

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

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**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  $\delta^{18}\text{O}$  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

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## 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

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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).

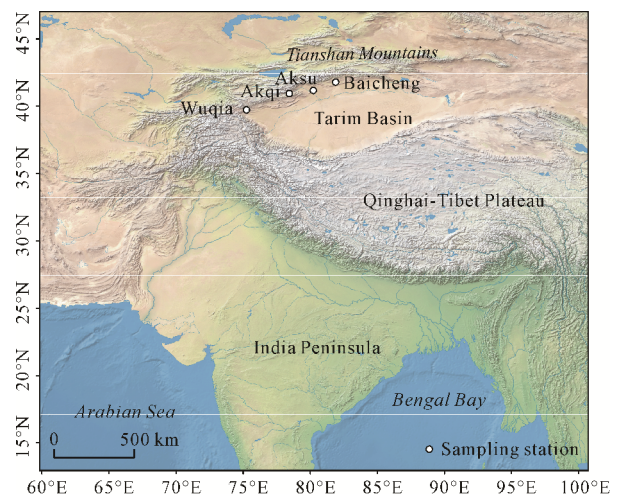
A series of rainstorms occurred at the southwestern part of the southern Tianshan Mountains during the period from late-May to mid-June 2013, causing flood disasters in this region (Zhang et al., 2014), which is also listed as one of the annual ‘top ten weather/climate events’ in Xinjiang, China. Some 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°C, 16.6°C, 22.0°C and 19.2°C, 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,

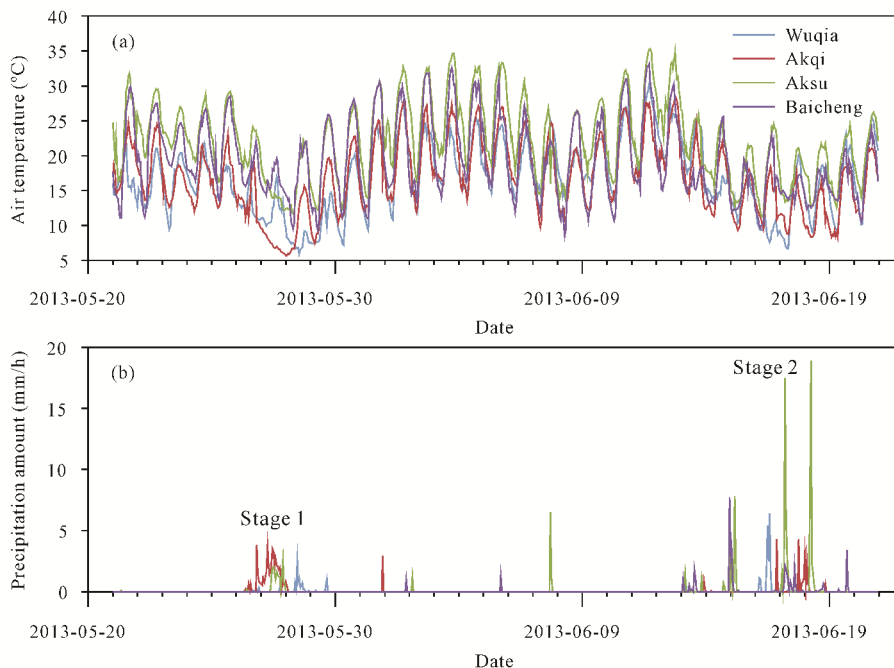
every standard and sample was injected six times and the arithmetic mean of last four was considered as the valid measurement value. The oxygen isotope ratio is expressed as delta-values relative to V-SMOW (Vienna standard mean ocean water):

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

where  $R_{\text{sample}}$  and  $R_{\text{standard}}$  are the  $^{18}\text{O}/^{16}\text{O}$  ratio in sample and V-SMOW, respectively. The measurement precision for the  $\delta^{18}\text{O}$  is  $\pm 0.2\text{‰}$  (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  $2.5^\circ \times 2.5^\circ$  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).

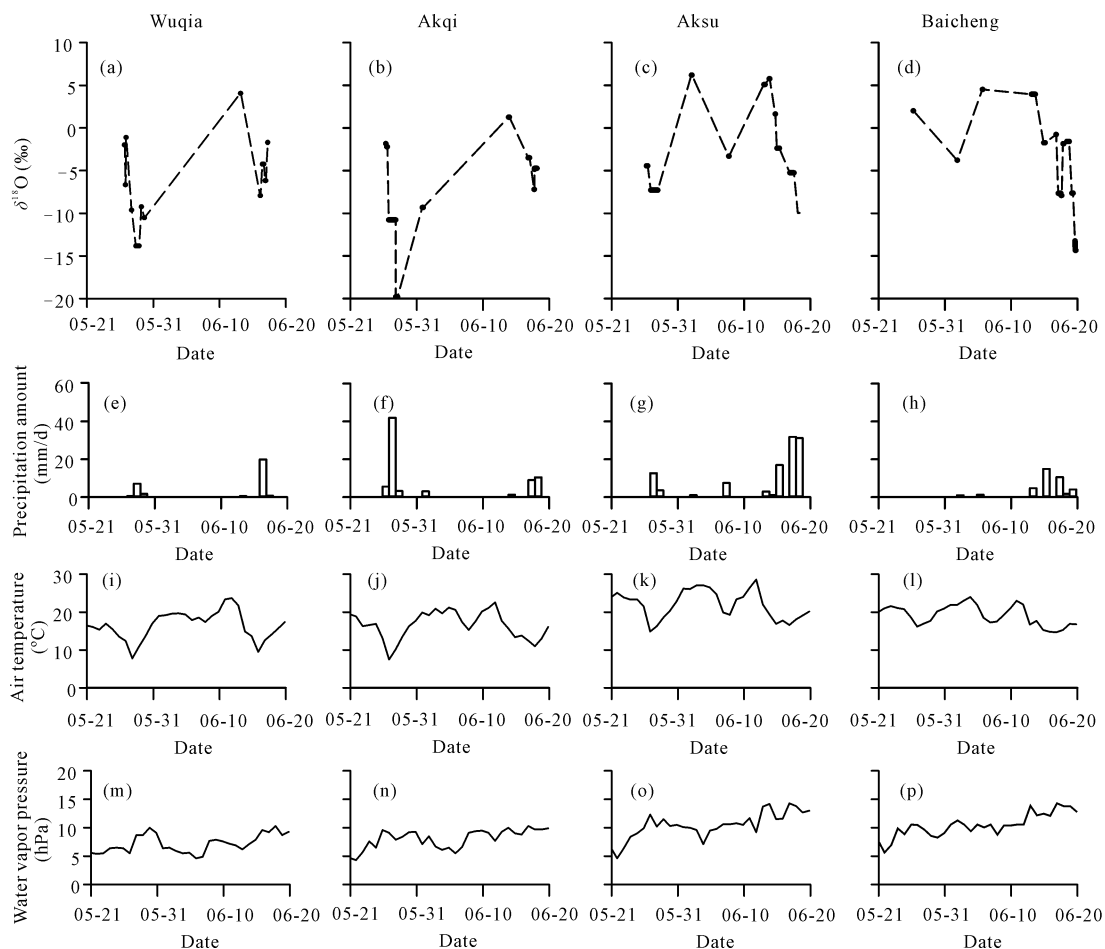
### 3 Results

#### 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,  $\delta^{18}\text{O}$  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  $\delta^{18}\text{O}$  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).



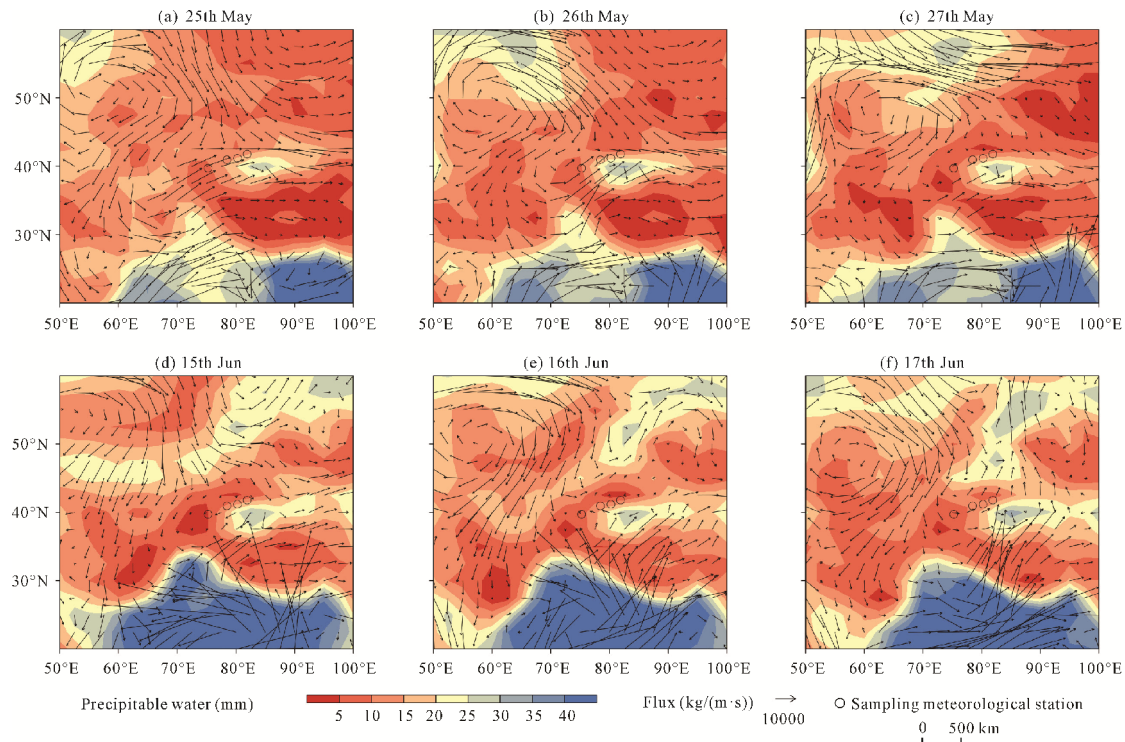
**Fig. 3** Variations of  $\delta^{18}\text{O}$  in event-based precipitation samples and daily meteorological parameters in stations of Wuqia, Akqi, Aksu and Baicheng from May to June 2013

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  $\delta^{18}\text{O}$  values depleted and then enriched during stage 2. In Aksu,  $\delta^{18}\text{O}$  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  $\delta^{18}\text{O}$  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

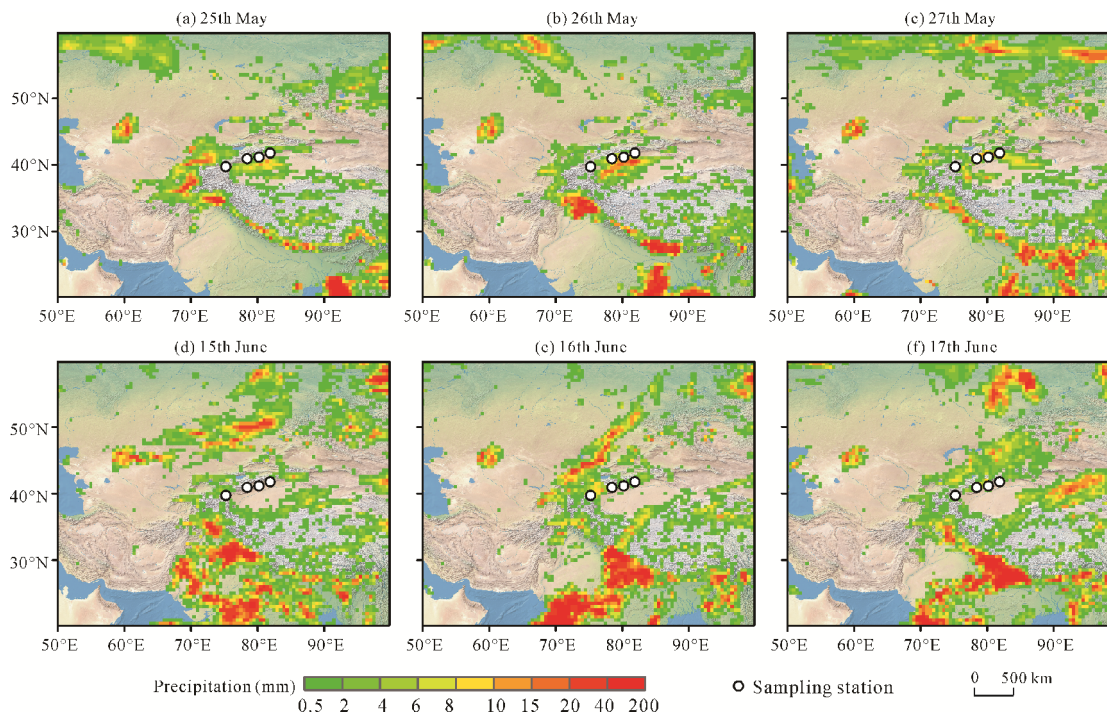
by warm/wet air mass from central Asia and cold air mass from Arctic, and stage 2 was affected by both warm/wet air from southwest ocean source and cold air mass from Arctic; which are consistent with the isotopic variability observed at four sampling stations.

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 through 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, corre-

sponds 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, Wujia, 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.

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