Quaternary International xxx (2015) 1–7

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Relationship between sub-cloud secondary evaporation and stable isotopes in precipitation of Lanzhou and surrounding area

Fenli Chen, Mingjun Zhang*, Shengjie Wang, Qian Ma, Xiaofan Zhu, Lei Dong

College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730070, China

A R T I C L E I N F O

Article history:
Available online xxx

Keywords:
Stable isotope
Secondary evaporation effect
Precipitation
Vapor pressure

A B S T R A C T

Based on the 420 samples of precipitation and related meteorological parameters obtained from the four sampling sites (Yongdeng, Gaolan, Lanzhou and Yuzhong) in Northwest China from April 2011 to February 2013, the influence of sub-cloud secondary evaporation effect on stable isotopes in precipitation was analyzed. Four main factors affecting the secondary evaporation were precipitation, air temperature, water vapor pressure, and relative humidity. The results showed that sub-cloud secondary evaporation had a significant effect on isotopes when the rainfall amount was small, but the correlation was not significant for snowfall or heavy rainfall. As the temperature increased, the secondary evaporation was enhanced. Water vapor pressure greatly impacted the sub-cloud secondary evaporation of the rain, but had less influence on the snow events. Relative humidity showed an influence on d-excess value, as well as the slope and intercept of the δD-δ^{18}O correlation equation of light rainfall, but had a small impact when snow occurred. The estimated secondary evaporation rate was generally lower in winter and higher in summer, and spatially varied depending on locations. During the summer monsoon period (June to September), the secondary evaporation rate was estimated to be between 5.90% and 10.50% for each station with the mean value of 8.30%, and during the winter monsoon period (October to May), the rate was between 3.20% and 5.62%, with the average value of 4.54%.

1. Introduction

Secondary evaporation effect refers to the evaporation process for rain drops falling from the bottom of clouds to the ground. With the evaporation in precipitation process (Dansgaard, 1964), light isotopes are preferentially depleted, and heavy isotope enriched (Miyake et al., 1968; Yapp, 1982; Jouzel, 1986). The raindrops experiencing sub-cloud secondary evaporation usually show the enrichment of δ^{18}O values and reduction of d-excess value (Liu et al., 2008). Additionally, the kinetic isotope effect during below-cloud secondary evaporation is expected to cause a decrease of the slope of the δD-δ^{18}O correlation in precipitation (Dansgaard, 1964; Stewart, 1975). The observed change of the δD-δ^{18}O slope and the d-excess value in precipitation can also be used to assess the sub-cloud secondary evaporation effect (Peng et al., 2007; Kress et al., 2010; Steen-Larsen et al., 2011). Precipitation, air temperature, atmospheric water vapor pressure and relative humidity are the main factors affecting secondary evaporation (Peng et al., 2007; Liu et al., 2008; Meng and Liu, 2010), and the longer duration of falling drops may cause more mass evaporation (Stewart, 1975). Thus, the secondary evaporation effect under clouds must be considered in studies using isotopic approaches (Gat and Matsui, 1991; Gat et al., 1994; Peng et al., 2007; Froehlich et al., 2008; Liu et al., 2008; Meng and Liu, 2010; Peng et al., 2010; Kong et al., 2013).

Lanzhou, the capital city of Gansu Province of China, lies at the junction of the eastern monsoon region, northwest arid region, and the Qinghai-Tibet Plateau. Sub-cloud secondary evaporation has been widely recognized under arid conditions, including the study region in Lanzhou (Zhang et al., 2012; Chen et al., 2013; Ma et al., 2014). However, the internal mechanism between secondary evaporation and stable isotopes, especially the meteorological forcing for the study region, still needs further investigation. Based on precipitation samples and related meteorological parameters in an observation network in Lanzhou city and surrounding area during recent years, the relationship between sub-cloud secondary evaporation and stable isotopes in precipitation was analyzed.

* Corresponding author.
E-mail address: mjzhang2004@163.com (M. Zhang).

http://dx.doi.org/10.1016/j.quaint.2014.12.051

2. Data and method

2.1. Study area

Lanzhou is the capital city of Gansu Province of Northwest China (Fig. 1). According to the long-term climatology (1981–2010) observed at Lanzhou National Basic Meteorological Station (36.05°N, 103.88°E, 1517.2 m), the annual mean precipitation is 293.9 mm, mainly concentrated from June to September, and the observed pan evaporation is 1504.8 mm. The annual average air temperature is 10.4 °C, ranging from −4.5 °C in January to 23.1 °C in July. The relative humidity is 53% on an annual basis, and the annual days of precipitation and snowfall are 70.2 days and 21.9 days, respectively.

2.2. Sample collection and analysis

An observation network was established including four stations in the study region, namely, Yongdeng (36.75°N, 103.25°E, 2118.8 m), Gaolan (36.35°N, 103.93°E, 1668.5 m), Lanzhou (36.10°N, 103.73°E, 1548.0 m) and Yuzhong (35.87°N, 104.15°E, 1874.4 m). Yongdeng, Gaolan, and Lanzhou are located north of the Yellow River, and Yuzhong station is located to the south (Fig. 1). The samples of Lanzhou station were collected at the Northwest Normal University, and the samples from other stations were taken at the national meteorological stations of Yongdeng, Gaolan and Yuzhong.

In order to prevent water evaporation, a funnel was placed inside the rain barrel, and a polyethylene ball was used. After raining, the rain water samples were collected immediately to minimize the influence of evaporation. If precipitation was liquid, the sample was filled into plastic bottles, and then the capped bottles were sealed using tapes. For solid precipitation (snow), the sample was packed into an airtight plastic bag, and then put into a bottle after it melted completely. The surface air temperature, precipitation amount, atmospheric water vapor pressure and relative humidity were recorded at the initial and end time of each precipitation event. All samples were kept frozen.

The sampling period was from April 2011 to February 2013. A total of 482 samples of precipitation were collected, and 420 samples was used in this study due to the absence of meteorological parameters, with 139, 107, 68 and 106 samples in Yongdeng, Gaolan, Lanzhou and Yuzhong station, respectively. All the samples were chemically analyzed in the Geography and Environmental Science College, Northwest Normal University by using a liquid water isotope analyzer (LGR, DLT − 100). Samples were melted at room temperature, before they were analyzed for stable isotopes. Isotope values are expressed as:

$$\delta^{18}O(‰) = \left[R_{sample}/R_{VSMOW} - 1\right] \times 1000 \quad (1)$$

where R_{sample} is the ratio of $^{18}O/^{16}O$ in precipitation, R_{VSMOW} is the ratio of $^{18}O/^{16}O$ in the VSMOW (the Vienna Standard Mean Ocean Water). The measurement precision was 0.2‰ for $\delta^{18}O$ and 0.6‰ for δD, respectively.

3. Results and analysis

Peng et al. (2007) found that under the influence of secondary evaporation, the $\delta^{18}O$ value increases, d-excess value decreases, and the δD-$\delta^{18}O$ slope also decreases. The secondary evaporation is usually considered to be influenced by precipitation, temperature, atmospheric vapor pressure, and relative humidity. The four meteorological parameters were chosen in this study, and the differences between different intervals of each parameter were further discussed.

3.1. Influence of precipitation

Global Meteoric Water Line (GMWL) was the mean value of the world's meteoric water line, and was a worldwide reference for the isotope composition studies. Influenced by the water vapor condensation temperature, water vapor sources and its transmissions as well as seasonality of meteorological factors during precipitation, the slope and intercept of the local meteoric water line (LMWL) are usually different from those of GMWL. According to the event-based precipitation samples in Lanzhou and its

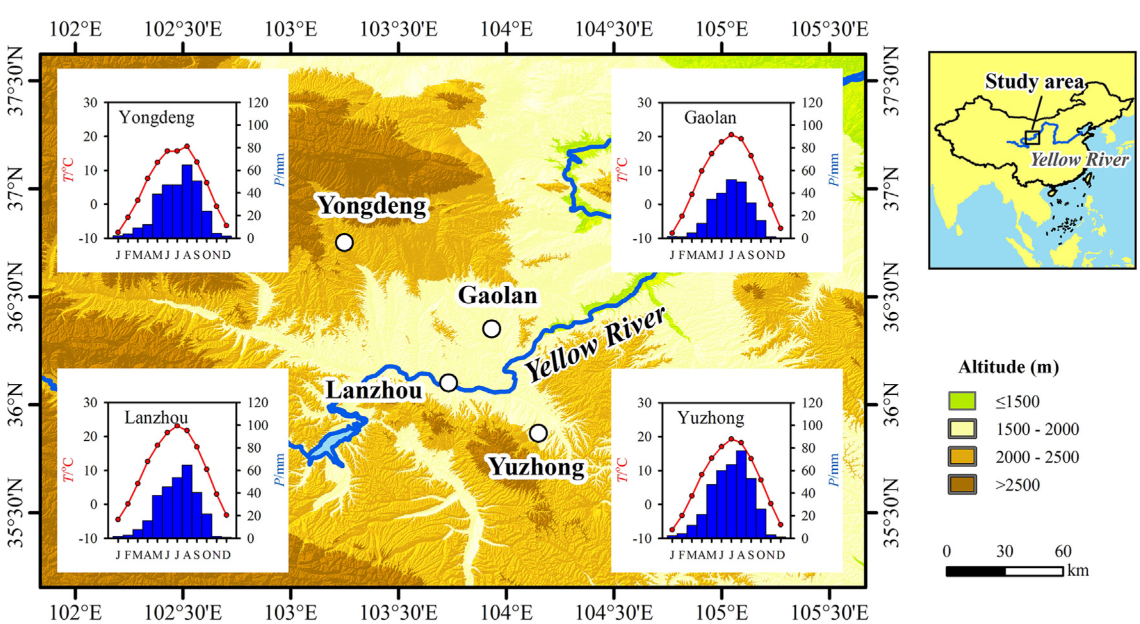

Fig. 1. Location of study area and sampling stations in Lanzhou city and surrounding area. The monthly average air temperature (*T*, lines) and precipitation (*P*, bars) during 1981–2010 for each station are also shown.