Ekoloji 28(107): 981-988 (2019)

Environmental Research on Spatial Pattern of Hydrogen and Oxygen Stable Isotopes of Atmospheric Precipitation in China Influenced by Both Southwest Summer Monsoon and South Sea Summer Monsoon

Wei Zhao [1], Chengyuan Hao [1*], Chuanyang Xu [1]

[1] College of Surveying & Land Information Engineering, Henan Polytechnic University, Jiaozuo, Henan, CHINA

[*] Corresponding author: hao.chengyuan@163.com

Abstract

Environmental hydrogen and oxygen isotopes are ideal tracers of water, as they are incorporated in the water molecules and their behaviours and variations reflect the origin of, and the hydrological and geochemical processes undergone by, natural water bodies. Water vapor source is always one of the important topics in geosciences. It is more important scientific and practical significance to carry out the identification of interaction region influenced by the low latitude water vapor channels in China, especially under the background of the global climate system changing in recent years. This paper regards the interaction region influenced possibly by both Southwest Moisture and South Sea Moisture as the research target, by means of stable isotope ratio mass spectrometer MAT253 measuring the content of hydrogen and oxygen stable isotopes of 239 effective samples at 16 samples atmospheric precipitation from April to October of 2014 in Yunnan Province and Guangxi Zhuang Autonomous Region between 23-24°N. We have achieved spatial pattern of δD and $\delta^{18}O$ based on ArcGIS13.0 software by trend analysis, and demarcated boundaries between the moisture from Southwest and the moisture from South Sea. There are three main results. Firstly, spatial patterns of both δD and $\delta^{18}O$ are consistent basically both in the whole rainy season precipitation and a rainfall process. Secondly, both rainfall factor and continental factor have affected the spatial pattern of hydrogen and oxygen stable isotopes in atmospheric precipitation. Thirdly, Southwest vapor met the South Sea vapor nearby points among Honghe, Gejiu and Meingzi, in the whole rainy season precipitation or a rainfall process. So the zone among points of Honghe, Gejiu and Mengzi is probably the region, in which both Southwest vapor and South Sea vapor interact on each other.

Keywords: Southwest moisture, South sea moisture, identify the interaction region, stable isotopic technique, environmental factors

Zhao W, Hao C, Xu C (2019) Environmental Research on Spatial Pattern of Hydrogen and Oxygen Stable Isotopes of Atmospheric Precipitation in China Influenced by Both Southwest Summer Monsoon and South Sea Summer Monsoon. Ekoloji 28(107): 981-988.

INTRODUCTION

The ^{18}O and D isotopes in the atmospheric precipitation are important climatic tracers, whose relative abundance can be used to infer or diagnose the regional atmospheric circulation and the climatic or meteorological characteristics (Zhang et al. 2012). The regional climatic or meteorological characteristics are quite different in Southwest China, and its causes are not only directly related to the complex terrain and great landforms, but also closely related to the interaction of different types of monsoon system (Hao et al. 2007). Among these monsoon systems, the Pacific monsoon and the India Ocean monsoon are two adjacent systems with distinct features, and they are also the most important water vapor channels to China. Earlier in the 1980s, scientists noticed the shifting of hydrogen and oxygen stable isotopes in the precipitation of China Southwest, and some of the analytical results had been applied to the revision of climate regionalization in China and the reconstruction of the paleo-environment in East Asia (Zhu et al. 2014). In particular, Zhang *et al.*, Liu *et al.*, and Chen *et al.*, investigated the features of the environmental effects of the hydrogen and oxygen isotopes in the precipitation in China, such as the effects of rainfall, land, temperature, and latitude (Chen et al. 2010, Liu et al. 2009, Zhang et al. 2009).

Many research results have shown that the dry-wet condition in the summer of Southwest China is not only controlled by the India Ocean monsoon, but also influenced by the Pacific monsoon. Zhou *et al*. analyzed

 Received: 17 Dec 2017 / Accepted: 27 Apr 2018

years of data of the water vapor flux in the east of the Tibetan Plateau, and the results indicated that the water vapor in summer mainly comes from both the bay of Bengal and the South China Sea area (Zhou et al. 2007). More importantly, based on the stable hydrogen and oxygen isotopic data collected at the New Delhi station in the India Ocean monsoon area and the Hongkong station in the Pacific monsoon area, Pang *et al*. found the origins of water vapor and transfer paths of different summer monsoons, and the results generally agreed with the background of atmospheric circulation, showing the trend of relatively low $\delta^{18}O$ in Guangxi and Guizhou, and increasingly higher to the eastern and western sides, as a result of the joint action of the Pacific monsoon and the India Ocean monsoon (Pang et al. 2005). Zhang *et al*. drew a temporal-spatial distribution map of $\delta^{18}O$ in China based on the data collected by the network monitoring isotopes in the global atmospheric precipitation, proposed three routes of water-vapor transport affecting the change of $\delta^{18}O$ in the precipitation of China, and concluded after analyzing the spatial pattern that the air-mass properties must be one of the most important factors leading to the seasonal variations of stable isotopes in the precipitation of the southwest area (Zhang et al. 2009). That is, the combined Yunnan-Guangxi area is most likely to be one of the areas subjected to the interactive action of the southwest summer monsoon water vapor and the summer southeast monsoon water vapor in China. Moreover, the monsoon region in China is one of areas with the largest inter-annual variation in the global climate system, especially since the 1980s when the variation of global climate significantly accelerated. Widespread droughts and floods have caused serious damage to the agricultural production, accounting for 70% of the total economic loss of all natural disasters (Huang et al. 2006). Therefore, in the background of a varying global climate system, the combined Yunnan-Guangxi area is taken as the study area to determine the boundaries of the region affected by the interaction of two marine monsoon circulations affecting the summer precipitation in China, and this investigation has important theoretical value and practical significance.

GEOGRAPHIC PROFILE OF STUDY AREA

Study area includes Yunnan Province and Guangxi Zhuang Autonomous Region in China, located at the boundary of tropical and subtropical regions in the Northern Hemisphere and connected with each other in geographical space. In the west of the study area, Yunnan Province, the terrain is dominantly mountains and plateaus with large surface relief. Mount Ailao in Yunnan Province is a huge mountain range running in the northwest – southeast direction through the middle-west of the study area, with the peak elevation of more than 3100m and almost orthogonal to the India Ocean monsoon flow. In contrast, in the east of the study area, Guangxi Zhuang Autonomous Region, the elevation is lower, and the overall terrain is high in the northwest and low in the southeast. Its mountains with low and middle altitudes are mostly distributed in the northern part while plains and hills are mostly located in the southern part.

DATA AND METHODS

Data Collection

In terms of the spatial distribution, 16 weather station points as close as possible to the Tropic of Cancer and evenly distributed in the space located in 23～24°N and 98～112°E were chosen as the points of collecting samples of atmospheric precipitation, including ten points in Yunnan Province and six points in Guangxi Zhuang Autonomous Region (**Table 1**). Regarding the data collecting time, it was from April to October, because the rainy season in Yunnan Province is from May to October while the rainy season in Guangxi Zhuang Autonomous Region is from April to September. And the year is 2014 in this research. According to the requirements of precipitation sample collection standards, one sample should be collected when the daily precipitation was equal to or greater than 25mm, i.e. a heavy rain, and the standard amount of water sample quantity was 2 ml.

In this research, 239 effective samples were collected, and the specific information is shown in **Table 1**. All the samples were measured with an MAT253 stable isotope mass spectrometer in the Isotopic Hydrology Laboratory of Henan Polytechnic University, and the instrument ensured that the precision of $\delta^{18}O$ and δD could reach 0.025‰ and 0.100‰, respectively. All the results of analysis were expressed in difference in a thousand points with respect to the Vienna standard of mean ocean water.

Table 1. Basic information of 16 sampling sites and stable isotope data of precipitation in study area in 2014

Sites	Altitude/m	Latitude/°N	Longitude/°E	Sample Number	Whole rainy season average		A certain rainfall process	
					δD	$\delta^{18}O$	δD	$\delta^{18}O$
Zhenkang	1008.4	23.92	98.96	18	-67.36	-8.52	-64.70	-9.11
Gengma	1104.9	23.55	99.40	17	-54.71	-7.60	-64.03	-9.85
Shuangjiang	1044.1	23.46	99.80	16	-80.97	-11.28	-63.50	-9.63
Jinggu	913.2	23.50	100.70	16	-71.75	-7.56	-63.10	-6.34
Mojiang	1281.9	23.43	101.71	17	-81.16	-11.04	-62.40	-9.49
Honghe	974.5	23.36	102.43	12	-93.79	-12.64	-74.64	-10.88
Gejiu	1695.0	23.23	103.09	13	-109.67	-15.32	-74.90	-10.68
Mengzi	1300.7	23.38	103.38	11	-92.71	-12.98	-13.60	-3.88
Yanshan	1561.1	23.62	104.33	15	-84.36	-12.05	-29.20	-5.58
Funing	685.8	23.65	105.63	16	-52.78	-6.02	-51.70	-5.71
Debao	65.0	23.35	106.60	15	-62.46	-9.06	-44.00	-6.83
Pingguo	108.8	23.32	107.58	16	-49.57	-7.24	-44.00	-6.84
Shanglin	126.0	23.43	108.58	15	-46.79	-6.47	-32.20	-5.29
Linbin	84.9	23.75	109.23	13	-38.80	-5.08	-60.70	-7.31
Pingnan	40.0	23.55	110.40	15	-33.12	-5.60	-29.80	-5.29
Wuzhou	114.8	23.48	111.30	14	-38.74	-5.87	-68.80	-9.25

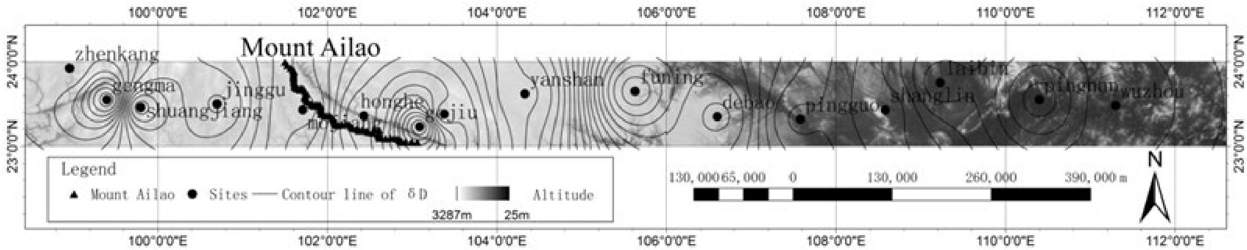

Fig. 1. Spatial pattern of δD in rainy season precipitation in study area

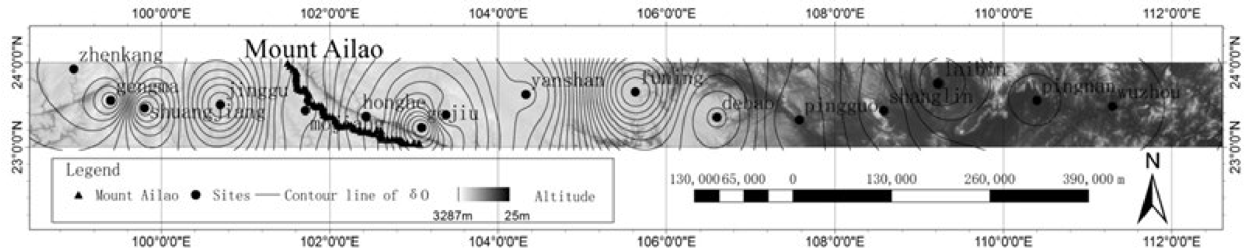

Fig. 2. Spatial pattern of $\delta^{18}O$ in rainy season precipitation in study area

Theory and Methods

(1) Hydrogen and oxygen stable isotope tracer in atmospheric precipitation

According to the Rayleigh fractionation theory, the values of D and ^{18}O in the atmospheric precipitation with a single origin of water vapor keep decaying on the path of water vapor transport. Therefore, the content of isotope in the samples of atmospheric precipitation should be higher on both the eastern and western sides of the study area, and lower in the central region. For the atmospheric precipitation originates from the South China Sea water vapor and the bay of Bengal water vapor, respectively (Liu et al. 2008).

(2) GIS-platform based contour line method

The Kriging interpolation method is based on the analysis of spatial structure and uses the spatial correlation among points, and can fully reflect the anisotropy of the space field and automatically identify the spatial distribution of sample points (Price 2000). The contour method uses a set of contour lines to express the gradual change of the quantitative characteristics of geographical events distributed in continuous surfaces, and the density of the contour lines can be used to determine the spatial variation of geographical events (Codrea and Nevalainen 2005).

RESULTS AND ANALYSIS

Stable Isotopes over the Whole Rainy Season

Three main results are obtained from the analysis of spatial distribution characteristics of the mean values of water stable isotopes in the atmospheric precipitation during the rainy season. See **Fig. 1** and **Fig. 2**.

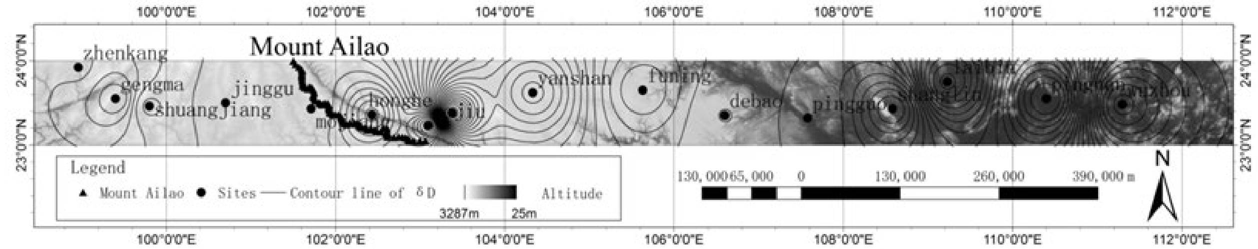

Fig. 3. Spatial pattern of δD in a rainfall process in study area

(1) The dense contour lines of δD and $\delta^{18}O$ indicate a large spatial variation of isotopes in the region between points of Gengma and Shuangjiang in the west of the study area, which must be caused by the rainfall effect induced by great landform. Point Gengma lies on the west side of Mount Bangma and is also located on the windward slope of the India Ocean monsoon, so a large amount of precipitation can be formed. Hence, the rainfall effect leads to higher contents of δD and $\delta^{18}O$ at point Gengma, but lower contents of δD and $\delta^{18}O$ at point Shuangjiang, located on the leeward slope of the India Ocean monsoon.

(2) The δD and $\delta^{18}O$ contour lines also vary greatly in region between points Honghe and Mengzi, which are located in the west of the study area, and two possible reasons are considered. The first reason is the blocking effect of Mount Ailao. After the southwest summer monsoon coming from the water source in the bay of Bengal passes over the great Mount Wuliang and Mount Ailao, the amount of precipitation decreases, and the Pacific monsoon coming from the water source in South China Sea may mix there, and their joint effect can lead to large variation in the contents of δD and $\delta^{18}O$ in the adjacent region. Consequently, among the 16 sampling points, the contents of δD and $\delta^{18}O$ of atmospheric precipitation at points of Honghe, Gejiu, and Mengzi are ranked the last three, and Gejiu has the lowest value (Having seen from **Table 1**). Secondly, Points of Honghe, Gejiu and Mengzi are almost located in the inland, and the continental effect on the stable isotope in the atmospheric precipitation is also one of the main reasons causing large variations in the contents of δD and $\delta^{18}O$.

(3) The isotope contour lines of both hydrogen and oxygen are relatively sparse in the eastern part of the study area, which suggests that Guangxi Zhuang Autonomous Region could not be located in the region under the interactive influence of the southwest water vapor and the South China Sea water vapor. Meanwhile, the elevation of the region within 23-24°N in Guangxi Zhuang Autonomous Region is lower than 800 m, and the 6 sampling points in this area are all lower than 130 m in elevation, so no strong blocking effect exists on the movement path of monsoon water vapor.

In sum, the spatial distribution pattern of stable hydrogen and oxygen isotope in the atmospheric precipitation in the rainy season show that the contour lines of both δD and $\delta^{18}O$ basically have the same pattern of spatial variation, and the large-scale topography of Mount Ailao is one of main reason that the spatial distribution pattern of both hydrogen and oxygen isotopes formed. But, Rayleigh fractionation theory is the main reason for the formation of spatial pattern of stable isotope. Considering both the spatial distribution of large-scale topography and environmental factors of atmospheric precipitation, it can be inferred that the region between points of Honghe and Mengzi could be subjected to the interactive influence of the southwest water vapor and the southeast water vapor in China.

Stable Isotopes during Rainfall Process

Given a rainfall process in middle-late June, (from 19 to 21 in June) in 2014 as a case in point, it demonstrates the pattern of short-term spatial distribution of both hydrogen and oxygen isotopes in the atmospheric precipitation, and the specific data is shown in **Table 1**. The spatial distributions of both hydrogen and oxygen isotopes in a rainfall process mainly have the following three characteristics. See **Fig. 3** and **Fig. 4**.

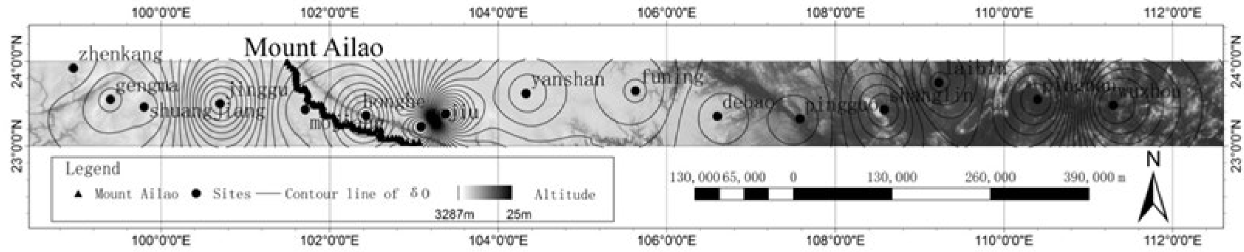

Fig. 4. Spatial pattern of δ^{18}O in a rainfall process in study area

(1) The spatial distribution patterns of both δD and δ^{18}O have basically the same trend of variation in this rainfall process, and are also similar to the spatial distribution of stable hydrogen and oxygen isotopes in the atmospheric precipitation from April to October. They both show the trend of progressive decreasing from the eastern and western sides of the region to the middle region, and the contents of δD and δ^{18}O at points of Honghe and Gejie are ranked the last two among the 16 sampling points, with the lowest value at point Gejiu.

(2) In the western part of the study area, the δD and δ^{18}O contour lines are dense between points of Gejiu and Mengzi, possibly because this rainfall process occurs in middle-late June, when the southwest water vapor crossed Mount Ailao meeting with the southeast water vapor near point Gejiu. Two air currents are both strong, resulting in significant changes in the contents of δD and δ^{18}O (Chen et al. 2015).

(3) In the eastern of the study area, the contour densities of both δD and δ^{18}O between points of Pingnan and Wuzhou also suggest large spatial variation of these two stable isotopes. The hills located between Pingnan and Wuzhou, such as Mount Dayao and Mount Darong, may be the major cause varied of both δD and δ^{18}O. Moreover, this rainfall process occurs in the middle-late June when the South China Sea monsoon trough is quite active, and the rainfall effect on the stable isotopes in the atmospheric precipitation is another main reason (Chen et al. 2015).

In short, Based on the stable hydrogen and oxygen isotope data in a certain rainfall process in middle-late June, it is found that the spatial distribution patterns of δD and δ^{18}O are consistent. Meanwhile, significant changes not only appearances near points of Honghe and Gejiu in Yunnan Province, but significant differences are also found between points of Pingnan and Wuzhou in Guangxi Zhuang Autonomous Region. However, the former is more likely to be the region under the interactive influence of the southwest water vapor and the southeast water vapor, because the events are not only related to the large topography of Mount Ailao, but also related to the strong impact of the South China Sea airflow on Yunnan Province in June (Lin et al. 2005).

Boundary under the Influence of two currents of Water Vapor

The spatial variation of hydrogen and oxygen isotopes in the atmospheric precipitation is manipulated by the running path of summer monsoon water vapor and the speed of attenuation of water vapor. Moreover, it is not only affected by the source location of water vapor, but also has close relationship with positive landforms, such as plateaus and mountainous. Analysis of the spatial distribution trends of hydrogen and oxygen isotopes over the whole rainy season and in a rainfall process in middle-late June show that the values of δD and δ^{18}O are both negative in 2014. The marine nature of water vapor origin is the main cause, and it also supports the rule that both hydrogen and oxygen stable isotopes keep declining with the transport of summer monsoon water vapor to the inland. More importantly, based on the spatial distribution pattern of stable hydrogen and oxygen isotopes in the atmospheric precipitation over the whole rainy season, it can be inferred that the region of between points of Honghe and Mengzi should be under the interactive influence of the southwest water vapor and the southeast water vapor, although the δD and δ^{18}O contour lines near points of Gengma and Shuangjiang are also dense. Meanwhile, the contour lines of both hydrogen and oxygen stable isotope in a rainfall process in middle-late June also show clear spatial boundaries near points of Honghe and Gejiu. The strong South China Sea airflow causes frequent movement of water vapor, which passes the Yunnan Plateau from the east of the study area to the west and meets with the water vapor coming from the bay of Bengal in the west and passing over Mount Ailao in the region of Gejiu and Mengzi. They together cause the dense contour lines of both δD and δ^{18}O, and then the lowest content.

In conclusion, based on the integrated results of stable hydrogen and oxygen isotopes in the atmospheric precipitation in the region within 23~24°N in Yunnan Province and Guangxi Zhuang Autonomous Region over the whole rainy season and in a rainfall process in 2014, the region between points of Honghe and Mengzi is considered to be the boundary of the regions under the influence of both the southwest summer monsoon and southeast summer monsoon.

DISCUSSIONS

The southwest region of China is characteristic of typical monsoon climate, and the origins of water vapor and the factors affecting precipitation are numerous (Ming 2007). The precipitation in the rainy season mainly has two main branches of water vapor origins. One is the southwest water vapor from the bay of Bengal (Hu and Wang 2015), reflecting the influence of the Southwest summer monsoon, who is the origin of most water vapor in the atmospheric precipitation in the India Ocean monsoon region in China. The other is the water vapor from the western Pacific (Li and Ju 2013), reflecting the impact of the Pacific monsoon. Some research scholars have also discussed the scope of their impact, but by different means and with different representation methods. Some of the results are similar to the conclusions above obtained in this research. For example, Qiang *et al*., by having been based on the divergence of water vapor flux, had computed that the eastern region of Yunnan Province was firstly affected by the Pacific monsoon and after the outbreak of the India Ocean monsoon, was also affected by their common influence (Qiang et al. 1998). Hence it had named the junction of two kinds of monsoon, the confluence region of both the southwest water vapor and the South China Sea water vapor. Hu *et al*. had chosen the middle and southern region of the combination between Mounts of Ailao and Wuliang as the study area, had studied the correlation between the regional topography and the confluence of monsoons by having been based on the spatial differentiation of precipitation in the rainy season, and obtained how the confluence region of the India Ocean monsoon and the Pacific monsoon vary with the development of monsoon (Hu et al. 2011). Indeed, having been based on the data of natural geographical elements in the southern region of Yunnan Province and using the nonlinear classifier of SOFM model, one of the earlier studies of our research group had divided the regional boundaries, and concluded that Mount Ailao not only blocked the cold winter air from the north, but also was one of the main factors determining the scope of influence of the India Ocean monsoon and the Pacific monsoon. A significant variation in the climate and vegetation around points of Gejiu and Mengzi had suggested that the region was likely to be a regional division of some or a geographical factor (Hao et al. 2008).

CONCLUSIONS

Based on the precipitation δ18O values from the datasets of the Global Network of Isotopes in Precipitation (GNIP), the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis data, and previous researches, we explored the temporal and spatial variations of precipitation δ18O in the PRB and adjacent regions. Based on the data of atmospheric precipitation collected at 16 points of in both Yunnan Province and Guangxi Zhuang Autonomous Region from April to October in 2014, the contents of δD and $\delta^{18}O$ are measured with an MAT253 stable isotope mass spectrometer, and then the spatial interpolation method based on the ArcGIS platform combined with the regional differentiation of terrain landform are used to define the boundaries of the region under the interactive influence of the water vapor from the bay of Bengal and the water vapor from the South China Sea. This research mainly has the following four conclusions.

(1) The values of δD and $\delta^{18}O$ in both the whole rainy season and a rainfall process are both negative, mainly because of the Rayleigh fractionation of hydrogen and oxygen isotopes. The water vapor entering the study area is already short of heavy isotope, and with the movement of the monsoon carrying water vapor further toward inland, the content of heavy isotope shows an overall trend of progressively decline.

(2) The trend of the spatial variation of the hydrogen and oxygen isotopes over the rainy season show that the region between points of Honghe and Mengzi may be under the interactive influence of different summer monsoon circulations, while the isotopic data in a rainfall process in middle-late June strongly supports again it.

(3) Over the whole rainy season and in a rainfall process, the contents of δD and $\delta^{18}O$ have basically the same trends of spatial variation. The pattern of variation is mainly controlled by the rainfall effect and the continental effect, and the barrier of great landforms, such as Ailao Mountain and Yunnan Plateau, is also one of the main reasons.

(4) Based on the data of stable oxygen and hydrogen isotopes over the whole rainy season in 2014 and in a rainfall process in middle-late June, the region between points of Honghe and Mengzi should be the boundary of the region under the influence of the India Ocean summer monsoon and the Pacific summer monsoon.

However, the influencing factors of both hydrogen and oxygen stable isotopes in atmospheric precipitation are more complicated, these are not quantitative, such as the climatic conditions of water vapor source, the migration path of water vapor, and local terrain effects. So, they resulted in certain conclusions are not clear, for example, the values of $\delta^{18}O$ varies greatly while the values of δD has no change in the region nearby points both Shuangjiang and Jinggu in Yunnan Province. Especially, the trend of the summer monsoon vapor source is not obvious, which is indicated by the spatial pattern of excess deuterium, calculated by both hydrogen and oxygen stable isotope data. But, the analysis on its origin is not put it in place in this paper. These two aspects are also the key contents of the next work.

ACKNOWLEDGEMENTS

This project is partially supported by the National Science Foundation of China (No. 41371105).

REFERENCES

Chen J, Liang WL, Gao AN, Chen WB, Tang W (2015) Analysis on features of monsoon trough rains in South China. Journal of Tropical Meteorology, 31(4): 536-548.

Chen ZX, Cheng J, Guo PW, Lin ZY, Zhang FY (2010) Distribution Characters and its control factors of stable isotopes in precipitation over China. Transactions of Atmospheric Sciences, 33(6): 667-679.

Codrea MC, Nevalainen OS (2005) Note: an algorithm for contour-based region filling. Computer & Graphics, 29(3): 441-450.

Hao CY, Wu SH, Li SC (2007) Measurement of climate complexity using permutation entropy. Geographical Research, 31(4): 536-548.

Hao CY, Wu SH, Li SC (2008) Study on the method of areal differentiation based on SOFM. Progress in Geography, 27(5): 121-127.

Hu H, Wang JL (2015) On characteristics of hydrogen and oxygen isotope in precipitation in Yunnan and analysis of moisture sources. Journal of Southwest China Normal University, 40(5): 142-149.

Hu JM, He DM, Li YG (2011) Discussion on monsoons' interfacing around Ailaoshan through analyzing regional variation of wet season rainfall. Advances in Earth Science, 26(2): 183-192.

Huang RH, Cai RS, Chen JL, Zhou LT (2006) Inter-decadal variations of drought and flooding disasters in China and their association with the East Asia climate system. Chinese Journal of Atmospheric Sciences, 30(5): 730-741.

Li T, Ju JH (2013) Comparison of climate features between the Southwest Summer Monsoon of the Bay of Bengal and the South China Sea Summer Monsoon. Chinese Journal of Geophysics, 56(1): 27-37.

Lin JA, Wang AN, Feng RQ, Tang TY, Wu CS, Li GL, Li JN, Wu SS (2005) The climatic characteristics of maintaining period of south Sea Summer Monsoon I—40 yearly average. Journal of Tropical Meteorology, 21(2): 113-122.

Liu JR, Song XF, Yuan GF, Sun XM, Liu X, Wang SQ (2009) Characteristics of δ 18O in precipitation over East Monsoon China and the water source. Chinese Science Bulletin, 54(22): 3521-3531.

Liu JR, Song XF, Yuan GF, Sun XM, Liu X, Wang ZM, Wang SQ (2008) Stable isotopes of summer monsoonal precipitation in southern China and the moisture sources evidence from δ 18O signature. Journal of Geographical Sciences, 18(2): 155-165.

Ming QZ (2007) A study on regional change of natural environment of China influenced by Southwest Monsoon. Yunnan Geographic Environment Research, 19(4): 93-97.

Pang HX, He YQ, Zhang ZL, Lu AG, Gu J, Zhao JD (2005) δ 18O in monsoon precipitation and the origin of precipitation. Chinese Science Bulletin, 50(20): 2263-2266.

Price DT (2000) A comparison of two statistical methods for spatial interpolation of Canadian monthly mean climate data. Agricultural and Forest Meteorology, 101(2-3): 81-94.

Qiang XM, Ju JH, Zhang HH (1998) A diagnostic analysis of the summer monsoon in Yunnan. Journal of Yunnan University, 20(1): 75-79.

Zhang XP, Guan HD, Sun ZA, Sun GL, Zhang XZ, Wu HW (2012) Simulations of stable isotopic variations in precipitation and comparison with measured values in Yunnan Province, China. Scientia Geographica Sinica, 32(1): 121-128.

Zhang XP, Liu JM, Masayoshi N, Xie ZC (2009) Vapor origins revealed by deuterium excess in precipitation in southwest China. Journal of Glaciolgy and Geocryology, 31(4): 613-619.

Zhou CY, Li YQ, Li W, Li LX (2005) Climatological characteristics of water vapor transport over eastern part of Qinghai-Xizang Plateau and its surroundings. Plateau Meteorology, 24(6): 880-888.

Zhu L, Fan T, Guo H (2014) Sources and stable isotope Characteristic of precipitation in southwest of China. Yunnan Geographic Environment Research, 26(5): 61-67.