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Isotope amount effects in hydrologic and climate reconstructions of monsoon climates: Implications of some long-term data sets for precipitation

C.J. Eastoe *, D.L. Dettman

Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA

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ABSTRACT

Many studies of Quaternary climate make use of terrestrial stable isotope records which are interpreted based on seasonal patterns of stable isotopes in modern precipitation. Multi-decade records of isotopes in rainfall allow testing of the assumed behavior of isotope signals used for this interpretation on multi-year to decadal scales. A 32-year record of stable O and H isotopes in precipitation in Tucson, Arizona permits a detailed examination of stable isotope amount effects, at time scales ranging from individual events to decades, in a location with summer monsoonal and winter frontal rainy seasons. Amount effects are weak to non-existent in Tucson at seasonal and longer time scales, and are not useful for discriminating either wetter or drier rainy seasons or wetter or drier decades. Amount effects are also weak to non-existent in published data for annual and multi-year amount-weighted averages for monsoonal precipitation in New Delhi and Hong Kong, but an annual amount effect appears to be present on Guam (U.S. Territory). In addition, site-specific amount effects do not correlate with measures of regional monsoon intensity. This data analysis challenges the general validity of paleoclimate reconstructions based on short-term (sub-annual) relationships observed in precipitation isotope data when applied to long-term records such as speleothem studies.

1. Introduction

Time-series stable isotope data are frequently enlisted as proxies of climate variations during the late Quaternary and on longer time scales. Often, stable isotope ratios in a geological archive are interpreted as somehow related to the isotopic composition of ancient precipitation and that inferred variance in ancient rainfall or surface water is related to changes in the ancient climate at that location. Some examples of this are the use of oxygen isotopes in lacustrine carbonates, mollusk shells, ice cores, speleothems and tree rings among many others. For example, speleothem carbonates hold oxygen isotope records interpreted in terms of changes (qualitative or quantitative) in local temperature or rainfall amounts through time. In ice cores, O or H isotope ratios are related to temperature changes in the record. In each of these approaches, interpretation of a stable isotope record tends to rely on an idealized conception of the behavior of water isotopes in the hydrologic cycle. Most commonly, authors extrapolate a short-term (seasonal or annual) relationship between stable isotopes in precipitation and a climate variable and apply this relationship to time scales of interest in climate research; or authors may take modern regional or spatial relationships and apply them through time (e.g. Fleitman et al., 2003; Paulsen et al. 2003, Cheng et al., 2006; Yadava et al., 2004; Yadava and Ramesh, 2005; Yuan et al., 2004). It is not clear if the use of short term or local relationships is valid in the interpretation of stable isotope records that span thousands of years and record transitions in climate. As longer records of modern isotopes in precipitation become available some of these relatively simplistic relationships can be tested on a multi-year to decadal basis, although questions clearly remain about the validity of extrapolation to millennial climate variability.

In this paper, we present a new data set for Tucson, Arizona (Table 1). The data have few gaps across a span of 32 years, a period including an observed change in local climate. Our aims are: first, to examine the relationships between $\delta^{18}O$ and precipitation amount (the "amount effect") at a single location (Tucson) at seasonal to decadal time scales, using raw data, and amount-weighted and arithmetic means; and second, to discuss the results in the context of hydrologic and paleoclimate reconstructions, particularly those deriving from speleothem isotope data. We focus on the amount effect because: 1. Precipitation data from Tucson have been cited as an example of rainfall isotope data depending in part on seasonal amount (Wright et al., 2001; Wagner et al., 2010); 2. Seasonal amount-effects have been proposed elsewhere in the region (e.g. central Texas, Pape et al., 2010); 3. Explanations of rainfall isotope data in western North America in

* Corresponding author at: Department of Geosciences (retired), University of Arizona, Tucson AZ 85721, USA. Tel.: +1 520 791 7430.
E-mail addresses: eastoe@email.arizona.edu (C.J. Eastoe), dettman@email.arizona.edu (D.L. Dettman).

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terms of sources and paths of atmospheric water vapor generally apply at short time scales (days, weeks), and do not preclude amount effects at longer time scales (see Section 2); 4. Tucson's warm (mean annual temperature = 21.6 °C) and arid climate, low latitude setting (32°N), and monsoon rainfall pattern are factors usually thought to be associated with the amount effect (e.g. Hoffmann et al., 2005; Cheng et al., 2006); and 5. Determining past changes in precipitation amount from monsoon region isotope data archives is one of the persistent aims of speleothem isotope research. The results for Tucson prompted a re-examination, also presented here, of long-term rain isotope data from New Delhi (India), Hong Kong (China) and Guam (U.S. Territory), data that have been cited in previous paleoclimate studies reviewed below.

2. Modern isotopes in precipitation and paleo-isotope records

The interpretation of oxygen isotope ratios in speleothems (after some assessment of equilibrium behavior in the geochemistry) usually invokes a demonstrable relationship between isotopes in the modern meteoric water at the cave location and the climatic phenomenon of interest (Quade, 2003). In the middle latitudes (35–55°), $\delta^{18}O$ variation in precipitation is often correlated with seasonal (monthly) temperature change (Rozanski et al., 1993). Speleothem studies in this region often use this seasonally-based $\delta^{18}O$ — temperature relationship, summed with the temperature dependent fractionation of oxygen isotopes in calcite, to determine the sense of paleo-temperature change from variation in speleothem $\delta^{18}O$ values (e.g. Hellstrom et al., 1998; Bar-Mathews et al., 1999; see also Quade, 2003). In contrast, low-latitude studies (<35°) commonly make use of the isotope amount effect in precipitation (Dansgaard, 1964). This proxy uses a correlation between the $\delta^{18}O$ of meteoric water and the amount of precipitation and usually assumes the effects of temperature change are small compared to changes in meteoric water $\delta^{18}O$ values (Quade, 2003). Where amount effects exist, the correlation between the amount of precipitation and the weighted mean $\delta^{18}O$ of the precipitation is commonly negative (e.g. Rozanski et al., 1993). Positive correlation is also possible, as in subtropical Brazil (Cruz et al., 2005).

Working with the IAEA Database of Isotopes in Precipitation, Dansgaard (1964) defined the amount effect as a low latitude anticorrelation between the isotopic composition and amount of rain based on monthly means. This has apparently led to a focus on monthly isotope variations in precipitation isotopes, often averaged over multiple years, in much subsequent research. Classic amount effect examples are cited for Guam, New Delhi and Hong Kong (Rozanski et al., 1993). Note that there are at least three mechanisms that can generate amount effects: the evaporation of raindrops falling through dry air (Dansgaard, 1964); progressive rainout at regional scale (Kurita et al., 2009); or change in moisture source between seasons with unequal amounts of rainfall (e.g. Cruz et al., 2005). The amount effect forms the basis for a number of studies of past monsoon intensity in South and East Asia using isotopic time series derived from speleothems (Fleitmann et al., 2003; Paulsen et al., 2003, Cheng et al., 2006; Yadava et al., 2004, Yadava and Ramesh, 2005; Yuan et al., 2004). More recent studies using similar methods include Wagner et al. (2010) in southwestern North America, Lachniet et al. (2012) in central Mexico, and Partin et al. (2012) in Guam. Although the amount effect is clearly present in the monthly isotopic data from New Delhi, Hong Kong, or Guam, it is not at all clear whether a monthly effect can be extrapolated to long term records, or to data with low time resolution, for the following reasons. In speleothem records single samples may represent multiple (up to hundreds) of years, and the isotopic time series generated can span hundreds of thousands of years (Wang et al., 2008; Cruz et al., 2005, Paulsen et al., 2003). Furthermore, isotope studies of cave drip water indicate that cave roof aquifers store water for periods of years to decades (Kaufman et al., 2003; Kluge et al., 2010), resulting in drip water with the isotope signature of local long-term average precipitation (Schwarz et al., 2009; Fuller et al., 2008; Yonge et al., 1985).

More recently a number of studies have broadened the definition of the amount effect to relate the stable isotope variation at one location (e.g. the site of the speleothem sample) to interannual changes in regional rainfall intensity, driven by progressive rain-out from air masses upwind of the site (Yuan et al., 2004; Cheng et al., 2006). Climate models with isotope capability (Liu et al., 2014; Le Grande and Schmidt, 2009; Pausata et al., 2011) can reproduce this effect. The models also suggest that speleothem isotope variations at millennial time-scales can be driven by global forcing of climate.

Other studies have raised questions about the validity of using the amount effect to interpret speleothem data. Bowen (2008) suggested that an isotope — climate relationship constructed from data for a particular monitoring station might not apply at a distant study site. Aggarwal et al. (2004) compared mean annual $\delta^{18}O$ values and precipitation amount across a region stretching from South Asia into the central Pacific. From the lack of correlation they argued that there is no amount effect in the region, but their definition of the amount effect is unusual, involving the comparison of average precipitation amounts at widely separated locations, rather than differences of amount over time at a single site. Lechler and Niemi (2011) adopted a similar approach in a study of 206 widely separated stations in the western USA, finding several instances of strong correlation (R^2 near 0.8) between mean annual precipitation and average $\delta^{18}O$. Vimeux et al. (2011), Moerman et al. (2013) and Lekshmy et al. (2014) suggested that an important control on $\delta^{18}O$ in low-latitude rainwater was the intensity of convective activity rather than amount.

Yet other authors have sought to account for isotope variation in precipitation in terms of source regions and trajectories of atmospheric vapor. Aggarwal et al. (2012), using monthly means at twelve sites representing latitudes from the equator to the poles, argued that most of the variation in $\delta^{18}O$ of meteoric water at a particular location is explained by atmospheric vapor residence times. Breitenbach et al. (2010), identified such a relationship on the time scale of individual rain events in northeast India. Dayem et al. (2010) showed that amount effects could account for less than half the amplitude of the long-term $\delta^{18}O$ variation in Chinese speleothems, and modeled changes in source of water vapor, vapor transport pathways, the proportions of different precipitation types, and the interplay of condensation and evaporation in the atmosphere as potential explanations. Large seasonal isotope variations were ascribed to changes in moisture source in East Asia by Xie et al. (2011), Peng et al. (2010), Tang et al. (2015), and Moerman et al. (2013). Friedman et al. (2002) and Strong et al. (2007), examining data for western North America, proposed that isotope variation in precipitation on a time scale of days is related to vapor source region and trajectory. At the monthly to annual time scale, it seems to be related to the strength of the Pacific/North America (PNA) teleconnection pattern (Liu et al., 2011), and to sea-surface temperatures in vapor source region (Wright et al., 2001).

Such correlations do not a priori preclude isotope amount effects at seasonal or longer time scales, for the following reasons. First, the reported correlations leave much of the variance of the isotope data unexplained. Second, short-term variables such as vapor trajectories and residence times with time scales of days tend to average out at longer time scales, potentially leaving wetter and drier seasons or years unexplained. Third, a long-term relationship between precipitation amount and variables like vapor trajectory and PNA index is not precluded by short-term correlations. All of the approaches discussed above leave open the possibility of an isotope amount effect related to year-to-year changes in precipitation amount at a particular location.

Speleothems form from groundwater that represents a combination of rainwater from many individual precipitation events. The wet season dominates the groundwater record in most wet/dry seasonal climates, and our discussion will therefore look mainly at isotope effects at the time-scales of individual wet seasons or longer. For example, we will ask the question: do wet seasons at one location differ in $\delta^{18}O$ signature