ARTICLE IN PRESS

Quaternary International xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Quaternary International

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

Stable isotope composition of precipitation at different elevations in the monsoon marginal zone

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ARTICLE INFO

Keywords:
Qilian mountains
Stable isotopes
Elevation effect
Moisture sources

ABSTRACT

The Qilian Mountains in western China are an important ecological and security barrier and are the primary water source for inland river basins. In this study, we collected precipitation samples and meteorological data from 4 sampling sites at different elevations on the northern slope of the Qilian Mountains from October 2016 to October 2017. The purpose was to analyse spatial and temporal variations of the isotope composition of precipitation and to evaluate the influence of temperature, elevation, monsoon circulation and continuous rainout processes on the measured values. The results show that the isotopic composition exhibit obvious seasonal variations; the higher $\delta^{18}O$ values occur in summer and autumn, and the lower values occur in winter and spring, while the lower *d*-excess values occur in spring and summer and the higher *d*-excess values occur in autumn and winter. Stable isotope values varied with elevation. $\delta^{18}O$ and δD values decreased with increasing elevation, and *d*-excess increased with increasing elevation. The average annual elevation gradient for $\delta^{18}O$ was -0.26‰/100 m, δD was -1.77‰/100 m, and *d*-excess was 3‰/100 m, and the elevation gradient in summer was higher than in winter. The slope and intercept of LMWL increased with increasing elevation. The elevation gradients for slopes and intercepts are 0.07/100 m and 1/100 m, respectively. The temperature effect is most significant below 0 °C. Local moisture recycling and sub-cloud evaporation also play an important role. Moisture sources are mainly controlled by westerly circulation. Influenced by moisture from the Asian monsoon, the $\delta^{18}O$ and δD values of precipitation show a weak "precipitation effect" in July and August, and the values gradually become more negative with continued rainout. This study improves knowledge of the isotope evolution of precipitation in the Qilian mountains, and lays the foundation for further research on isotope hydrology in cold and arid regions.

1. Introduction

Atmospheric precipitation is the primary source of water resources in basins and plays an important role in local moisture recycling processes (Lavers et al., 2015; Pu et al., 2013; He et al., 2006). Research on atmospheric precipitation is a prerequisite for studying global and local moisture recycling (Breitenbach et al., 2010; Aggarwal et al., 2012). Stable isotope, although content is low, are an important tracer of the water cycle, are very sensitive to environmental changes, record information about water circulation, and have been widely used in hydrology, climatology, ecology and other fields of study (Dansgaard, 1953, 1964; Zhu et al., 2016; Aggarwal et al., 2016). For example, $\delta^{18}O$ and δD have been used to determine the components of stream flow in different environments (Pu et al., 2017; Barras and simmonds, 2008; He et al., 2006; Cai et al., 2015), determine the source of moisture in atmospheric precipitation (Araguás-Araguás et al., 2015; Cappa et al., 2002; Gonfiantini et al., 2001; Sánchez-Murillo et al., 2016; Yu et al., 2014), study water sources in different habitats, distinguish living types and plant species (Martorell and Ezcurra, 2002; Kang et al., 2017; Cheng et al., 2013; Ding et al., 2018), and determine regional climate variations from studies of tree-rings (Miller et al., 2006; Saurer et al., 2010; Chen et al., 2017). The study of stable hydrogen and oxygen isotopes in precipitation provides an important foundation and basic parameters in the application of isotope technology to various disciplines (Gu, 2011; Lin, 2013).

In the past few decades, researchers have analysed stable isotope variations in precipitation and the environmental significance and have arrived at several important conclusions (Gat et al., 2013; Yao et al., 1999; Pang et al., 2011; Zhang and Yao, 1998; Zhang and Yan-Qing, 2007). Breitenbach et al. (2010) found that the isotopic composition of

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https://doi.org/10.1016/j.quaint.2018.06.038
Received 17 February 2018; Received in revised form 21 June 2018; Accepted 26 June 2018

Please cite this article as: Xinggang, M., Quaternary International (2018), https://doi.org/10.1016/j.quaint.2018.06.038

precipitation was directly linked to sources of moisture. Sánchez-Murillo et al. (2016) used isotopes to track the transportation of monsoon moisture and found that the magnitude of isotopic fractionation in precipitation was closely related to monsoon strength. The values of δ^{18}O and δD in precipitation became negative due to moisture transportation over long distances (Breitenbach et al., 2010). Barras and Simmonds (2008) suggested that stable isotopes values of precipitation were affected by local weather conditions, while topographical conditions restricted the variations (Gonfiantini et al., 2001). Evaporation and condensation (precipitation) processes were also shown to have an important influence on isotope variations (Tian et al., 2007; Bisselink and Dolman, 2009). Dansgaard (1964) defined the concept of *d*-excess (where *d*-excess = δD-8δ^{18}O) and determined a global *d*-excess average of about 10‰. *d*-excess is mainly influenced by the temperature and relative humidity of the moisture source (Landais et al., 2012). By analysing variations in *d*-excess and the local meteoric water line, the source of moisture in precipitation can be determined (Gat et al., 2013). A large number of studies on stable isotopes in precipitation have indicated the following: (1) condensation can lead to negative values of stable isotopes in precipitation (Yao et al., 1999; Li et al., 2016; Tian et al., 2007); (2) evaporation can lead to enrichment of stable isotopes in precipitation (Zhu et al., 2016; Wang et al., 2016; Pang et al., 2011); (3) stable isotopes in precipitation show different temperature effects, precipitation effects, elevation effects, and seasonal effects that are affected by geographic location, atmospheric circulation, weather systems, topography and other factors (Gonfiantini et al., 2001; Wang et al., 2008; Li et al., 2015; Tian et al., 2007). The Qilian Mountains are an important ecological barrier and environmental functional area in northwest China (Jia, 2012). The mountains are also the core water source for the inland area of the Hexi corridor, where surface runoff originates mainly from precipitation in adjacent mountainous areas (Li et al., 2016). Researchers have conducted numerous studies on the stable isotope composition of precipitation in the Qilian Mountains (Wang et al, 2008, 2016; Wu et al., 2016; Wang and tang, 2013; Ma et al., 2012; Zhao et al., 2015). These studies have indicated that stable isotopes in precipitation in the Qilian Mountains displayed significant seasonal effect, temperature effect and weak precipitation amount effect; however, the elevation effect has rarely been studied.

The Xiying River originates from the Lenglong ridge on the northern slope of the Qilian Mountains, which is in a climatic ecotone. The climate differs from arid areas and monsoon regions. In the past, due to the difficulty of making observations and for other reasons, there has been no systematic study of stable isotope in precipitation in the Xiying River Basin. In this paper, we analysed the temporal and spatial variations of hydrogen and oxygen stable isotopes in precipitation from different elevations along the northern slope of the Qilian Mountains in a climatic ecotone and evaluated the effects of temperature, elevation, monsoon circulation and continuous precipitation processes on isotopic variations. This paper provides a theoretical basis for further research into isotopic hydrological processes in the Xiying River Basin on the northern slope of the Qilian Mountains.

2. Data and methods

2.1. Study area

The Qilian Mountains are located in the northeast of the Qinghai-Tibet plateau in the northwest of China between 36° 30′ N ~39°30′ N and 93° 30′ E ~103° E (Fig. 1). The region stretches a thousand kilometres from southeast to northwest and has a semi-arid climate typical of the continental alpine. There are obvious climate differences with respect to distance and elevation in the study area, in that precipitation decreases and the snow line increases from east to west, and the temperature decreases but precipitation increases with elevation. The Xiying River Basin is in the upstream area of the Shiyang River, which originates from the Lenglong ridge on the northern slope of the Qilian Mountains. It is a typical alpine stream, and the river's banks are mountains. From the southwest to the northeast along the river, the Xiying River merges with the Shuiguan River, Ningchang River, Xiangshui River, and eventually joins the Xiying Reservoir, which discharges into the Shiyang River. The average annual temperature in the Xiying River Basin is below 6 °C, and annual precipitation is about 400 mm.

2.2. Data sources and methods

A total of 253 samples were collected at Lenglong station, Ningchang station, Huanjian station and Xiying station on the northern slope of the Qilian Mountains from October 2016 to October 2017, with measurements of corresponding meteorological parameters including the amount of precipitation, temperature, relative humidity and atmospheric pressure (Fig. 1, Table 1). Precipitation samples were collected using plastic funnel–bottle sets immediately after each rainfall event in order to decrease the influence of evaporation. Snow samples were collected in plastic bags and warmed so that they could be melted and poured into bottles. Samples were collected in two 50-mL polyethylene bottles. After samples were collected, all samples were kept in cold storage at −18 °C. At the same time, meteorological data were recorded by automatic meteorological stations in the four sampling locations. δ^{18}O and δD values in precipitation were analysed using a liquid water isotope analyser (Los Gatos Research IWA-45EP) at the Laboratory of Stable Isotope in the College of Geography and Environmental Science at Northwest Normal University. The results are reported relative to Vienna Standard Mean Ocean Water (VSMOW). The measurement accuracy is ± 0.1‰ for δ^{18}O and ± 0.5‰ for δD.

Water vapour transportation vectors were calculated using NCEP/NCAR 2.5° × 2.5° reanalysis data at 700 hpa (NCEP/NCAR Reanalysis 1), which were obtained from the National Centers for Environmental Prediction (http://www.esrl.noaa.gov).

We used the HYSPLIT model (https://ready.arl.noaa.gov/hypub-bin/trajtype.pl) to research the trajectory of the air masses arriving at the sampling site (37.7°N, 101.89°E). The model utilised NCEP GDAS 1° × 1° meteorological data. We set the starting time of the backward trajectory at 16:00 Beijing time (08:00 UTC), and the backtracking time was 10 days. The calculation for the starting height was based on the barometric formula (Barnes, 2010).

3. Results and analysis

3.1. Temporal variation of isotope compositions

Isotope measurements exhibited wide variations in all precipitation events collected from the four sampling sites (Fig. 2). The δ^{18}O values varied from −25.67‰ (Lenglong station) to −0.07‰ (Ningchang station), with a mean value of −9.66‰; and the δD values ranged from −184.1‰ (Huajian) to 23.2‰ (Xiying), with a mean value of −61.22‰. The *d*-excess fluctuated from −9.11‰ (Huajia) to 35.75‰ (Ningchang), with a mean value of 16.06‰. The wide variation of stable isotope values may be influenced by different sources of moisture and complex weather conditions during the precipitation processes (Wu et al., 2016). In winter (from December 2016 to February 2017), δ^{18}O, δD and *d*-excess mean values were −19.95‰, −144.09‰ and 15.51‰, respectively, and were −7.02‰, −42.24‰ and 13.93‰, respectively, in summer (from June 2017 to August 2017). Daily δ^{18}O values gradually became increasingly negative from October 2016 to February 2017, after which they fluctuated upward until August 2017 and reached a maximum value in mid-August, before gradually decreasing. Higher δ^{18}O mostly occurred in August, for example, the δ^{18}O was −0.08‰ on August 10 at Ningchang station and 3.2‰ on August 17 at Xiying station. Lower δ^{18}O values mostly occurred in winter, such as a δ^{18}O value of −25.67‰ on February 25, 2017, at Lenglong station and −22.32‰ on December 25, 2016, at Huajian station. High *d*-excess