western TP in recent decades, which is linked to an increase of precipitation recycling (Hua et al., 2016; van der Velde et al., 2014). The increasing soil moisture would increase the fluxes of heat and vapor originated from the land surface (Tuttle & Salvucci, 2016), thus altering the d excess in local precipitation. The increasing evaporation and soil moisture could serve to increase recycled precipitation and supply for regional precipitation.

6. Conclusions

In this study, we calculated the contribution of local moisture recycling to precipitation on the northwestern TP during the past decades using the $\delta^{18}O$, δD, and d excess records in the ice cores from Chongce and Zangser Kangri. The estimated local moisture contribution shows large interannual variability during the past decades. Temporally, the contribution of local moisture is relatively low from 1960s to the end of 1980s but has intensified since 1990s. This enhanced moisture recycling may be caused by regional climatic and environmental changes. First, the increase of temperature and precipitation lead to enhanced evaporation, contributing to more local moisture in the atmosphere. Second, the changes in land surface condition, such as the increase of vegetation cover, glacier melt, and lake surfaces, could also lead to increased soil moisture and evapotranspiration from land surfaces. Based on this study, we suggest that the interaction between atmosphere and land surface should be adequately taken into account in the model, especially for the TP region with complex surface types. Moreover, in present study, the absolute values of local moisture recycling fraction evaluated for the northwestern TP may be rough, due to lack of observations and the uncertainties in the model. Further efforts are needed to provide a more accurate estimation of local moisture recycling over the northwestern TP, as well as other parts of the TP.

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References

Adler, R. F., Huffman, G. J., Chang, A., Ferraro, R., Xie, P.-P., Janowiak, J., … Nelkin, E. (2003). The version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979-Present). *Journal of Hydrometeorology*, *4*(6), 1147–1167. https://doi.org/10.1175/1525-7541(2003)004%3C1147:TVGPCP%3E2.0.CO;2

Aemisegger, F., Pfahl, S., Sodemann, H., Lehner, I., Seneviratne, S. I., & Wernli, H. (2014). Deuterium excess as a proxy for continental moisture recycling and plant transpiration. *Atmospheric Chemistry and Physics*, *14*(8), 4029–4054. https://doi.org/10.5194/acp-14-4029-2014

Alsabti, K., Ranka, S., & Singh, V. (1997). An efficient k-means clustering algorithm. *Electrical Engineering and Computer Science*, *43*. Retrieved from https://surface.syr.edu/eecs/43

An, W., Hou, S., Zhang, W., Wang, Y., Liu, Y., Wu, S., & Pang, H. (2016). Significant recent warming over the northern Tibetan Plateau from ice core δ18O records. *Climate of the Past*, *12*(2), 201–211. https://doi.org/10.5194/cp-12-201-2016

An, W., Hou, S., Zhang, W., Wu, S., Xu, H., Pang, H., … Liu, Y. (2016). Possible recent warming hiatus on the northwestern Tibetan Plateau derived from ice core records. *Scientific Reports*, *6*(1), 32813. https://doi.org/10.1038/srep32813

Bershaw, J., Penny, S. M., & Garzione, C. N. (2012). Stable isotopes of modern water across the Himalaya and eastern Tibetan Plateau: Implications for estimates of paleoelevation and paleoclimate. *Journal of Geophysical Research*, *117*, D02110. https://doi.org/10.1029/2011JD016132

Bothe, O., Fraedrich, K., & Zhu, X. (2010). The large-scale circulations and summer drought and wetness on the Tibetan Plateau. *International Journal of Climatology*, *31*, 832–846. https://doi.org/10.1002/joc.2124

Bowen, G. J., Kennedy, C. D., Henne, P. D., & Zhang, T. (2012). Footprint of recycled water subsidies downwind of Lake Michigan. *Ecosphere*, *3*, art53. https://doi.org/10.1890/ES12-00062.1

Chen, B., Xu, X., Yang, S., & Zhang, W. (2012). On the origin and destination of atmospheric moisture and air mass over the Tibetan Plateau. *Theoretical and Applied Climatology*, *110*, 423–435. https://doi.org/10.1007/s00704-012-0641-y

Collins, W. D., Rasch, P. J., Boville, B. A., Hack, J. J., McCaa, J. R., Williamson, D. L., … Zhang, M. (2006). The formulation and atmospheric simulation of the Community Atmosphere Model version 3 (CAM3). *Journal of Climate*, *19*, 2144–2161. https://doi.org/10.1175/JCLI3760.1

Cui, B. L., & Li, X. Y. (2015). Stable isotopes reveal sources of precipitation in the Qinghai Lake Basin of the northeastern Tibetan Plateau. *Science of the Total Environment*, *527-528*, 26–37. https://doi.org/10.1016/j.scitotenv.2015.04.105

Curio, J., Maussion, F., & Scherer, D. (2015). A 12-year high-resolution climatology of atmospheric water transport over the Tibetan Plateau. *Earth System Dynamics*, *6*(1), 109–124. https://doi.org/10.5194/esd-6-109-2015

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., … Vitart, F. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*, 553–597. https://doi.org/10.1002/Qj.828

Feng, L., & Zhou, T. (2012). Water vapor transport for summer precipitation over the Tibetan Plateau: Multidata set analysis. *Journal of Geophysical Research*, *117*, D20114. https://doi.org/10.1029/2011JD017012

Froehlich, K., Gibson, J. J., & Aggarwal, P. (2002). *Deuterium Excess in Precipitation and its Climatological Significance*. Ontario, Canada: International Atomic Energy Agency.

Froehlich, K., Kralik, M., Papesch, W., Rank, D., Scheifinger, H., & Stichler, W. (2008). Deuterium excess in precipitation of Alpine regions-moisture recycling. *Isotopes in Environmental and Health Studies*, *44*, 61–70. https://doi.org/10.1080/10256010801887208

Gao, Y., Lan, C., & Zhang, Y. (2014). Changes in moisture flux over the Tibetan Plateau during 1979–2011 and possible mechanisms. *Journal of Climate*, *27*(5), 1876–1893. https://doi.org/10.1175/JCLI-D-13-00321.1

Gat, J. R., Bowser, C., & Kendall, C. (1994). The contribution of evaporation from the Great Lakes to the continental atmosphere: Estimate based on stable isotope data. *Geophysical Research Letters*, *21*(7), 557–560. https://doi.org/10.1029/94GL00069

Gat, J. R., & Matsui, E. (1991). Atmospheric water-balance in the Amazon Basin—An isotopic evapotranspiration model. *Journal of Geophysical Research*, *96*(D7), 13,179–13,188. https://doi.org/10.1029/91JD00054

Gibson, J. J., Birks, S. J., & Edwards, T. W. D. (2008). Global prediction of δ_A and δ^2H-$\delta^{18}O$ evaporation slopes for lakes and soil water accounting for seasonality. *Global Biogeochemical Cycles*, *22*, GB2031. https://doi.org/10.1029/2007GB002997

Henderson-Sellers, A., McGuffie, K., Noone, D., & Irannejad, P. (2004). Using stable water isotopes to evaluate basin-scale simulations of surface water budgets. *Journal of Hydrometeorology*, *5*, 805–822. https://doi.org/10.1175/1525-7541(2004)005%3C0805:USWITE%3E2.0.CO;2

Hua, L., Zhong, L., & Ke, Z. (2016). Precipitation recycling and soil–precipitation interaction across the arid and semi-arid regions of China. *International Journal of Climatology*, *36*(11), 3708–3722. https://doi.org/10.1002/joc.4586

Immerzeel, W. W., Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the Asian water towers. *Science*, *328*, 1382–1385. https://doi.org/10.1126/science.1183188

Jasechko, S., Sharp, Z. D., Gibson, J. J., Birks, S. J., Yi, Y., & Fawcett, P. J. (2013). Terrestrial water fluxes dominated by transpiration. *Nature*, *496*(7445), 347–350. https://doi.org/10.1038/nature11983

Joswiak, D. R., Yao, T., Wu, G., Tian, L., & Xu, B. (2013). Ice-core evidence of westerly and monsoon moisture contributions in the central Tibetan Plateau. *Journal of Glaciology*, *59*(213), 56–66. https://doi.org/10.3189/2013JoG12J035

Kong, Y. L., Pang, Z. H., & Froehlich, K. (2013). Quantifying recycledmoisture fraction in precip itation of an arid region using deuterium excess. *Tellus B*, *65*(1), 19,251. https://doi.org/10.3402/tellusb.v65i0.19251

Kreutz, K. J., Wake, C. P., Aizen, V. B., Cecil, L. D., & Synal, H. A. (2003). Seasonal deuterium excess in a Tien Shan ice core: Influence of moisture transport and recycling in Central Asia. *Geophysical Research Letters*, *30*(18), 1922. https://doi.org/10.1029/2003GL017896

Kurita, N., & Yamada, H. (2008). The role of local moisture recycling evaluated using stable isotope data from over the middle of the Tibetan Plateau during the monsoon season. *Journal of Hydrometeorology*, *9*, 760–775. https://doi.org/10.1175/2007JHM945.1

Lei, Y., Yao, T., Yang, K., Sheng, Y., Kleinherenbrink, M., Yi, S., … Zhang, G. (2017). Lake seasonality across the Tibetan Plateau and their varying relationship with regional mass changes and local hydrology. *Geophysical Research Letters*, *44*(2), 892–900. https://doi.org/10.1002/2016GL072062

Li, J., Sheng, Y., Luo, J., & Shen, Z. (2011). Remotely sensed mapping of inland lake area changes in the Tibetan Plateau. *Journal of Lake Science*, *23*(3), 311–320. https://doi.org/10.18307/2011.0301

Li, W., Zhao, L., Wu, X., Zhao, Y., Fang, H., & Shi, W. (2015). Distribution of soils and landform relationships in the permafrost regions of Qinghai-Xizang (Tibetan) Plateau. *Chinese Science Bulletin*, *60*, 1–2226. https://doi.org/10.1097/SS.0000000000000075

Li, Y., Zeng, Z., Zhao, L., & Piao, S. (2015). Spatial patterns of climatological temperature lapse rate in mainland China: A multi–time scale investigation. *Journal of Geophysical Research: Atmospheres*, *120*, 2661–2675. https://doi.org/10.1002/2014JD022978

Liu, Z. F., Tian, L. D., Yao, T. D., & Yu, W. S. (2008). Seasonal deuterium excess in Nagqu precipitation: Influence of moisture transport and recycling in the middle of Tibetan Plateau. *Environmental Geology*, *55*, 1501–1506. https://doi.org/10.1007/s00254-007-1100-4

Lu, N., Qin, J., Gao, Y., Yang, K., Trenberth, K. E., Gehne, M., & Zhu, Y. (2014). Trends and variability in atmospheric precipitable water over the Tibetan Plateau for 2000–2010. *International Journal of Climatology*, *35*(7), 1394–1404. https://doi.org/10.1002/joc.4064

Majoube, M. (1971). Fractionnement en oxygene-18 et en deuteriumentre l'eau et sa vapeur. *The Journal of Chemical Physics*, *197*, 1423–1436.

Merlivat, L., & Jouzel, J. (1979). Global climatic interpretation of the deuterium−oxygen 18 relationship for precipitation. *Journal of Geophysical Research*, *84*(C8), 5029–5033. https://doi.org/10.1029/JC084iC08p05029

Pang, H. X., Hou, S., Kaspari, S., Mayewski, P., Introne, D., Masson-Delmotte, V., … Qin, D. (2012). Atmospheric circulation change in the central Himalayas indicated by a high-resolution ice core deuterium excess record. *Climate Research*, *53*, 1–12. https://doi.org/10.3354/cr01090

Pausata, F. S. R., Battisti, D. S., Nisancioglu, K. H., & Bitz, C. M. (2011). Chinese stalagmite $\delta^{18}O$ controlled by changes in the Indian monsoon during a simulated Heinrich event. *Nature Geoscience*, *4*, 474–480. https://doi.org/10.1038/ngeo1169

Pekel, J., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, *540*(7633), 418–422. https://doi.org/10.1038/nature20584

Pfahl, S., & Sodemann, H. (2014). What controls deuterium excess in global precipitation? *Climate of the Past*, *10*(2), 771–781. https://doi.org/10.5194/cp-10-771-2014

Qin, J., Yang, K., Liang, S., & Guo, X. (2009). The altitudinal dependence of recent rapid warming over the Tibetan Plateau. *Climatic Change*, *97*, 321–327. https://doi.org/10.1007/s10584-009-9733-9

Rayner, N., Parker, D. E., Horton, E., Folland, C., Alexander, L., Rowell, D., … Kaplan, A. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research*, *108*(D14), 4407. https://doi.org/10.1029/2002JD002670

Salih, A. A. M., Zhang, Q., Pausata, F. S. R., & Tjernström, M. (2016). Sources of Sahelian-Sudan moisture: Insights from a moisture-tracing atmospheric model. *Journal of Geophysical Research: Atmospheres*, *121*, 7819–7832. https://doi.org/10.1002/2015JD024575

Shen, M., Piao, S., Jeong, S. J., Zhou, L., Zeng, Z., Ciais, P., … Yao, T. (2015). Evaporative cooling over the Tibetan Plateau induced by vegetation growth. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(30), 9299–9304. https://doi.org/10.1073/pnas.1504418112

Shi, Y., Li, S., Ye, B., Liu, C., & Wang, Z. (2008). *Concise Glacier Inventory of China* [in Chinese]. Shanghai, China: Shanghai Popular Science Press.

Steen-Larsen, H. C., Johnsen, S. J., Masson-Delmotte, V., Stenni, B., Risi, C., Sodemann, H., … White, J. W. C. (2013). Continuous monitoring of summer surface water vapor isotopic composition above the Greenland Ice Sheet. *Atmospheric Chemistry and Physics*, *13*(9), 4815–4828. https://doi.org/10.5194/acp-13-4815-2013

Stewart, M. K. (1975). Stable isotope fractionation due to evaporation and isotopic exchange of falling water drops: Applications to atmospheric processes and evaporation of lakes. *Journal of Geophysical Research*, *80*(9), 1133–1146. https://doi.org/10.1029/JC080i009p01133

Sturm, C., Zhang, Q., & Noone, D. (2010). An introduction to stable water isotopes in climatemodels: Benefits of forward proxymodelling for paleoclimatology. *Climate of the Past*, *6*, 115–129. https://doi.org/10.5194/cp-6-115-2010

Tian, L., Yao, T., Sun, W., & Jouzel, J. (2001). Relationship between δD and δ^{18}O in precipitation on north and south of the Tibetan Plateau and moisture recycling. *Science in China Series D*, *44*(9), 789–796. https://doi.org/10.1007/BF02907091

Tian, L., Yao, T., White, J. W. C., Yu, W. S., & Wang, N. (2005). Westerly moisture transport to the middle of Himalayas revealed from the high deuterium excess. *Chinese Science Bulletin*, *50*, 1026–1030. https://doi.org/10.1360/04wd0030

Tuttle, S., & Salvucci, G. (2016). Empirical evidence of contrasting soil moisture–precipitation feedbacks across the United States. *Science*, *352*(6287), 825–828. https://doi.org/10.1126/science.aaa7185

van der Ent, R. J. (2009), A new perspective on continental moisture recycling, MSc thesis, Water Management, Delft University of Technology, Delft.

van der Velde, R., Salama, M. S., Pellarin, T., Ofwono, M., Ma, Y., & Su, Z. (2014). Long term soil moisture mapping over the Tibetan plateau using Special Sensor Microwave/Imager. *Hydrology and Earth System Sciences*, *18*(4), 1323–1337. https://doi.org/10.5194/hess-18-1323-2014

Vuille, M., Werner, M., Bradley, R. S., & Keimig, F. (2005). Stable isotopes in precipitation in the Asian monsoon region. *Journal of Geophysical Research*, *110*, D23108. https://doi.org/10.1029/2005JD006022

Wang, X., Pang, G., & Yang, M. (2017). Precipitation over the Tibetan Plateau during recent decades: A review based on observations and simulations. *International Journal of Climatology*. https://doi.org/10.1002/joc.5246

Watanabe, T., & Yamazaki, K. (2012). Influence of the anticyclonic anomaly in the subtropical jet over the western Tibetan Plateau on the intraseasonal variability of the summer Asian monsoon in early summer. *Journal of Climate*, *25*, 1291–1303. https://doi.org/10.1175/JCLI-D-11-00036.1

Wu, H., Li, X., Li, J., Jiang, Z., Li, G., & Liu, L. (2015). Evaporative enrichment of stable isotopes (δ^{18}O and δD) in lake water and the relation to lake-level change of Lake Qinghai, Northeast Tibetan Plateau of China. *Journal of Arid Land*, *7*(5), 623–635. https://doi.org/10.1007/s40333-015-0048-6

Wu, H., Yang, K., Niu, X., & Chen, Y. (2015). The role of cloud height and warming in the decadal weakening of atmospheric heat source over the Tibetan Plateau. *Science in China Series D*, *58*(3), 395–403. https://doi.org/10.1007/s11430-014-4973-6

Wu, J., & Gao, X. (2013). A gridded daily observation dataset over China and comparison with the other dataset [Chinese with English abstract]. *Chinese Journal of Geophysics*, *56*, 1102–1111.

Wu, Y., Wu, S., Wen, J., Xu, M., & Tan, J. (2015). Changing characteristics of precipitation in China during 1960–2012. *International Journal of Climatology*, *36*(3), 1387–1402. https://doi.org/10.1002/joc.4432

Xu, Y., Kang, S., Zhang, Y., & Zhang, Y. (2011). A method for estimating the contribution of evaporative vapor from Nam Co to local atmospheric vapor based on stable isotopes of water bodies. *Chinese Science Bulletin*, *56*, 1511–1517. https://doi.org/10.1007/s11434-011-4467-2

Yang, K., Wu, H., Qin, J., Lin, C., Tang, W., & Chen, Y. (2014). Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: A review. *Global and Planetary Change*, *112*, 79–91. https://doi.org/10.1016/j.gloplacha.2013.12.001

Yang, K., Ye, B., Zhou, D., Wu, B., Foken, T., Qin, J., & Zhou, Z. (2011). Response of hydrological cycle to recent climate changes in the Tibetan Plateau. *Climatic Change*, *109*, 517–534. https://doi.org/10.1007/s10584-011-0099-4

Yang, M., Yao, T., Gou, X., & Tang, H. (2007). Water recycling between the land surface and atmosphere on the Northern Tibetan Plateau-a case study at flat observation sites. *Arctic, Antarctic, and Alpine Research*, *39*, 694–698. https://doi.org/10.1657/1523-0430(07-509)%5BYANG%5D2.0.CO;2

Yang, W., Ye, D., & Wu, G. (1992). The influence of the Tibetan Plateau on the summer thermal and circulation fields over East Asia I. The humidity on the northwestern Tibetan Plateau in the height of summer [in Chinese]. *Chinese Journal of Atmospheric Sciences*, *16*, 41–51.

Yao, T., Masson-Delmotte, V., Gao, J., Yu, W., Yang, X., Risi, C., … Hou, S. (2013). A review of climatic controls on δ18O in precipitation over the Tibetan Plateau: Observations and simulations. *Reviews of Geophysics*, *51*(4), 525–548. https://doi.org/10.1002/rog.20023

Yao, T. D., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., … Joswiak, D. (2012). Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change*, *2*, 663–667. https://doi.org/10.1038/nclimate1580

Yu, W., Tian, L., Risi, C., Yao, T., Ma, Y., Zhao, H., … Qu, D. (2016). δ^{18}O records in water vapor and an ice core from the eastern Pamir Plateau: Implications for paleoclimate reconstructions. *Earth and Planetary Science Letters*, *456*, 146–156. https://doi.org/10.1016/j.epsl.2016.10.001

Yu, W., Yao, T., Tian, L., Li, Z., Sun, W., & Wang, Y. (2006). Relationships between δ^{18}O in summer precipitation and temperature and moisture trajectories at Muztagata, northwestern China. *Science in China Series D*, *49*(1), 27–35. https://doi.org/10.1007/s11430-004-5097-1

Yu, W., Yao, T., Tian, L., Ma, Y., Kurita, N., Ichiyanagi, K., … Sun, W. (2007). Stable isotope variations in precipitation and moisture trajectories on the northwestern Tibetan Plateau, China. *Arctic, Antarctic, and Alpine Research*, *39*, 688–693. https://doi.org/10.1657/1523-0430(07-511)%5BYU%5D2.0.CO;2

Yuan, F., Sheng, Y., Yao, T., Fan, C., Li, J., Zhao, H., & Lei, Y. (2011). Evaporative enrichment of oxygen-18 and deuterium in lake waters on the Tibetan Plateau. *Journal of Paleolimnology*, *46*(2), 291–307. https://doi.org/10.1007/s10933-011-9540-y

Zhang, C., Tang, Q., & Chen, D. (2017). Recent changes in the moisture source of precipitation over the Tibetan Plateau. *Journal of Climate*, *30*(5), 1807–1819. https://doi.org/10.1175/JCLI-D-15-0842.1

Zhang, G., Yao, T., Xie, H., Kang, S., & Lei, Y. (2013). Increased mass over the Tibetan Plateau: From lakes or glaciers? *Geophysical Research Letters*, *40*(10), 2125–2130. https://doi.org/10.1002/grl.50462

Zhang, G., Zhang, Y., Dong, J., & Xiao, X. (2013). Green-up dates in the Tibetan Plateau have continuously advanced from 1982 to 2011. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(11), 4309–4314. https://doi.org/10.1073/pnas.1210423110

Zhao, H. B., Xu, B. Q., Yao, T. D., Wu, G. J., Lin, S. B., Gao, J., & Wang, M. (2012). Deuterium excess record in a southern Tibetan ice core and its potential climatic implications. *Climate Dynamics*, *38*, 1791–1803. https://doi.org/10.1007/s00382-011-1161-7

Zhu, L., Xie, M., & Wu, Y. (2010). Quantitative analysis of lake area variations and the influence factors from 1971−2004 in the Nam Co basin of the Tibetan Plateau. *Chinese Science Bulletin*, *55*, 1294–1303. https://doi.org/10.1007/s11434-010-0015-8

Zhu, Z., Piao, S., Myneni, R. B., Huang, M., Zeng, Z., Canadell, J. G., … Zeng, N. (2016). Greening of the Earth and its drivers. *Nature Climate Change*, *6*(8), 791–795. https://doi.org/10.1038/nclimate3004