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Research papers

Meteoric water lines in arid Central Asia using event-based and monthly data

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ABSTRACT

The local meteoric water line (LMWL) reflects the relationship between stable oxygen and hydrogen isotopes in precipitation, and is usually calculated using an ordinary least squares regression (OLSR). When event-based data are used to calculate a LMWL, the differences in precipitation amount of samples are not considered using OLSR, which in turn may influence the representativeness of the LMWL for local hydrology. Small rain events occur widely in arid Central Asia (annual mean precipitation < 150 mm), and where smaller precipitation has lower deuterium excess, this results in LMWLs with slopes and intercepts lower than the global average. Based on an observation network of isotopes in precipitation across the Tianshan Mountains in arid Central Asia, LMWLs for 23 stations are calculated from event-based data from 2012 to 2013 ($n = 978$), using ordinary least squares, reduced major axis and major axis regressions and their precipitation-weighted counterparts. For the northern slope and mountainous areas, the LMWL slope and intercept are close to the Global Meteoric Water Line (GMWL), but the slope and intercept are lower for the southern slope indicating the greater dominance of sub-cloud evaporation. The effect of moisture recycling in the irrigated areas on the northern slope also can be seen where the LMWL slopes are > 8. Using a precipitation weighted regression method with event-based data (especially precipitation-weighted reduced major axis regression, PWRMA) is generally consistent with the OLSR regression using monthly data. However, event-based datasets provide a wider range of values to better constrain the regression than can be achieved using monthly data over a short period, providing a sounder basis for determining LMWLs for relatively short-term sampling campaigns in an arid setting. The use of the PWRMA regression is preferred for determining the LMWL for the Tianshan Mountains, and results in a regional meteoric water line of $\delta D = 7.9\delta^{18}O + 10.16$.

1. Introduction

The stable isotopes of hydrogen (δD) and oxygen ($\delta^{18}O$) in precipitation have been widely applied in studies of hydrological processes (e.g., Aggarwal et al., 2016; Sprenger et al., 2016; Zhang and Wang, 2016; Fischer et al., 2017), and the relationship between δD and $\delta^{18}O$ in precipitation underpins many studies using isotopic approaches. A strong linear relationship between δD and $\delta^{18}O$ in natural water was noticed in the mid-20th century (Friedman, 1953). Based on approximately 400 samples (~40% from North America and the rest distributed across the world), the best-fit line of $\delta D \sim \delta^{18}O$ ($\delta D = 8\delta^{18}O + 10$) was presented by Craig (1961), and was later named the global meteoric water line (GMWL). With the establishment of the Global Network of Isotopes in Precipitation (GNIP) (IAEA/WMO, 2017), the GMWL was updated using longer time series and more stations worldwide (e.g., Yurtsever and Gat, 1981; Rozanski et al., 1993; Gourcy et al., 2005), which confirmed that $\delta D = 8\delta^{18}O + 10$ was still a good approximation for the GMWL. The equation relating δD to $\delta^{18}O$ at a site is defined as a local meteoric water line (LMWL), and can provide a reference point for interpretation of stable isotopic compositions of a range of water samples in an area. Influenced by many geographic and meteorological factors, the slopes and intercepts of LMWLs vary depending on location. The comparison of the LMWL and GMWL can be used to assess moisture sources and precipitation processes and may

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indicate the degree of sub-cloud evaporation or the contribution of re-evaporated moisture to precipitation at a site.

An ordinary least squares regression (OLSR) is widely used to determine the LMWL, and this regression method logically gives all data points equal weighting (IAEA, 1992; Hughes and Crawford, 2012). Regarding the data used to calculate the regression, three options are commonly considered: 1) Use each month of data or each sample for event-based sampling; 2) Use the precipitation amount weighted average δ^{18}O and δ^{2}H values for each month (n = 12); and 3) Use annual precipitation amount weighted averages of δ^{18}O and δ^{2}H (n = years of record). To reduce the influence of precipitation amount on LMWL, monthly and annual weighted values have been recommended by the IAEA (1992). The method of pooling all samples in one month and measuring the composite (as is generally done for GNIP stations) does in fact partly weight the data for the size of events, particularly where rainfall occurs frequently.

The isotopic composition of event-based samples can provide detailed information about water processes, especially the short-term water vapor transport and rainout (e.g., Risi et al., 2008; Baldini et al., 2010; Crawford et al., 2013). During recent years, stable isotopes in event-based precipitation have been widely investigated, often based on sampling durations of approximately one or two years. The relatively short duration of studies may increase the uncertainty of LMWLs determined using event-based samples. Impacted by secondary evaporation of falling raindrops in the atmosphere, the equations relating δD to δ^{18}O for smaller amount events usually show lower slopes and intercepts (Peng et al., 2007), and light precipitation events usually have a relatively enriched δ^{18}O (Dansgaard, 1964; Bony et al., 2008) and low deuterium excess (D-excess, defined as $d = \delta\text{D}-8\delta^{18}\text{O}$) (Liu et al., 2008; Wu et al., 2015). In some studies, the smaller precipitation samples are even totally excluded in calculation (e.g., Harvey, 2001; Hughes and Crawford, 2013). Small rain events, which occur widely in arid and semi-arid regions (Fu et al., 2008; Liu et al., 2011), may therefore influence the representativeness of a LMWL for local conditions. In studies of major flow processes and water storage, heavy rainfall events normally play a dominant role, and applying equal weights to each sample may lead to a hydrologically unrepresentative result. Alternative methods (including precipitation-weighted approaches) are therefore valuable in determining LMWLs, especially in arid climates (Hughes and Crawford, 2012; Crawford et al., 2014).

Besides OLSR, a reduced major axis least squares regression (RMA) was introduced by IAEA (1992), and is suitable for the constant ratio of y and x-value standard deviations. An error-in-variables generalized least squared regression (GENLS) was presented by Argiriou and Lykoudis (2006), and allowed the errors of variables to be non-constant and instead incorporate the measurement uncertainties. Hughes and Crawford (2012) introduced the use of precipitation-weighted least squares regression (PWLSR) which can reduce the biases of small rainfall events to increase the usefulness for groundwater and surface hydrology applications. Crawford et al. (2014) then introduced two additional precipitation-weighted regressions to determine LMWL, and made a comparison between these and non-weighted regressions using GNIP data; all regressions result in a similar fit if a strong linear relationship exists, but the difference in fit is significant for some coastal and oceanic sites with a poor linear relationship between δD and δ^{18}O (even though monthly precipitation weighted values were used). In the current version of IAEA (International Atomic Energy Agency) Water Isotope System for Data Analysis (IAEA/WMO, 2017), three types of LMWL are available for each GNIP station, including OLSR, RMA and PWLSR.

The arid region of Central Asia lies at the inland of the Eurasian continent, where marine moisture from surrounding oceans rarely reaches (Fig. 1). The westerlies and polar vapor are usually considered as the dominant precipitation sources (Araguás-Araguás et al., 1998; Tian et al., 2007; Wang et al., 2017; Yao et al., 2013; Zhang and Wang, 2018). Regional mean precipitation in arid Central Asia is < 150 mm per year (Chen, 2012), ranging from < 10 mm at some desert basins to > 500 mm at some mountainous sites. The Tianshan Mountains (also known as Tien Shan), spanning multiple countries, are the main mountain ranges in arid Central Asia. A series of oases are distributed along the northern and southern slopes of the Tianshan Mountains, and many low-lying deserts such as the Taklimakan and Gurbantunggut deserts lie near the mountains. The oasis belt is also called the Tianshan Corridor, and is a vital section of the ancient Silk Road. In such an arid region, the local meteoric water line is an important reference in hydrological studies, and development of a meteoric water line using limited precipitation samples needs to be carefully considered (Oberhänsli et al., 2009; Huang and Pang, 2010). However, across the Tianshan Mountains the only existing LMWLs are for several closely located sites near Urumqi (Pang et al., 2011; Liu et al., 2014) and for the whole region (Wang et al., 2016c). In this study, LMWLs for 23 sampling stations covering ~500,000 km^2 across the Tianshan Mountains, China, are presented using multiple regressions. Although the observation period is still relatively short, the network provides a platform to understand the spatial pattern of LMWL. In addition, the differences between precipitation-weighted and unweighted regressions are considered, and meteorological controls on LMWLs are discussed.

2. Data and methods

2.1. Observation network

According to the physico-geographic regionalization of arid land in China (Chen, 2010), there are five natural areas across this region (Fig. 1 and Table 1): (1) The Junggar Basin desert area: This area generally lies at the northern slope of the Tianshan Mountains, and many small inland rivers flow to the northern desert. Due to the moisture path of westerlies, the precipitation amount for the western portion is larger than that for the eastern portion. (2) The Ili-Bayanbulak mountain area: This area generally consists of a westward river valley at the western portion (Ili) and a high-altitude basin at the eastern portion (Bayanbulak). For the Ili portion, the topography of westward valley captures plenty of westerly moisture, and leads to a relatively humid climate and a westward Ili River flowing to the Balkhash Lake; For the Bayanbulak portion, a vast wetland is located at the center, and the river flows to the southern desert. (3) The Tarim Basin desert area: This area lies at the southern slope of the Tianshan Mountains, and the climate is more arid than that in the northern slope due to the rain shadow effect of surrounding high mountains (i.e., the Tianshan Mountains and the Tibetan Plateau). The inland rivers originating from the mountains flow to the southern desert. (4) The Turpan Basin desert area: The area is a very arid basin with minimum elevation of −154 m, and lies at the southern slope of the eastern Tianshan Mountains. China's long-term meteorological record with the lowest mean precipitation amount (< 10 mm) occurs for this area. (5) The Hami Gobi desert area: This area lies at the eastern extremity of the southern slope of the Tianshan Mountains, and is at the western edge of the vast Gobi desert. In 2012, an integrated observation network of stable isotopes in precipitation was established across the Tianshan Mountains, arid Central Asia (Wang et al., 2016c). In this network, all the natural areas across the Chinese Tianshan Mountains were well covered. Considering the climate type and observation network, the neighboring Hami Gobi and Turpan Basin are combined in this study (Turpan-Hami).

Under a typical continental climate, air temperature in arid Central Asia shows a seasonal variation with warm/wet summers and cold/dry winters (Wang et al., 2016c). Generally the annual mean temperatures (Fig. 2a) of Junggar and Ili-Bayanbulak are lower than the other natural areas, although the temperature in Ili-Bayanbulak shows a wide spatial variability due to the complex topography in the mountains. In Fig. 2b, the precipitation amount in Ili-Bayanbulak is usually larger than the other areas, and the very limited precipitation is seen in Turpan-Hami.