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Comparison of recycled vapor contribution to precipitation in urban vs. rural area—A case study in western China

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While urbanization's strong effect on local precipitation has been widely documented, knowledge of how urbanization affects isotopic composition in precipitation is still lacking. In the present study, deuterium-excess (d-excess) served to quantify the contribution of recycled vapor to precipitation in Chengdu city (China) and a nearby rural area. Precipitation from the urban and rural areas showed no significant difference in $\delta^{18}O$ values ($p > 0.05$). The rural area had significantly higher d-excess (24.29 ± 7.39‰) than the urban (12.71 ± 4.88‰) through the seasons due to higher evapotranspiration flux in the rural area. In summer, however, urban precipitation amount was higher than that of the rural area. Based on d-excess model, the average ratio of recycled vapor was 8.2% in Chengdu, which was lower than in the rural area (36.1%). This highlights the effect of urbanization in decreasing the proportion of vapor from local evapotranspiration contributing to precipitation but blocked much advected moisture. This also implied that precipitation taken in cities were used to represent upwind advected vapor or used as referenced isotopic records for paleoclimate reconstruction based on tree rings or stalagmites sampled in rural area may be erroneous as the effect of urbanization on precipitation vapor. Further studies are needed to explore the effect of urbanization on vapor source of precipitation under different climatic zones.

KEYWORDS
hydrogen and oxygen stable isotopes, recycled vapor ratio, evapotranspiration, urbanization, precipitation

Introduction

With the development of global urbanization, the variation of urban hydrological processes has become increasingly prominent, and the mechanism of urban water cycle has undergone profound changes, resulting in increasing water risks and water environmental problems, such as frequently happened storm, shortage of water resources and deterioration of water quality (Mrekva et al., 2012; Wang et al., 2014; Sang and Yang, 2017). These disasters have caused huge economic losses and threaten the safety of infrastructure and human lives (Yang et al., 2021). Among multiple effects of urbanization on the natural environment, the greatest ones are changes to surface air temperature and precipitation (Ren et al., 2008; Hamdi et al., 2009; Song et al., 2014). However, exploring how urbanization induces changes in rainfall patterns is difficult, due to the heterogeneity of spatiotemporal distribution of rainfall, a lack of direct observations of precipitation vapor source and the unrelenting progress of urbanization (Liu and Niyogi, 2019).

Water vapor contributing to precipitation consists of advected vapor from the ocean and recycled vapor from the continent (Gimeno et al., 2020). The accelerated climate change has imposed great impacts on the contribution of vapor sources to precipitation. Under the trend of global warming, recycled vapor has played an increasingly important role in the formation of precipitation due to the increase in surface evapotranspiration capacity (Singh et al., 2017; Ampuero et al., 2020; Cui et al., 2022). However, quantifying the effect of urbanization on the precipitation composition is still a challenge in hydrological studies especially through field observation.

Hydrogen and oxygen stable isotopes, which are widely used tools for hydrological tracing, are closely associated with the atmospheric recycling pattern and water source of precipitation. For example, satellite-derived estimation identified that continental evapotranspiration are slightly isotope-depleted compared to oceanic evaporation, leading to decreased D/H isotope in summer precipitation at a global scale (Good et al., 2015). However, Cluett et al. (2021) found that increases in local evaporation will promote the enrichment of D/H isotope in precipitation. Isotope-enabled climate models also demonstrated that transpiration yielded more isotope-enriched atmospheric vapor than ocean evaporation, suggesting continental evapotranspiration would increase heavy isotopes contents in summer precipitation at many sites (Risi et al., 2013). These inconsistent findings reflect that under the influences of global warming and human activities such as urbanization, the variation patterns of isotopes in precipitation are complex and uncertain (Masson-Delmotte et al., 2021). The precipitation isotopes record the information of climate change and human activities' effects. Consequently, a better understanding of these effects on precipitation isotopes could improve our knowledge on the information contained in precipitation isotope proxies such as tree ring or stalagmite. In addition, sampling of precipitation for isotopic analysis has mostly been carried out in cities, particularly megacities (IAEA, 2014). These isotopic records are often used as references for paleoclimatic reconstruction by isotopic values measured in tree rings or stalagmites, which are primarily located in depopulated zones (e.g., mountains or rural areas). A systematic comparison of water vapor and isotopic composition in precipitation between urban and rural areas will be helpful in answering questions regarding the effects of urbanization on precipitation patterns, and the possible uncertainties of precipitation isotope-based paleoclimate reconstruction brought by sampling locations.

Several studies have analyzed the amount of recycled vapor in precipitation using simple bulk methods or conceptualizations of the hydrological cycle (Van Der Ent et al., 2014; Baker and Spracklen, 2022). However, these methods provided only a rough estimate of vapor dynamics over a large region, and are subject to several assumptions (Van Der Ent et al., 2014). Hydrogen and oxygen isotopes in water (i.e., δ^2H and δ^{18}O, respectively) and the derivative proxy of d-excess [$d = \delta^2H - 8\ \delta^{18}O$ (‰)], have been shown to be useful indicators for the variability of moisture recycling (Dansgaard, 1964). The d-excess depends strictly on environmental factors in the vapor source area, remains stable during the transport process, and is influenced by the sub-cloud secondary evaporation and recycled moisture (Pang et al., 2011; Wang S. J. et al., 2016). Therefore, this proxy can be used to indicate the meteorological conditions in the oceanic vapor source and reflect the degree of isotopic non-equilibrium fractionation during landing process (Froehlich et al., 2004). However, quite few studies were conducted to compare the isotopic composition and d-excess between adjacent urban and rural areas, limiting the exploring of water vapor sources and local atmospheric cycling processes. Assuming that local precipitation consists of land surface evaporated (recycled) vapor and advected vapor, Peng et al. (2005) proposed a d-excess-based model for estimating the proportion of recycled vapor in precipitation, whose accuracy in calculating the vapor source was further validated by Griffis et al. (2016).

In Sichuan Basin of southwest China, the precipitation is mainly sourced from the South China Sea, Western Pacific and Indian Ocean, driven by the monsoon alternation (Xia et al., 2020). Previous study has shown that this region presents complex temporal isotopic characteristics, associated with both water vapor source and environmental factors (Xia et al., 2020). In this study, this model was employed to determine the vapor composition of precipitation sampled in the city of Chengdu and a nearby rural area, based on the hypothesis that urban and rural areas would have the same recycled moisture ratio in their monthly precipitation. The findings will help improve the understanding of the impact of urban development on the atmospheric circulation and provide insights for further optimization of isotope-based paleoclimate reconstruction.

Materials and methods

Locations of the study sites

Chengdu (102°54′–104°53′E, 30°05–31°26′N), the provincial capital of Sichuan Province, is the most important city in western China in terms of economic activity and tourism. The population density increases greatly and economy grows fastly since the 1980s, associated with rapid urbanization. The Chengdu sampling site was situated at Sichuan University (30.63°N, 104.08°E). The corresponding rural area was monitored in the village of Jieliu, at an experimental station of the Chinese Academy of Sciences (31.26°N, 105.45°E), some 148 km away from the Chengdu site (**Figure 1**). Chengdu site is located in the hinterland of Chengdu plain where the terrain is flat. Jieliu site is located in Yanting County, an area whose topography is medium to deep hills, where multi-stage terraces form due to the horizontal sand mudstone interlayers. Both urban and rural areas belong to subtropical monsoon climate zone, with distinct dry and rainy seasons. During the rainy season (May to October), they are mainly controlled by the southeast monsoon from the northwest Pacific Ocean and the southwest monsoon from the Indian Ocean, with concentrated precipitation and high temperature; in the dry season (November to May of the following year), they are controlled by the northwest monsoon from Siberia, with little precipitation and low temperature. In Chengdu City, the annual mean precipitation is about 1000 mm and the mean temperature is 16°C. In Yanting County, the annual mean precipitation is 826 mm and the mean temperature is 17.3°C. In both sites, precipitation distributes unevenly through the year. About 70 % of the total amount happens in summer months. The total population of Chengdu City reaches 21 million and that of Yanting County is only 0.38 million. The main types of land uses in the urban and rural sites are urban-and-industrial land and forest land, respectively.

Quantification of recycled moisture proportion

Monthly d-excess was calculated by weighting the quantity of precipitation for each precipitation event:

$$d = \frac{\sum_{i=1}^{i=n} d_i \cdot P_i}{\sum_{i=1}^{i=n} P_i} \quad (1)$$

where,

d is the monthly d-excess,

d_i is the d-excess of i^{th} precipitation event during the month,

i is the number of the precipitation event considered,

n is the total number of precipitation events considered, and P_i is the amount of precipitation received during the month's i^{th} event.

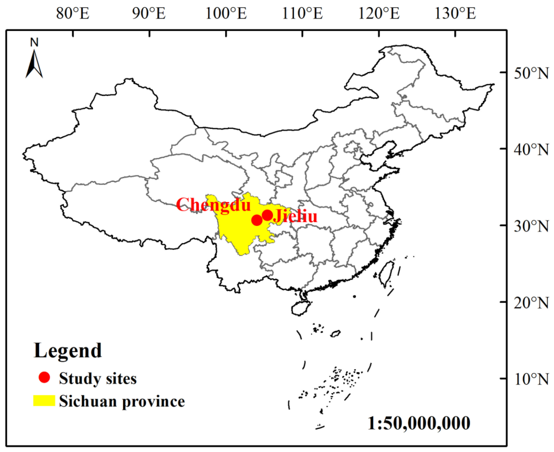

FIGURE 1
The study locations of Chengdu (urban) and Jieliu village (rural) in western China.

The d-excess model used for the recycled moisture proportion could be expressed as follows (Zhang et al., 2021):

$$d_c = (d_e \cdot f_e) + (d_t \cdot f_t) + (d_{ad} \cdot f_{ad}) \quad (2)$$

$$f_e = \frac{1}{m+1} \cdot f_{re} \quad (3)$$

$$f_t = \frac{1}{m+1} \cdot f_{re} \quad (4)$$

$$m = \frac{f_t}{f_e} \quad (5)$$

where,

d_c, d_e, d_t, and d_{ad} represent the d-excess values of precipitation at the cloud base, in evaporation vapor, in transpiration vapor, and in advected vapor, respectively,

f_{ad} f_t and f_e are the proportional contributions of advected vapor, transpiration vapor and evaporation vapor to overall precipitation, respectively,

f_{re} is the recycling ratio of transpired and evaporated vapor within the total precipitation,

m in the model was assumed to be equivalent to the ratio of monthly transpiration flux (E_t) to monthly evaporation flux (E_e), which were derived from the GLEAM model output of the v3.5b dataset (Martens et al., 2017).

Monthly E_t, E_e and m values in Chengdu and Jieliu are shown in **Supplementary material**.

Based on Eqs 1–5, the fraction of recycled ratio in local precipitation can be obtained as (Zhang et al., 2021):

$$f_{re} = \frac{d_c - d_{ad}}{\frac{d_e + (m \cdot d_t)}{m+1} - d_{ad}} \quad (6)$$

The d-excess values of the advected vapor (d_{ad}) at each study area was assessed from precipitable water simulated by Isotope Reanalysis data version 2 (IsoGSM2) (Yoshimura et al., 2008).

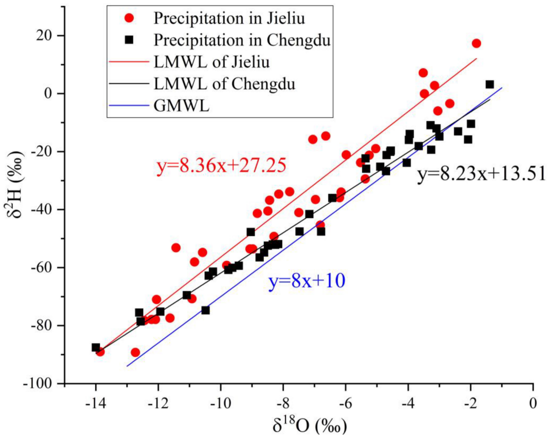

FIGURE 2
Comparison of the local meteoric water lines (LMWLs) of Chengdu and Jieliu, along with the global meteoric water line (GMWL).

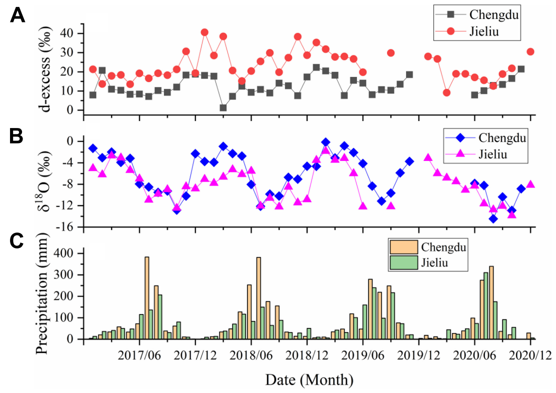

FIGURE 3
Temporal variations of **(A)** d-excess, **(B)** δ^{18}O, **(C)** precipitation amount. In Jieliu there was no isotopic precipitation sampling in July, August, October to December 2019 and in November 2020. Isotopic data for precipitation were not available from December 2019 to May 2020, and in December 2020 in Chengdu.

We assumed there to be no difference between the advected moisture for Chengdu and Jieliu because of the relatively small distance between them. The d_e can be calculated using the Craig-Gordon model (Craig and Gordon, 1965) (see **Supplementary material**). Assuming that the initial isotopic composition of the precipitation at the cloud base is in isotopic equilibrium with the surrounding water vapor, d_c can be calculated by the model proposed by Froehlich et al. (2008) (see **Supplementary material**). The d_t depends on the value of weighted multi-year precipitation, assuming there is no isotopic fractionation during plant uptake and transpiration at the specific study sites (Dawson and Ehleringer, 1991).

An unpaired statistical *t*-test was used to compare the difference of variables between the urban and rural areas by R software (R Core Development Team, 2020).

Results and discussion

Isotopic compositions of precipitation at urban and rural sites

Figure 2 compares local meteoric water lines (LMWLs) for Chengdu and Jieliu, along with the global meteoric water line (GMWL). The δ^2H/δ^{18}O slopes of the two sites were similar and both were slightly greater than that of the GMWL. The intercept value of the LMWL of Jieliu was greater than that of the GMWL, suggesting that Jieliu was strongly affected by recycled moisture over the entire year. The intercept value of the LMWL of Chengdu was close to that of GMWL, suggesting that the proportion of recycled moisture in the precipitation was small (Trenberth et al., 2003).

The d-excess, δ^{18}O and precipitation amount were compared between the urban and rural sites from January 2017 to December 2020 (**Figure 3**). The d-excess in Chengdu varied substantially (1.23—22.28‰, with an average value of 12.71 ± 4.88 ‰. This mean value was close to the global average of 10‰. The d-excess in Jieliu precipitation ranged from 9.13 to 40.62‰, with an average value of 24.29 ± 7.39‰. The d-excess at the rural site showed significantly greater values than those found in the urban area ($p \leq 0.05$).

The δ^{18}O values at Chengdu ranged from −14.45 to −0.15‰ with an average value of −6.40 ± 3.86‰ during the period of observation. At Jieliu, precipitation δ^{18}O values ranged from −13.85 to −1.81‰ with an average value of −7.96 ± 3.30‰. Precipitation δ^{18}O at the rural site showed a smaller range and more depleted values compared to the city, although they were not significantly different ($p = 0.051$).

In the summer months, precipitation in the city was usually greater than in rural areas (**Figure 3C**). The mean value of monthly precipitation amounts throughout the 4-year observation period in Chengdu was 94.88 ± 137.59 mm, which was greater than the 65.14 ± 65.81 mm in Jieliu although the difference was not significant ($p > 0.05$). Simultaneously, the variation of the amount of precipitation in the city was also higher than that in the village. While precipitation amounts over the study period were not significantly higher in Chengdu city than in Jieliu village across all seasons, monthly precipitation amounts in spring, autumn and winter were greater (though not significantly so) in the rural area than in the urban area. In other areas across the world, higher precipitation amount happens in urban area than in the rural area has also been widely reported (Huff and Changnon, 1972; Rao, 1980; Çiçek and Turkoglu, 2005). Such pattern exists because buildings in urban area block the continuous landward penetration of a regional climatic rainband. This change in rainfall variation is associated with a slowing of the penetration of wind with rain by urban friction which actually lead to the enhanced convergence over the city (Li et al., 2021).

The d-excess at the urban site clearly showed much lower values compared to those at the rural site. During the water evaporation process, the ratio between ^{18}O and ^{2}H in the remaining water become higher compared with that under equilibrium condition due to the dynamic isotope fractionation, leading to decreased d-excess (<10‰) (Froehlich et al., 2008). Conversely, following the mass balance, d-excess of evaporated vapor would increase, and the precipitation formed by this vapor would also be characterized by a higher d-excess value (larger than 10‰). A relatively high d-excess commonly indicates the involvement of a large proportion of recycled vapor in local precipitation (Froehlich et al., 2008; Pang et al., 2011).

Comparing the recycling ratio in urban and rural areas

In this study, the d-excess of advected moisture in Chengdu and Jieliu was obtained by modeled results from IsoGSM2. However, this dataset failed to calculate the recycled moisture in Chengdu as most d-excess in precipitation (12.71 ± 4.88‰) was lower than the advected moisture derived from the IsoGSM2 model (16.76 ± 1.80‰). As the evaporated water presented higher d-excess than the remaining water, the d-excess of precipitation did not plot inside the triangle area formed by the d-excess of three end-members including advected, evaporated and transpired vapor.

In this study, we tried to use the global average d-excess value of 10‰ instead of the d-excess of modeled advected moisture. A comparison of monthly fluctuations of the recycling ratio (f_{re}) including the fraction of evaporation (f_{ev}) is shown in **Figure 4**. The f_{re} varied greatly with time throughout the entire year in both Chengdu and Jieliu. In Chengdu, the f_{re} ranged from 0 to 51.8% with an average annual value of 8.2%, while f_{ev} showed a narrower range, from 0 to 16.9% with a mean of 4.05%. In Jieliu, f_{re} ranged from 0 to 97.4% with an average annual value of 36.1%, while f_{ev} ranged from 0 to 28.5% with a mean value of 12.3%. The contribution of recycled vapor to precipitation in Chengdu was lower than that in Jieliu in terms of less transpirational and evaporative sources. In previous studies, it was widely reported that the evapotranspiration strength is closely related to urban development and would be reduced in urban areas, by water balance, remote sensing and meteorological methods (Dow and DeWalle, 2000; Wang C. et al., 2016; Jiang and Weng, 2017). Our results verified this kind of urban climatic change by employing an isotope-based model to conduct rural-urban vapor source comparison in southwest China. The low proportion of recycled vapor in urban precipitation can be explained by the reduced contribution from evapotranspiration sources caused by the decreased vegetation coverage and construction of urban facilities. On one hand, the decreased vegetation coverage will reduce the transpiration of plants. On the other hand, the rapid drainage process and impervious surface (e.g., cement pavements and buildings) will have an impact on the spatial and temporal changes of surface evaporation in urban areas. The construction of urban drainage systems and the increased area of impervious or weakly pervious surface have improved the efficiency of rainwater drainage, and evaporation can only occurs in a short period after precipitation. It is reported in other study areas that light and moderate rainfall is lower in cities than in areas with high vegetation cover (Yuan et al., 2017), which agrees with the results of vapor sources comparison in our study. In both Chengdu and Jieliu, the ratios of recycled vapor were characterized by relatively low values in summer and autumn and high values in winter and spring. This was consistent with the reported values in other regions using this d-excess-based method (Wang S. et al., 2016; Zhu et al., 2019). Wang S. et al. (2016) found that f_{re} of large oases in Urumqi was much higher than that of small oases (15.2 vs. <5%). Using the same method, Zhu et al. (2019) concluded that in the monsoon marginal zone, the f_{re} of an oasis (28%) was significantly higher than that of mountain areas (17%) and desert areas (15%). This phenomenon was attributed to the high vegetation cover in the oases, which added significant amounts of evaporated (e.g., interception by the canopy) and transpired vapor to local precipitation.

Our study reveals the difference of recycled vapor contribution in local precipitation between urban and rural areas, which derived from significant difference in isotopic composition and calculated indicators such as d-excess. Currently, neighboring stations from global network of isotopes in precipitation (GNIP) have often been used as references and/or in calculations in many studies involved in $\delta^{18}O$ or $\delta^{2}H$ at local or regional scales (Hobson et al., 2019; Zhang et al., 2021). However, as precipitation samples for most GNIP stations are taken in cities, these precipitation-isotope-related variables, especially d-excess, should be used with caution in isotopic studies (e.g., paleoclimate reconstruction by tree rings or stalagmites) conducted in rural or depopulated areas, as indicated in the present study.

There's limitation in the estimation of recycled vapor ratios in the present study. The assumption that d-excess value of advected vapor is 10‰ might bring some uncertainty to the calculation of recycled vapor ratio in precipitation. Also, this value cannot reflect the change of advected moisture. For example, precipitation d-excess over several months was lower than 10‰, which implied that advected vapor with a d-excess lower than 10‰ participated in the precipitation formation. Most previous studies used the calculated d-excess

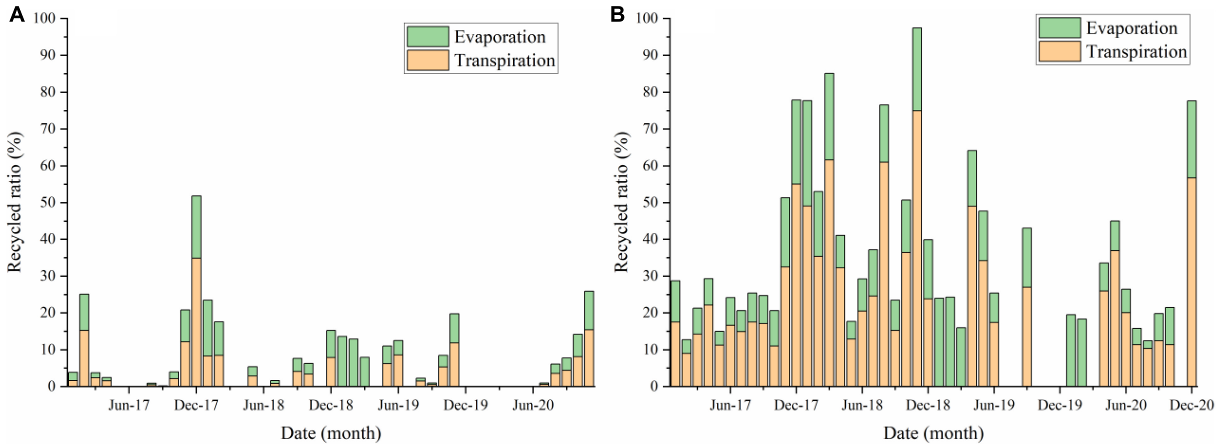

FIGURE 4
Monthly fluctuations of the recycled vapor ratio (f_{re}), including contributions of transpiration and evaporation in **(A)** Chengdu and **(B)** Jieliu. Negative values in Chengdu were set to 0 assuming no recycled vapor in the precipitation.

of precipitation from upwind sites to represent advected vapor (Wang S. J. et al., 2016; Zhang et al., 2021). However, the continuous and long-term records of precipitation isotopes at upwind sites were not available for most cases. For this reason, datasets with records in different periods, such as the widely used GNIP observations during the 1970s and 80s, were usually selected as substitution. This also introduced error for the different study periods. In addition, the precipitation vapor is also from local evaporation and transpiration which may vary following the progress of urbanization. This implied that upwind precipitation isotopes may not represent the actual values of d-excess of advected vapor. Therefore, more accurate measurement or calculation of the d-excess in advected moisture is needed for better usage of the d-excess model and understanding the effects of climate change and human activities on precipitation composition in the future.

Conclusion

Based on the 4-year observation on precipitation isotopes and meteorological variables in Chengdu and Jieliu in southwest China, this study compared the isotopic characteristics between urban and rural areas, and analyzed differences in the contribution of recycled vapor in local precipitation accordingly. Compared with the urban area, $\delta^{18}O$ in precipitation showed lower values and smaller variation range in the rural area, while the d-excess exhibited significant higher values, as well as the intercept of LMWL. Summer precipitation amount showed higher value in urban area than rural one due to the influence of urban land covers on vapor transportation. Fraction of recycled vapor in local precipitation is quantified by d-excess-based model. During dry seasons, it showed higher recycled vapor contribution in precipitation in rural site than that in urban. This indicating that precipitation forms primarily from evapotranspiration in a rural area rather than advected vapor in an urban area. This highlights the effect of urbanization on the source composition of rainfall moisture and precipitation intensity, further resulting in alterations of atmospheric and hydrological cycles in urban areas. Consequently, urbanization is an important driving factor controlling the amount and composition of precipitation. In the further study focusing on the source and transport of water vapor, vapor contributions identified by isotope-based method should be verified in combination with other technologies such as remote sensing inversion or more field monitoring studies. Relationship between the expansion area of urban and precipitation composition should be quantitatively explored by comparison between the precipitation in more urban and rural regions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

PZ: formal analysis, software, methodology, writing-original draft, and writing–review and editing. CX: investigation, formal analysis, and writing–review and editing. GL: supervision and writing–review and editing. JT and MZ: investigation and data curation. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer WM declared a shared affiliation with the authors JT and MZ.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2022.1012071/full#supplementary-material

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