Chin. Geogra. Sci. 2020 Vol. 30 No. 1 pp. 180–188
https://doi.org/10.1007/s11769-019-1091-6
Springer Science Press
www.springerlink.com/content/1002-0063

Stable Isotope Signatures and Moisture Transport of a Typical Heavy Precipitation Case in the Southern Tianshan Mountains

WANG Liwei[1], ZHANG Mingjun[1], WANG Shengjie[1, 2, 3], Athanassios A. ARGIRIOU[4], WANG Gaofei[5], Vasileios SALAMALIKIS[4], SHI Mengyu[1], JIAO Rong[1]

(1. *College of Geography and Environmental Science*, *Northwest Normal University*, *Lanzhou* 730070, *China*; 2. *Institute of Desert Meteorology*, *China Meteorological Administration*, *Ürümqi* 830002, *China*; 3. *State Key Laboratory of Cryospheric Sciences*, *Northwest Institute of Eco-Environment and Resources*, *Chinese Academy of Sciences*, *Lanzhou* 730000, *China*; 4. *Laboratory of Atmospheric Physics*, *Physics Department*, *University of Patras*, *Patras GR*-26500, *Greece*; 5. *Meteorological Bureau of Jeminay County*, *Xinjiang Altay* 836500, *China*)

Abstract: Stable oxygen isotopes in precipitation contain meaningful environmental information on a synoptic scale and can be applied to diagnose hydrometeorological processes. A series of rainstorms occurred at the southern Tianshan Mountains during the period from May to June 2013, and the event-based precipitation was sampled along the mountain range from west to east. Based on δ^{18}O values in precipitation samples as well as the corresponding meteorological parameters, the moisture transport paths during the sampling period were identified. In late-May (stage 1), isotopes in precipitation collected generally showed a depleting trend. In mid-June (stage 2), there was no coherent trend of isotopes in precipitation for these stations, and only isotope values in Aksu showed a continually depleting trend. Checking other meteorological proxies during the sampling period, the event-based precipitation isotopes sensitively reflected the moisture process. In central Asia, both the westerly and monsoon moisture can be delivered to cause extreme precipitation events, and the isotopic information provides an alternative tool to investigate the atmospheric processes.
Keywords: precipitation; stable isotope; moisture source; Tianshan Mountains

Citation: WANG Liwei, ZHANG Mingjun, WANG Shengjie, Athanassios A. ARGIRIOU, WANG Gaofei, Vasileios SALAMALIKIS, SHI Mengyu, JIAO Rong, 2020. Stable Isotope Signatures and Moisture Transport of a Typical Heavy Precipitation Case in the Southern Tianshan Mountains. *Chinese Geographical Science*, 30(1): 180–188. https://doi.org/10.1007/s11769-019-1091-6

1 Introduction

Since the mid-20th century, significant increasing trends in precipitation have been evidenced in arid inland of Asia (Zheng et al., 2017; Meng et al., 2018; Yao et al., 2018b); the frequency of precipitation extremes has also increased (Zhang et al., 2017; Chen et al., 2019). Many meteorological analyses showed that heavy precipitation in northwest China may be greatly influenced by the monsoon moisture from the low-latitudes (especially the Arabian Sea and the Bengal Bay of the Indian Ocean), that is, for some rainstorms the Indian monsoon moisture rises over the Tibetan Plateau and then reach the inland basin (Yang et al., 2011; Zhao et al., 2016). In recent reviews of meteorological diagnoses in Xinjiang (Yao Lianmei et al., 2018; Yang Sen et al., 2018), the moisture originating from the Arabian Sea was considered as an important contribution for heavy precipitation. However, constrained by the isotopic data available, this viewpoint has not been verified using isotope records in precipitation.

Regarding the methods to diagnose the moisture

Received date: 2019-03-06; accepted date: 2019-06-28
Foundation item: Under the auspices of National Natural Science Foundation of China (No. 41701028, 41971034, 41161012), Scientific Research Program of Higher Education Institutions of Gansu Province (No. 2018C-02)
Corresponding author: WANG Shengjie. E-mail: geowang@126.com
© Science Press, Northeast Institute of Geography and Agroecology, CAS and Springer-Verlag GmbH Germany, part of Springer Nature 2020

transport, the stable water isotopes have gained increasing attentions in past decades (Gimeno et al., 2012; Esquivel-Hernández et al., 2019). The measurement and simulation of stable isotopes in precipitation or water vapor provide an effective approach to understand the precipitation process on synoptic, seasonal, and annual scales, which is a useful addition to traditional hydrometeorological studies (Zhang and Wang, 2016; Bowen et al., 2019). In arid northwest China, precipitation is isotopically depleted in winter and enriched in summer (Li et al., 2010; Wang et al., 2016c; Wang et al., 2019), which is usually attributed to the westerlies in most isotope-based studies across this region (Araguás-Araguás et al., 1998; Tian et al., 2007; Zhang and Wang, 2018). Some studies focused on the detailed regimes of the westerly path and isotope signature in precipitation. The southward westerly from lower latitudes usually results in isotopically enriched precipitation (Liu et al., 2015; Yang J et al., 2018). The meteorological parameters along moisture trajectory may also be considered in moisture source diagnosis (Wang et al., 2017).

A series of rainstorms occurred at the southwestern part of the southern Tianshan Mountains during the period from late-May to mid-June 2013, causing flood disasters in this region (Zhang et al., 2014), which is also listed as one of the annual 'top ten weather/climate events' in Xinjiang, China. Some meteorological researches aimed to diagnose the formation of rainstorm during this period, and the main finding was that the westerly and monsoon moistures play important roles in different formation stages respectively (Zhang et al., 2014; 2015; Zhao et al., 2017). This provides a good case to examine the isotope variations under different moisture sources.

In this study, based on the in-situ observation of precipitation isotopes at four stations along the southern Tianshan Mountains from west to east as well as the meteorological records, the isotope characteristics are determined for different stages, and the connection between moisture sources and isotopes was discussed. The purpose of this work was to provide a case study of stable isotope signatures of heavy precipitation events in arid central Asia. This study will be useful to understand the moisture regime of precipitation extremes in arid central Asia, and provides an evidence of moisture diagnostic using stable isotope method for an arid setting.

2 Data and Method

2.1 Study area

The Tianshan Mountains is one of the main mountain ranges across the arid central Asia. The total length from west to east is approximately 2500 km, and the eastern part is in Xinjiang of northwestern China. Annual precipitation of this mountain range is much higher than that of surrounding regions. As a typical wet island in arid central Asia, the Tianshan Mountains are regarded as a hot spot of stable water isotope research (Zhang and Wang, 2018). In this study, four national meteorological stations, Wuqia (39°43′N, 75°15′E, 2175.7 m), Akqi (40°56′N, 78°27′E, 1984.9 m), Aksu (41°10′N, 80°14′E, 1103.8 m) and Baicheng (41°47′N, 81°54′E, 1229.2 m) from west to east, were selected along southern slope of the Tianshan Mountains (Fig. 1 and Table 1).

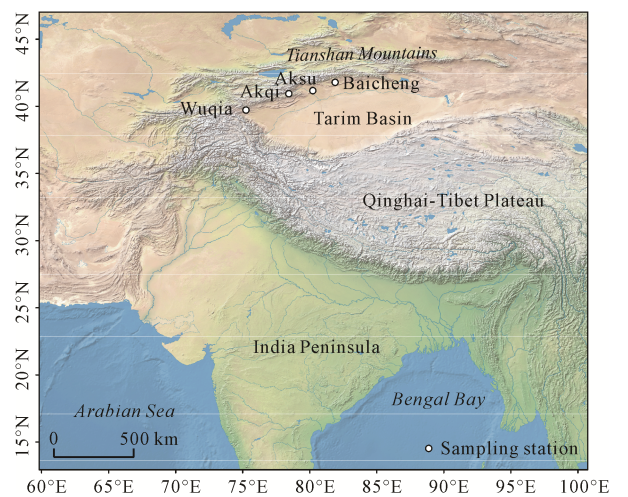

Fig. 1 Locations of four sampling meteorological stations along the southern Tianshan Mountains. The satellite-derived map was acquired from Natural Earth (http://www.naturalearthdata.com).

Table 1 Inventory of sampling stations and sample number in this study

Station	Latitude (N)	Longitude (E)	Altitude (m)	Sample number
Wuqia	39°43′	75°15′	2175.7	12
Akqi	40°56′	78°27′	1984.9	9
Aksu	41°10′	80°14′	1103.8	10
Baicheng	41°47′	81°54′	1229.2	12

2.2 Sample collection and analyzing

Event-based precipitation was sampled from late-May to mid-June 2013 by full-time weather reporter of local meteorological bureaus. Fig. 2 shows the variation of hourly surface air temperature and precipitation amount during the sampling period. The mean air temperature for the sampling period is 16.5℃, 16.6℃, 22.0℃ and 19.2℃, and the total precipitation amount is 31.4, 74.8, 109.5 and 39.0 mm in Wuqia, Akqi, Aksu and Baicheng from west to east, respectively. From May 21st to June 20th in 2013, 43 samples were collected at the four stations (Table 1). The precipitation event samples were directly filled into HDPE (low-density polyethylene) bottles; for the hail events, samples were melted in zip-locked bags at room temperature and then sealed into bottles. The data is a subset of compiled database of stable isotopes in precipitation across the Tianshan Mountains (Wang et al., 2016c). The meteorological data at these stations were also recorded by the corresponding meteorological bureaus.

The precipitation samples were analyzed in the Stable Isotope Laboratory, College of Geography and Environmental Science, Northwest Normal University using a liquid water isotope analyzer model DLT-100 (Los Gatos Research, Inc.). To remove the memory effect, every standard and sample was injected six times and the arithmetic mean of last four was considered as the valid measurement value. The oxygen isotope ratio is expressed as delta-values relative to V-SMOW (Vienna standard mean ocean water):

$$\delta_{\text{sample}} = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000‰ \quad (1)$$

where R_{sample} and R_{standard} are the $^{18}O/^{16}O$ ratio in sample and V-SMOW, respectively. The measurement precision for the $\delta^{18}O$ is ±0.2‰ (Wang et al., 2016c).

2.3 Identification of precipitation stages

To identify the stages of precipitation extremes, a non-parametric method of 99% and 95% percentiles (R99p and R95p, also called extremely wet days and very wet days, respectively) (Alexander et al., 2006; Klein Tank et al., 2006) were applied. The precipitation index R99p (R95p) denotes the day with precipitation amount larger than the 99th (95th) percentile of daily precipitation amounts during the reference period. In this study, the reference period was defined from date that measurements at the specific meteorological station started until 2013. As shown in Table 2, there were three extremely wet days (R99p) during this period, i.e., May

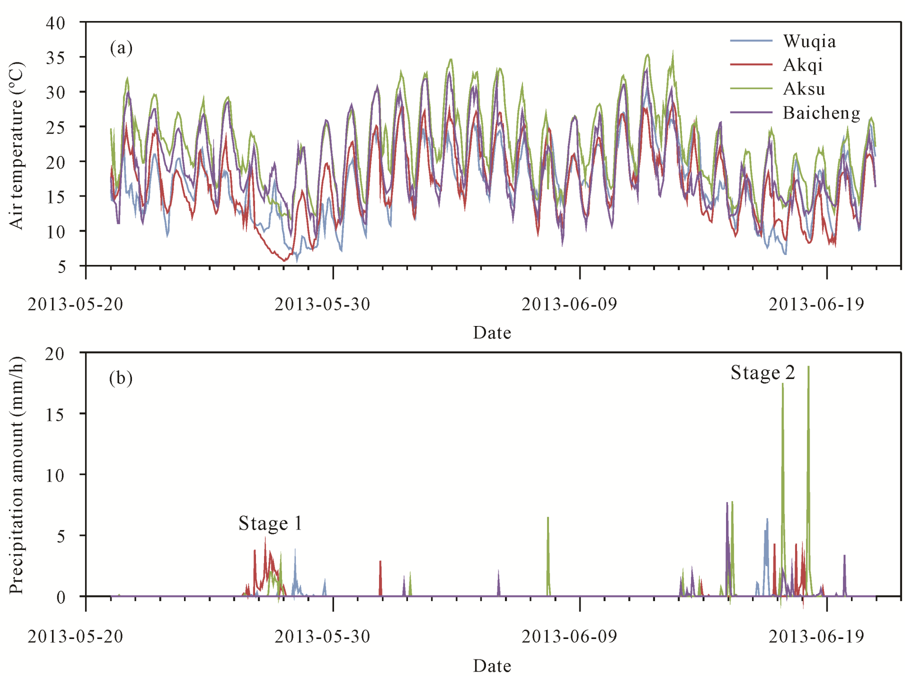

Fig. 2 Hourly variation of mean air temperature and precipitation amount in meteorological stations of Wuqia, Akqi, Aksu and Baicheng from late-May to mid-June 2013. Stage 1 is around May 27th, and Stage 2 is around June 17th.

Table 2 Date and daily precipitation amount (*P*) of extremely wet days (R99p) and very wet days (R95p) in Wuqia, Akqi, Aksu and Baicheng stations from late-May to mid-June 2013

Indices	Wuqia		Akqi		Aksu		Baicheng	
	Date	*P* (mm)	Date	*P* (mm)	Date	*P* (mm)	Date	*P* (mm)
R99p	–	–	May 27th	42.0	June 17th	31.8	–	–
					June 18th	31.3		
R95p	June 16th	19.9	May 27th	42.0	May 27th	12.7		
					June 15th	17.0	June 15th	14.9
					June 17th	31.8	June 17th	10.6
					June 18th	31.3		

27th (42.0 mm, Akqi), June 17th (31.8 mm, Aksu) and June 18th (31.3 mm, Aksu). According to the extremely wet and very wet days (Fig. 2 and Table 2), the precipitation events mainly concentrated at two stages: stage 1 around May 27th, and stage 2 around June 17th.

2.4 Global meteorological data

The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 (Kistler et al., 2001) with a spatial resolution of 2.5° × 2.5° was used to calculate the water vapor stream flux and precipitable water from the surface to 300 hPa isobaric level.

To assess the spatial distribution of precipitation across the study region, we also applied the CMORPH (NOAA CPC MORPHing Technique) product, a global precipitation analysis at high spatial and temporal resolution (Joyce et al., 2004). The accuracy of the CMORPH database in the study region has been assessed in many previous studies (Yang et al., 2014; Huang et al., 2016).

3 Results

3.1 Isotope signature variation in precipitation

Precipitation extremes occurred in Akqi on May 27th, and precipitation events higher than 5 mm were also recorded in Wuqia and Aksu that belongs to stage 1 (around May 27th) (Fig. 3). The isotopic depletion trend was detected at each station at this stage, which was explained by the amount effect (as continuing precipitation, heavy isotopes become increasingly depleted) along the trajectory. Regarding the respective meteorological records, air temperature suddenly decreased during this stage, and vapor pressure shows a peak. Although the air temperature drop was also observed in Baicheng, the easternmost station, there was no important precipitation at this site. Generally, if the precipitation of stage 1 was caused by a same air mass from west to east, the eastern sites would produce more isotopically depleted precipitation than the western sites. However, this was not the case shown in Fig. 3. In the study region along the Tianshan Mountains, the four sampling stations had large elevation differences, and the two western sites were much higher (approximately 1000 m) than the eastern ones. In an integrated investigation across the Tianshan Mountains (Wang et al., 2016c), precipitation isotope ratio negatively correlated with altitude in summertime, which meant that precipitation in high-elevation stations was usually isotopically depleted. This may influence the isotope variation in precipitation along the westerly path. Additionally, in stage 1, the precipitation amount in Akqi was much higher than that of the surrounding stations, and the amount effect maybe more significant.

After the precipitation process in stage 1, the following two weeks were generally arid. In the Tianshan Mountains (Wang et al., 2016b; 2016c), as the precipitation amount decreases, δ^{18}O usually shows an increasing trend, which indicates the influence of below-cloud evaporation of precipitation drops in an arid environment. Logically, the high isotope ratio in small precipitation events during this relatively arid period is associated with the below-cloud process. For example, in a sample in Aksu (June 2nd, 01:10 to 03:16 Beijing Time) from a precipitation height of 1.1 mm δ^{18}O was up to 6.2‰. It should also be mentioned that hail occurred at Akqi (May 31st) and Aksu (June 7th), which may have led to a different fractionation process. Hail may be subjected to a weak below-cloud evaporation, and consequently lead to samples having a relatively low isotope ratio (Jouzel et al., 1975; Zhao, 1988).

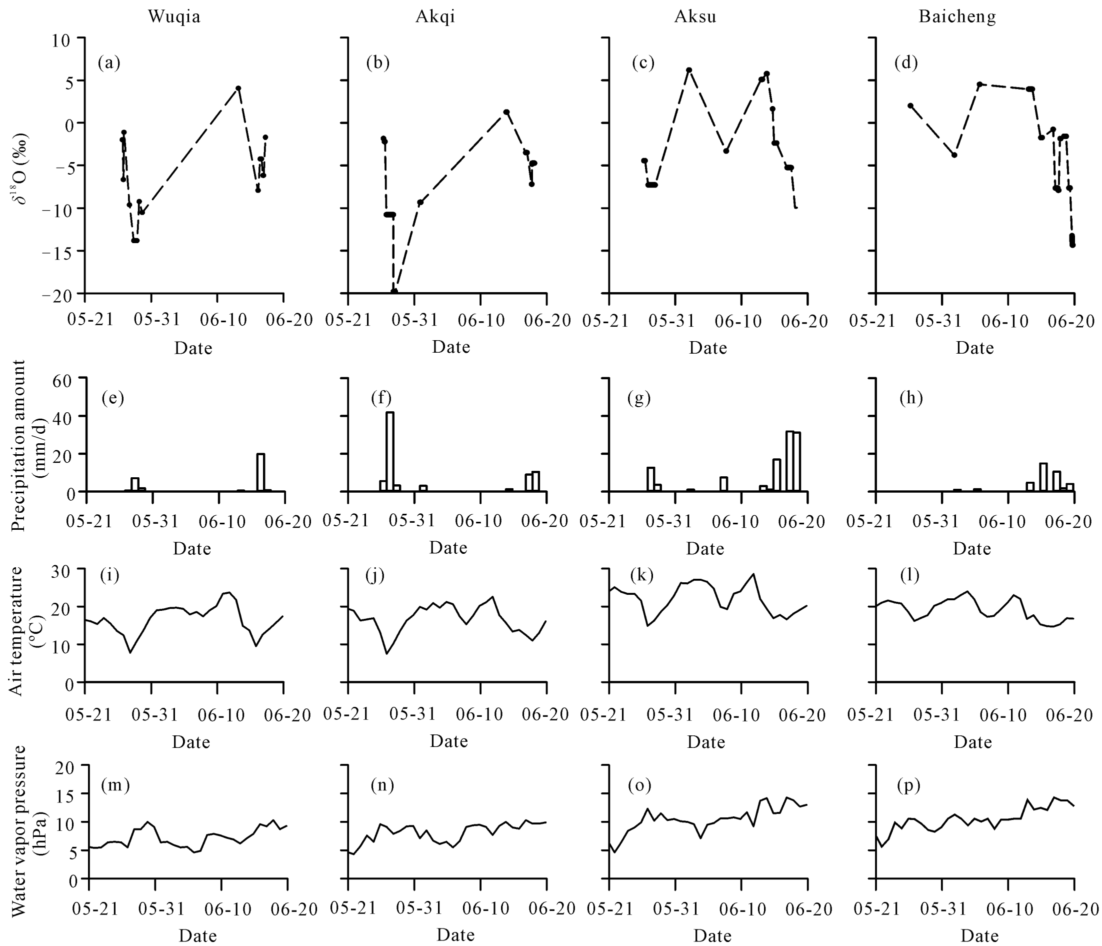

Fig. 3 Variations of δ^{18}O in event-based precipitation samples and daily meteorological parameters in stations of Wuqia, Akqi, Aksu and Baicheng from May to June 2013

Around June 17th, another episode of important precipitation occurred in the study region, referred hereafter to as stage 2. During this stage, precipitation occurred in all four stations. In Aksu two extremely wet days were recorded (June 17th and 18th). In Wuqia and Akqi, the δ^{18}O values depleted and then enriched during stage 2. In Aksu, δ^{18}O decreased continuously until precipitation ended. In Baicheng, a depletion-enrichment-depletion cycle was observed. The neighboring four stations showed incoherent isotopic patterns, which was not the case during stage 1. Regarding daily vapor pressure, at the eastern two stations vapor pressure remained higher than 10 hPa, but vapor pressures at the western two sites was generally lower than 10 hPa. This temporal variability of δ^{18}O as well as the meteorological parameters indicates that the moisture paths during stage 1 and stage 2 may have not been coherent.

3.2 Other moisture path evidence

According to the vapor stream flux derived from the NCEP/NCAR Reanalysis, a difference in moisture path can be detected for the two stages of precipitation extremes (Fig. 4). In stage 1 (Figs. 4a–4c), moisture stream came from the western direction. However, in stage 2 (Figs. 4d–4f), the moisture path appeared to be complex. On June 14th, westerly wind was dominant in the study region, and only limited precipitation events were observed; on June 15th, moisture from the Arabian Sea moved northward to southern Xinjiang and then met the cold air from the north, which produced precipitation in many stations; on June 16th (and after this date), the continuous transport of Arabian Sea moisture caused heavy precipitation extremes. As described in many meteorological analyses of this period (Zhang et al., 2014; 2015; Zhao et al., 2017), stage 1 was controlled

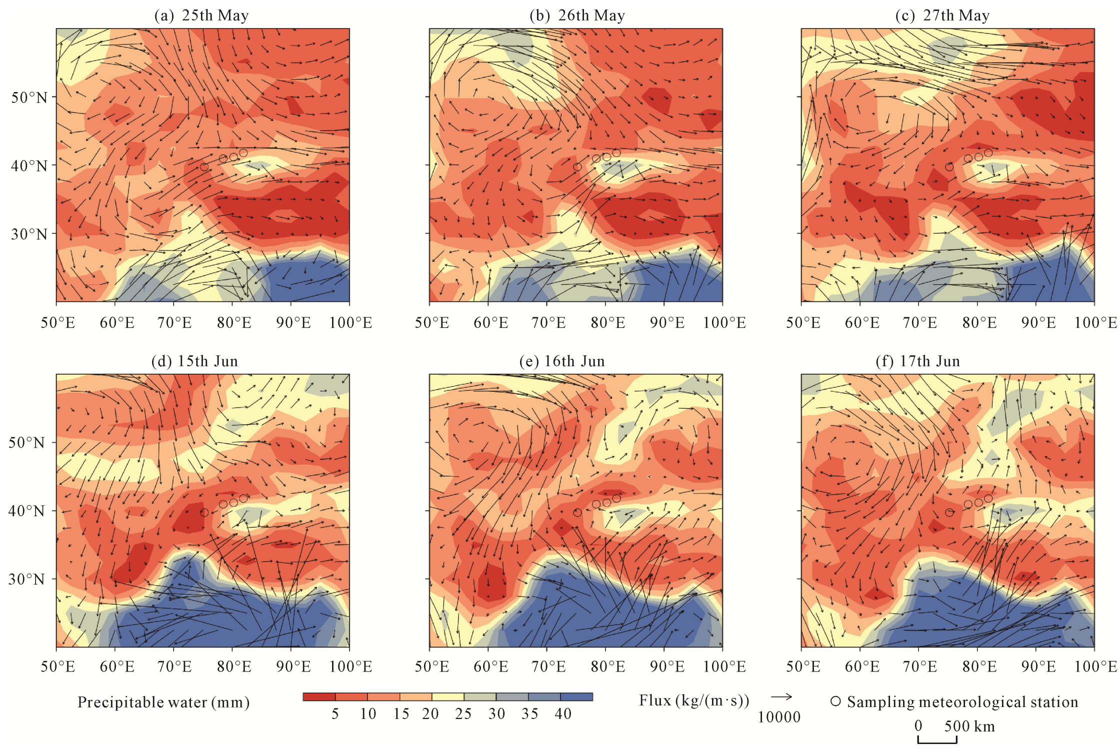

Fig. 4 Daily water vapor flux and precipitable water from surface to 300 hPa during May 25th–27th and June 15th–17th around the Tianshan Mountains

by warm/wet air mass from central Asia and cold air mass from Arctic, and stage 2 was affected by both warm/wet air from southwest ocean source and cold air mass from Arctic; which are consistent with the isotopic variability observed at four sampling stations.

Based on the CMORPH precipitation data, the spatial distribution of precipitation amount is shown in Fig. 5. During stage 1, it was clear that the precipitation zone moves from west to east along the Tianshan Mountains. The precipitation events in the study region were connected with the westerly moisture transferred via the central Asia, and there was no continuous precipitation zone from the Arabian Sea to the study region. On the contrary, during stage 2, there was always a continuous precipitation zone from the Arabian Sea to northwestern China. This meant that the moisture from the Arabian Sea may be delivered to arid central Asia, although the local recycled moisture cannot be ignored; this was generally consistent with the common meteorological analysis of this typical precipitation extreme events (Zhang et al., 2014).

4 Discussion

The westerly-delivered moisture from the Atlantic Ocean (and the terrestrial evaporation along the westerly path) is widely considered as the main source for precipitation in central Asia, especially in Xinjiang, northwest China. Li et al. (2015b) investigated the contribution of the eastern Asian monsoon (Pacific moisture) to the northeastern margin of the Tibetan Plateau using isotope techniques, but their work does not cover our study region showing a more arid setting. Can monsoon moisture reach arid central Asia, especially Xinjiang? Meteorological studies have observed the contribution of monsoon in such an arid condition, which can be identified using the reanalysis-based moisture flux field, satellite cloud photograph and many other techniques (Zhang and Deng, 1987; Yang et al., 2011; Yang Lianmei et al., 2018; Yao Junqiang et al., 2018). It is clear that the precipitation in Xinjiang can not be easily described as westerlies-derived, although westerlies controls the air regime of this region all year round. When frequent tropical depressions occur at the Indian Peninsula and the Arabian Sea, some marine moisture may rise and cross the Tibetan Plateau though the southwestern air flow and reach southern and even northern Xinjiang (Yang Lianmei et al., 2018; Yao Junqiang et al., 2018).

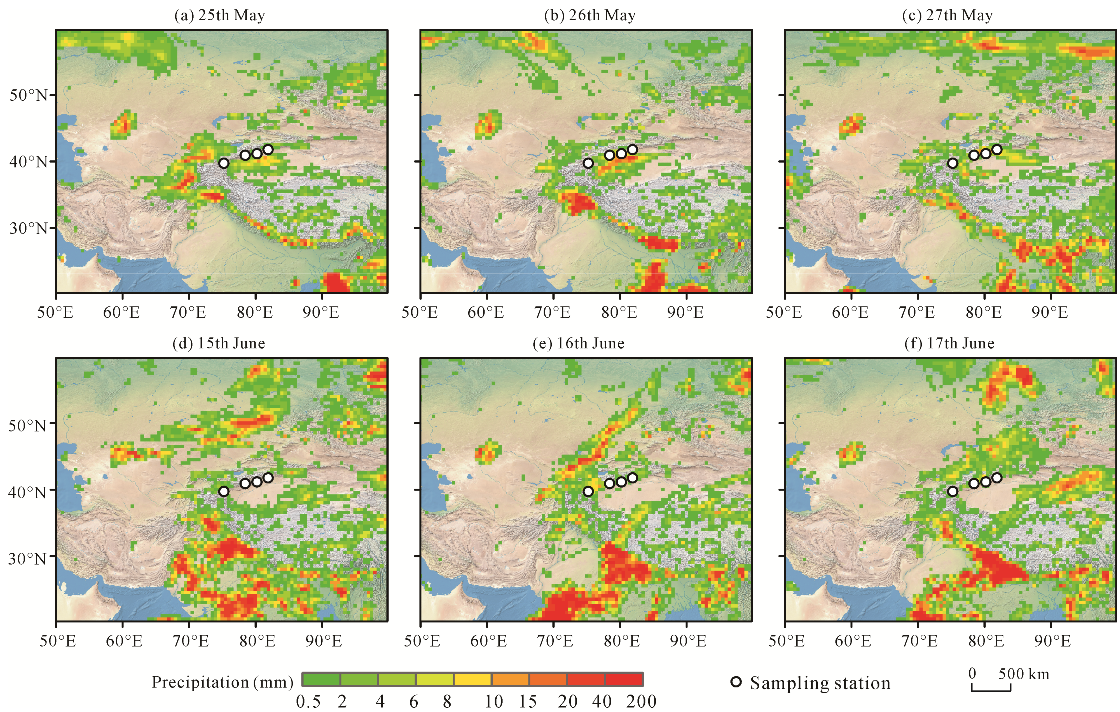

Fig. 5 Daily precipitation amount during May 25th–27th and June 15th–17th around the Tianshan Mountains

However, this viewpoint of monsoon moisture over the plateau is not well considered and has not been verified by stable water isotope studies, reducing thus the importance of stable isotope method in interpreting some modern meteorological phenomena. The moisture source or trajectory information in precipitation isotopes is modified due to below-cloud evaporation (Pang et al., 2011; Wu et al., 2015; Wang et al., 2016b), moisture recycling (Wang et al., 2016a; Li et al., 2019) and other processes (Wang et al., 2017). In addition, the moisture information can be hardly checked using in-situ observations without enough spatial and temporal resolution. The widely applied data of GNIP station are generally monthly, therefore many synoptic details have been smoothed. In this study event-based samples were collected, consequently more details on the different stages of moisture path have been detected.

In southern Xinjiang, the annual mean precipitation amount is very low. In many cases, when a precipitation extreme occurs, the daily amount may correspond to a large proportion of the annual total and even higher than that of the long-term climatology on an annual basis. In Aksu for example, the 1981–2010 long-term mean precipitation amount is 80.4 mm/yr, so the maximum daily amount (31.8 mm) during the sampling period, corresponds to approximately 40% of annual precipitation amount. In this and many other studies (e.g., Li et al., 2015a), heavy precipitation events usually are much isotopically depleted. If these records of low isotope ratios are well maintained in climate proxies like ice cores and stalagmites in arid central Asia, the interpretation of isotope variability should be carefully considered. In other words, in the study region, the information of short-period precipitation extremes may be mixed into the climate proxies and then lead to high uncertainty in paleoclimate reconstruction.

5 Conclusions

Among the modern technologies to diagnose the moisture transport, the stable hydrogen and oxygen isotopes have gained increasing attentions, which is considered as a useful addition to traditional hydrometeorological methods. From May to June of 2013, heavy precipitation occurred at the southern Tianshan Mountains, providing a good case to examine the linkage between stable isotope signature and moisture transport. In this study, 43 samples were collected at the four meteorological stations, Wuqia, Akqi, Aksu and Baicheng. We presented a case study in central Asia where both the westerly and monsoon moisture can be delivered as an extreme precipitation event. According to other proxies such as the reanalysis-based water vapor flux and satellite-derived precipitation, the event-based precipitation isotopes sensitively reflected the moisture process from different sources of monsoon and westerly. In arid central Asia, the stable isotope compositions can be an alternative tool to understand the atmospheric processes.

Acknowledgements

The authors greatly thank the prefecture meteorological bureaus of Aksu and Kizilsu and four meteorological stations (Wuqia, Akqi, Aksu and Baicheng) for collecting the precipitation samples and the colleagues in the Northwest Normal University for their help in laboratory analysis.

References

Alexander L V, Zhang X, Peterson T C et al., 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research*, 111(D5): D05109. doi: 10.1029/2005JD006290

Araguás-Araguás L, Froehlich K, Rozanski K, 1998. Stable isotope composition of precipitation over southeast Asia. *Journal of Geophysical Research*, 103(D22): 28721–28742. doi: 10.1029/98JD02582

Bowen G J, Cai Z, Fiorella R P et al., 2019. Isotopes in the water cycle: regional- to global-scale patterns and applications. *Annual Review of Earth and Planetary Sciences*, 47: 453–479. doi: 10.1146/annurev-earth-053018-060220

Chen A, He X, Guan H et al., 2019. Variability of seasonal precipitation extremes over China and their associations with large-scale ocean-atmosphere oscillations. *International Journal of Climatology*, 39(2): 613–628. doi: 10.1002/joc.5830

Esquivel Hernández G, Mosquera G M, Sánchez Murillo R et al., 2019. Moisture transport and seasonal variations in the stable isotopic composition of rainfall in Central American and Andean Páramo during El Niño conditions (2015–2016). *Hydrological Processes*, 33(13): 1802–1817. doi: 10.1002/hyp.13438

Gimeno L, Stohl A, Trigo R M et al., 2012. Oceanic and terrestrial sources of continental precipitation. *Reviews of Geophysics*, 50(4): RG4003. doi: 10.1029/2012RG000389

Huang A, Zhao Y, Zhou Y et al., 2016. Evaluation of multisatellite precipitation products by use of ground-based data over China. *Journal of Geophysical Research*: *Atmospheres*, 121(18): 10654–10675. doi: 10.1002/2016JD025456

Jouzel J, Merlivat L, Roth E, 1975. Isotopic study of hail. *Journal of Geophysical Research*, 80(36): 5015–5030. doi: 10.1029/JC080i036p05015

Joyce R J, Janowiak J E, Arkin P A et al., 2004. CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *Journal of Hydrometeorology*, 5(3): 487–503. doi: 10.1175/1525-7541(2004)005<0487:CAMTPG>2.0.CO;2

Kistler R, Kalnay E, Collins W et al., 2001. The NCEP–NCAR 50-year reanalysis: monthly means CD-ROM and documentation. *Bulletin of the American Meteorological Society*, 82(2): 247–268. doi: 10.1175/1520-0477(2001)082<0247:TNNYRM>2.3.CO;2

Klein Tank A M G, Peterson T C, Quadir D A et al., 2006. Changes in daily temperature and precipitation extremes in central and south Asia. *Journal of Geophysical Research*, 111(D16): D16105. doi: 10.1029/2005JD006316

Li J, Tao T, Pang Z et al., 2015a. Identification of different moisture sources through isotopic monitoring during a storm event. *Journal of Hydrometeorology*, 16(4): 1918–1927. doi: 10.1175/JHM-D-15-0005.1

Li Z, Gao Y, Wang Y et al., 2015b. Can monsoon moisture arrive in the Qilian Mountains in summer? *Quaternary International*, 358: 113–125. doi: 10.1016/j.quaint.2014.08.046

Li Z, Gui J, Wang X et al., 2019. Water resources in inland regions of central Asia: evidence from stable isotope tracing. *Journal of Hydrology*, 570: 1–16. doi: 10.1016/j.jhydrol.2019.01.003

Li Zhongqin, Li Huilin, DONG Zhiwen et al., 2010. Chemical characteristics and environmental significance of fresh snow deposition on Urumqi Glacier No. 1 of Tianshan Mountains, China. *Chinese Geographical Science*, 20(5): 389–397. doi: 10.1007/s11769- 010-0412-6

Liu X, Rao Z, Zhang X et al., 2015. Variations in the oxygen isotopic composition of precipitation in the Tianshan Mountains region and their significance for the Westerly circulation. *Journal of Geographical Sciences*, 25(7): 801–816. doi: 10.1007/s11442-015-1203-x

Meng X, Long A, Wu Y et al., 2018. Simulation and spatiotemporal pattern of air temperature and precipitation in Eastern Central Asia using RegCM. *Scientific Report*, 8: 3639. doi: 10.1038/s41598-018-21997-4

Pang Z, Kong Y, Froehlich K et al., 2011. Processes affecting isotopes in precipitation of an arid region. *Tellus B*, 63(3): 352–359. doi: 10.1111/j.1600-0889.2011.00532.x

Tian L, Yao T, MacClune K et al., 2007. Stable isotopic variations in west China: A consideration of moisture sources. *Journal of Geophysical Research*, 112(D10): D10112. doi: 10.1029/2006JD007718

Wang L, Dong Y, Han D et al., 2019. Stable isotopic compositions in precipitation over wet island in Central Asia. *Journal of Hydrology*, 573: 581–591. doi: 10.1016/j.jhydrol.2019.04.005

Wang S, Zhang M, Che Y et al., 2016a. Contribution of recycled moisture to precipitation in oases of arid central Asia: a stable isotope approach. *Water Resources Research*, 52(4): 3246–3257. doi: 10.1002/2015WR018135

Wang S, Zhang M, Che Y et al., 2016b. Influence of below-cloud evaporation on deuterium excess in precipitation of arid central Asia and its meteorological controls. *Journal of Hydrometeorology*, 17(7): 1973–1984. doi: 10.1175/JHM-D-15-0203.1

Wang S, Zhang M, Crawford J et al., 2017. The effect of moisture source and synoptic conditions on precipitation isotopes in arid central Asia. *Journal of Geophysical Research*: *Atmospheres*, 122(5): 2667–2682. doi: 10.1002/2015JD024626

Wang S, Zhang M, Hughes C E et al., 2016c. Factors controlling stable isotope composition of precipitation in arid conditions: an observation network in the Tianshan Mountains, central Asia. *Tellus B*, 68(1): 26206. doi: 10.3402/tellusb.v68.26206

Wu H, Zhang X, Li X et al., 2015. Seasonal variations of deuterium and oxygen-18 isotopes and their response to moisture source for precipitation events in the subtropical monsoon region. *Hydrological Processes*, 29(1): 90–102. doi: 10.1002/hyp.10132

Yang Lianmei, Guan Xuefeng, Zhang Yingxin, 2018. Atmospheric circulation characteristics of precipitation anomaly in arid regions in central Asia. *Arid Zone Research*, 35(2): 249–259. (in Chinese)

Yang Lianmei, Li Xia, Zhang Guangxing, 2011. Some advances and problems in the study of heavy rain in Xinjiang. *Climatic and Environmental Research*, 16(2): 188–198. (in Chinese)

Yang Sen, Zhang Mingjun, Wang Shengjie, 2018. Affecting mechanism of moisture sources of isotopes in precipitation in the Tianshan Mountains based on GCMs and ice core. *Arid Zone Research*, 35(2): 425–435. (in Chinese)

Yang Y, Luo Y, 2014. Evaluating the performance of remote sensing precipitation products CMORPH, PERSIANN, and TMPA, in the arid region of northwest China. *Theoretical and Applied Climatology*, 118(3): 429–445. doi: 10.1007/s00704-013-1072-0

Yao Junqiang, Yang Qing, Mao Weiyi et al., 2018. Progress of study on variation of atmospheric water cycle factors over arid region in Northwest China. *Arid Zone Research*, 35(2): 269–276. (in Chinese)

Yao J, Zhao Y, Chen Y et al., 2018. Multi-scale assessments of droughts: A case study in Xinjiang, China. *Science of the Total Environment*, 630: 444–452. doi: 10.1016/j.scitotenv.2018.02.200

Zhang Jiabao, Deng Zifeng, 1987. *An Introduction to Precipitation in Xinjiang*. Beijing: China Meteorological Press. (in Chinese)

Zhang Junlan, Wei Rongqing, Yang Liu, 2014. Comparison of precipitation area and intensity of two rare heavy rainfall over Southern Xinjiang in 2013. *Desert and Oasis Meteorology*, 8(5): 1–9. (in Chinese)

Zhang M, Chen Y, Shen Y et al., 2017. Changes of precipitation extremes in arid Central Asia. *Quaternary International*, 436(A): 16–27. doi: 10.1016/j.quaint.2016.12.024

Zhang M, Wang S, 2016. A review of precipitation isotope studies in China: basic pattern and hydrological process. *Journal of Geographical Sciences*, 26(7): 921–938. doi: 10.1007/s11442-016-1307-y

Zhang M, Wang S, 2018. Precipitation isotopes in the Tianshan Mountains as a key to water cycle in arid central Asia. *Sciences in Cold and Arid Regions*, 10(1): 27–37. doi: 10.3724/SP.J.1226.2018.00027

Zhang Yunhui, Li Haiyan, Lin Xilu et al., 2015. Analysis of continuous rainstorm circulation background and the dynamic process of synoptic-scale in west of Southern Xinjiang. *Meteorological Monthly*, 41(7): 816–824. (in Chinese)

Zhao Keming, Huang Yan, Yu Bixin, 2017. Water vapor characteristics of rainstorm weather processes over western South Xinjiang in 2013. *Meteorological Science and Technology*, 45(1): 121–129. (in Chinese)

Zhao Shixiong, 1988. Isotopic study of hailstones on the plateau. *Acta Meteorologica Sinica*, 2(3): 394–403. (in Chinese)

Zhao Yong, Huang Anning, Wang Qian et al., 2016. The relation between thermal anomaly contrast over the Tibetan Plateau and its surrounding areas in May and summer rainfall in Northern Xinjiang. *Climatic and Environmental Research*, 21(6): 653–662. (in Chinese)

Zheng Z, Ma Z, Li M et al., 2017. Regional water budgets and hydroclimatic trend variations in Xinjiang from 1951 to 2000. *Climatic Change*, 144(3): 447–460. doi: 10.1007/s10584-016-1842-7