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Spatial and temporal variability in the stable isotope systematics of modern precipitation in China: implications for paleoclimate reconstructions

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Abstract

The stable isotopic composition of materials such as glacial ice, tree rings, lake sediments, and speleothems from low-to-mid latitudes contains information about past changes in temperature (T) and precipitation amount (P). However, the transfer functions which link $\delta^{18}O_p$ to changes in T or P, $d\delta^{18}O_p/dT$ and $d\delta^{18}O_p/dP$, can exhibit significant temporal and spatial variability in these regions. In areas affected by the Southeast Asian monsoon, past variations in $\delta^{18}O$ and δD of precipitation have been attributed to variations in monsoon intensity, storm tracks, and/or variations in temperature. Proper interpretation of past $\delta^{18}O_p$ variations here requires an understanding of these complicated stable isotope systematics. Since temperature and precipitation are positively correlated in China and have opposite effects on $\delta^{18}O_p$, it is necessary to determine which of these effects is dominant for a specific region in order to perform even qualitative paleoclimate reconstructions. Here, we evaluate the value of the transfer functions in modern precipitation to more accurately interpret the paleorecord. The strength of these transfer functions in China is investigated using multiple regression analysis of data from 10 sites within the Global Network for Isotopes in Precipitation (GNIP). $\delta^{18}O_p$ is modeled as a function of both temperature and precipitation. The magnitude and signs of the transfer functions at any given site are closely related to the degree of summer monsoon influence. $\delta^{18}O_p$ values at sites with intense summer monsoon precipitation are more dependent on the amount of precipitation than on temperature, and therefore exhibit more negative values in the summer. In contrast, $\delta^{18}O_p$ values at sites that are unaffected by summer monsoon precipitation exhibit strong relationships between $\delta^{18}O_p$ and temperature. The sites that are near the northern limit of the summer monsoon exhibit dependence on both temperature and amount of precipitation. Comparison with simple linear models ($\delta^{18}O_p$ as a function of T or P) and a geographic model ($\delta^{18}O_p$ as a function of latitude and altitude) shows that the multiple regression model is more successful at reproducing $\delta^{18}O_p$ values at sites that are strongly influenced by the summer monsoon. The fact that the transfer function values are highly spatially variable and closely related to the degree of summer monsoon influence suggests that these values may also vary temporally. Since the Southeast Asian monsoon intensity is known to exhibit large variations on a number of timescales (annual to glacial–interglacial), and the magnitude and sign of the transfer functions is related to monsoon intensity, we suggest that as monsoon intensity changes, the magnitude and possibly even the sign of the transfer functions may vary. Therefore, quantitative paleoclimate reconstructions based on $\delta^{18}O_p$ variations may not

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be valid.

Keywords: stable isotopes; oxygen; precipitation; Asian monsoon; amount effect; paleoclimate; multiple regression; GNIP

1. Introduction

Since 1964, when Dansgaard [1] first reported that the $\delta^{18}O$ of precipitation ($\delta^{18}O_p$) at a given locale reflects environmental factors such as surface temperature (T), amount of precipitation (P), elevation, and source composition, numerous studies have attempted to infer paleoclimate information from the isotopic composition ($\delta^{18}O$ and δD) of paleoprecipitation preserved in natural archive materials, such as glacial ice, tree rings, lake sediments, freshwater mollusks, pedogenic carbonates, fluid inclusions in speleothems, and speleothem calcite. The particularly strong correlation between $\delta^{18}O_p$ and temperature (~ 0.55‰/°C) at mid- to high-latitude sites has led to the common utilization of $\delta^{18}O_p$ as a proxy for continental paleotemperature. However, this correlation is much weaker or non-existent in low latitudes, where different mechanisms of moisture transport predominate [2]. The goal of this study is to investigate the systematics of stable isotopes in precipitation in the Asian monsoon region of China, to improve interpretations of isotopic paleoclimate records obtained from archives in this region.

Oxygen isotopes in precipitation at low- to mid-latitudes may be significantly affected by the amount of precipitation in addition to temperature, leading to difficulties in interpretation of oxygen and hydrogen isotopic data from these regions. A negative relationship between $\delta^{18}O_p$ and amount of precipitation has been observed at lower latitudes (known as the 'amount effect'). This effect is important in convectively active regions where air mass trajectories have a large vertical component, leading to progressive depletion of ^{18}O and D in precipitation at a given site. The amount effect is analogous to the continental effect, in which horizontally transported air masses are progressively depleted in the heavy isotopes with distance from the source region. This effect can be amplified by the fact that isotopic exchange with vapor and evaporative enrichment of raindrops are both greatly reduced with heavy rains.

Hoffmann and Heimann [3] determined that the $\delta^{18}O_p$–P relationship in the Asian monsoon region, while weaker than that in tropical islands, is still a significant factor influencing $\delta^{18}O_p$ in China. The stable isotope systematics in this region are highly complex, however, due to the combined influence of temperature, precipitation, and circulation changes. Both temperature and precipitation are highest in the summer in the Asian monsoon region; therefore the temperature effect (positive $d\delta^{18}O_p/dT$) and the amount effect (negative $d\delta^{18}O_p/dP$) partially cancel each other out. In order to use $\delta^{18}O_p$ or δD in precipitation as a paleoproxy, it is necessary to determine the relative importance of each effect at a given site. In other words, we must investigate whether $\delta^{18}O_p$ is highest during the summer (T effect dominant) or lowest during the summer (P effect dominant). Previous paleoclimate studies from Southern and Central China have interpreted $\delta^{18}O_p$ records in speleothems [4] or δD records in tree rings [5] as proxies of paleomonsoon intensity or paleoprecipitation, while stable isotope records from more northern or western sites are interpreted in terms of paleotemperature [6–8].

The use of $\delta^{18}O_p$ or δD as a quantitative paleothermometer has been called into question in recent years, even at mid to high latitudes, where it was previously thought to be fairly straightforward. Recent studies have suggested that the transfer function, $d\delta^{18}O_p/dT$, may exhibit significant temporal and spatial variability. Cuffey et al. [9,10], for example, used borehole temperature profiles from ice cores in Greenland as an independent paleothermometer to demonstrate that the temporal $\delta^{18}O_p/T_s$ relationship may be as much as a factor of two weaker than the modern spatial relationship commonly used in paleotemperature reconstructions. In addition, Fricke and O'Neil [11] have shown that the slope of the $\delta^{18}O_p$–T relationship is somewhat dependent on climate mode. Thus, the use of a single relation for all time periods, encompassing different climate regimes, can lead to erroneous paleotemperature estimates. Hendricks et al. [12] found that between 45°N and 45°S, the $\delta^{18}O_p$–T relationship is significantly weaker than at higher latitudes, due to the greater degree of water vapor recycling in this region.

In the monsoon regions, where circulation patterns are particularly complicated, extreme caution must be used in interpreting past variations in $\delta^{18}O_p$. The East Asian monsoon system leads to seasonal changes in air pressure, wind, precipitation, and temperature gradients over East and Southeast Asia (Fig. 1). During the winter, cold air over the continent and warm air over the South China Sea cause a pressure gradient, producing dry northeasterly winds that flow over Southern Asia. This pressure gradient is reversed during the summer, as the air over the continent becomes warmer than the air over the South China Sea. Therefore, during the summer monsoon, moisture-bearing winds sweep over the continent. The presence of the Qinghai-Tibetan Plateau intensifies the uplift and cooling of these warm air masses, leading to increased precipitation over the continent.

Over long timescales, changes in solar insolation, albedo, glacial ice volume, continental snow cover, sea surface temperatures, and the Southern Oscillation all contribute to monsoon variability [13]. In order to understand the complex interactions between these forcing mechanisms, it is necessary to obtain and accurately interpret high-resolution proxy records of monsoon history from multiple sources. To date, continental paleoclimate records from the region include ice core records [6], loess records [14], speleothem records [4], lake records [15], and tree ring records [5]. These proxy records suggest that the intensity of the Asian monsoon has undergone dramatic changes throughout the Pleistocene and Holocene, with a much drier climate during glacial times due to a decrease in summer monsoon intensity, and an increase in the intensity of the dry winter monsoon [16]. Higher-frequency oscillations in monsoon intensity have also been observed during the late Pleistocene and Holocene through both instrumental and proxy records [17], and have been correlated with Heinrich and Dansgaard–Oeschger events in the North Atlantic region [18]. Interpretation of many of these proxy records relies on our understanding of the stable isotope systematics of precipitation in China.

In previous studies of areas affected by the Southeast Asian monsoon, past variations in $\delta^{18}O$ and δD of precipitation have been attributed to variations in monsoon intensity, storm tracks, and/or variations in temperature. In such studies, the modern relationship between T, P, $\delta^{18}O$, and

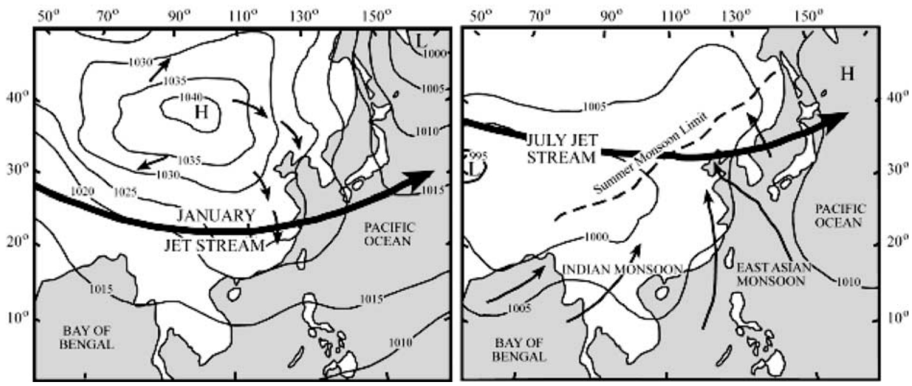

Fig. 1. Maps showing the winter and summer monsoon regimes of eastern Asia. Mean sea-level pressure (hPa), mean location of jet stream, and dominant vectors of surface winds for (A) January and (B) July. After Xiao and An [24].

δD has been used to infer paleotemperatures [6] and paleoprecipitation [5]. In this paper, we reassess the validity of using continental $\delta^{18}O_p$ and δD records as paleotemperature or paleoprecipitation records in monsoon regions, by determining the approximate values of $d\delta^{18}O_p/dT$ and $d\delta^{18}O_p/dP$ in modern precipitation near this region. To separate the temperature effect from the amount effect on $\delta^{18}O_p$, we performed a number of multiple regression analyses on isotopic and meteorological data from the Global Network for Isotopes in Precipitation (GNIP). Although we focus this investigation on precipitation in China, the results may have implications for the entire Asian monsoon region, as well as tropical and equatorial regions.

Accurate interpretation of paleomonsoon activity has important societal implications. Long-term records of monsoon activity will aid in the prediction of anomalous monsoons. The economic, environmental, and societal impacts of anomalous monsoon activity can be severe and widespread. The high population density in the agriculturally based societies found in many monsoon regions, such as Southeast Asia, has created a strong dependence on monsoon rainfall for producing adequate crop yields. Even small variations in the timing and intensity of the summer monsoon can have significant consequences, such as low crop yields during weak summer monsoons, or devastating floods during exceptionally strong summer monsoons [19].

2. Data and methods

To assess the suitability of stable isotope records of precipitation from China for use in paleoclimate reconstructions, we utilized data from the International Atomic Energy Agency-World Meteorological Organization GNIP database [20]. This database includes mean monthly $\delta^{18}O_p$, δD, precipitation amount, surface temperature, and vapor pressure values for 29 sites in China, although many of these records are discontinuous. To prevent inter-annual variability in stable isotope systematics from biasing our results, we chose to focus our study on 10 sites that have continuous records over the 3-year period from 1988 to 1990: Baotou (40.67°N, 109.85°E), Fuzhou (26.05°N, 119.17°E), Guilin (25.07°N, 110.08°E), Guiyang (26.35°N, 106.43°E), Hetian (37.08°N, 79.56°E), Hong Kong (22.32°N, 114.17°E), Lhasa (29.42°N, 91.08°E), Yantai (37.53°N, 121.40°E), Zhangye (38.93°N, 100.43°E), and Zunyi (27.7°N, 106.88°E) (Fig. 2).

Assuming that at any given site, surface temperature and amount of precipitation are the main environmental variables correlated with $\delta^{18}O_p$, these data are ideally suited for multiple regression analysis. Multiple regression analysis is a convenient method for viewing stable isotopes in precipitation in three dimensions, treating $\delta^{18}O_p$, for example, as a function of two variables: surface temperature and precipitation amount. This is analogous to linear regressions, such as those that are commonly performed between $\delta^{18}O_p$ and T at higher latitudes, but through the use of multiple regression, we separate out the confounding effects of precipitation that may obscure the underlying δ–T relationship at low latitudes and in the Asian Monsoon region. Our hypothesis is that $\delta^{18}O_p$ (or δD) at any given site, in regions where the amount effect is important, can be described as:

$$\delta^{18}O_p = \beta_0 + \beta_t T + \beta_P P + \varepsilon \quad (1)$$

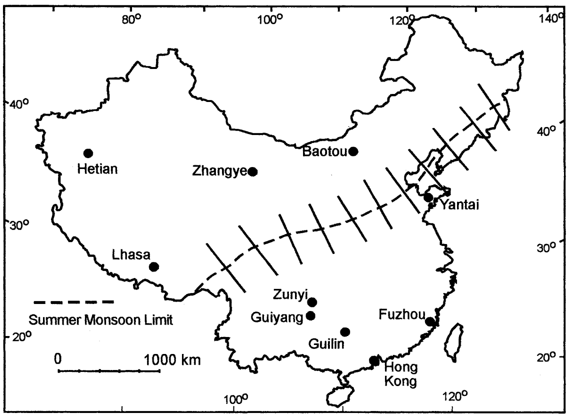

Fig. 2. Map indicating the locations of 10 sites in the IAEA/GNIP database selected for use in this study. The cross-hatched area denotes the approximate northern limit of the summer monsoon.

where β_0 is the y-intercept, β_t and β_P are the partial regression coefficients for temperature and precipitation respectively, and ε is the residual scatter that is not described by T or P.

The residual scatter, ε, represents the sum of all influences, other than T and P, on the stable isotopic composition of precipitation. In China, these other effects may be significant and are related to such things as orography, circulation changes, source of precipitation, and relative humidity. In order to most accurately model $\delta^{18}O_p$ in the Asian monsoon region, these additional effects should be included. This is best done using General Circulation Models (GCM). However, since P and T are more strongly correlated with $\delta^{18}O_p$ than these other factors, we believe that large-scale patterns can be elucidated using much simpler multiple regression models, which are easier and cheaper to run than GCMs. We therefore model $\delta^{18}O_p$ as a function of only T and P as:

$$\delta^{18}O_p = \beta_0 + \beta_t T + \beta_P P \quad (2)$$

We performed several checks to ensure that multiple regression is the appropriate analysis to use for our data. First, we investigated whether our dependent and independent variables, $\delta^{18}O_p$, and T and P, respectively, exhibit a Gaussian distribution. This was accomplished by plotting the distributions of $\delta^{18}O_p$ (‰), mean monthly T (°C), and P (mm/month) in order to check for any evidence of non-normality (Fig. 3). The distributions for all $\delta^{18}O_p$ and T are similar in shape and are close to normally distributed. The skewness values are −1.12 and −0.47 for $\delta^{18}O_p$ and T, respectively. Likewise, the kurtosis values are 1.47 and −0.54. The P distribution is positively skewed. To correct this, we chose to log transform this parameter, resulting in the following revised model:

$$\delta^{18}O_p = \beta_0 + \beta_t T + \beta_{\log P} \log P \quad (3)$$

The skewness and kurtosis values decreased from 2.77 and 11.44, respectively, for P, to −0.53 and −0.41 for log P. While the skewness and kurtosis values indicate that these distributions are not perfectly normal, they are close enough that they should not affect the overall reliability of this method.

Second, we had to consider the effects of serial correlation in which residuals from adjacent measurements in a time series are not independent of one another. In this type of data, there is often serial correlation that results from seasonal variations in T, P, and $\delta^{18}O_p$. We performed checks for serial correlation by plotting the multiple regression model residuals, ε_i, against their lags, ε_{i-1} and calculating the correlation coefficients, r. We set the critical value of $r = 0.32$ (95% confidence level), as the acceptable level for serial correlation. None of the models in this study required correction for serial correlation.

The third check we needed to make was for multicollinearity, or a correlation between our two independent variables, T and log P. Due to the fact that the climate in China is highly seasonal, and that the warmest season is also the rainiest

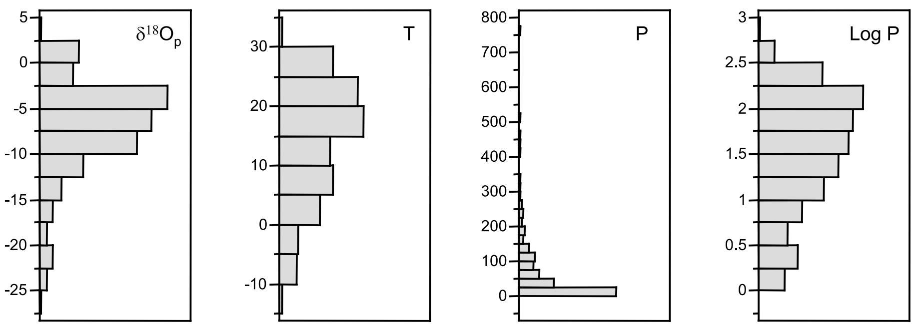

Fig. 3. Histograms showing the distribution of $\delta^{18}O_p$ (‰), T (°C), P (mm), and log P (log mm) for all 10 sites over the period 1988–1990.

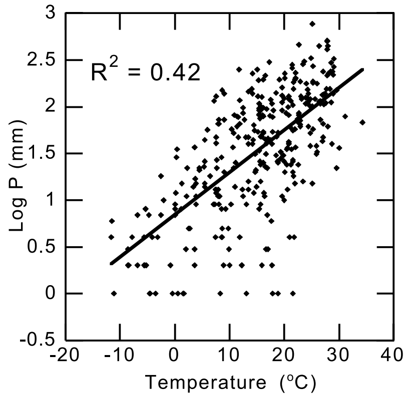

Fig. 4. Log P versus T for the 10 IAEA/GNIP sites. Each point represents monthly average values for an individual site.

season, there is a positive correlation between T and log P in the GNIP data (Fig. 4). This multicollinearity can lead to very large uncertainties in the partial regression coefficients. To check if this is a problem for these data, we calculated variance inflation factors (VIF) for the T–log P relationship at each site. The VIFs for all sites were all less than 2, so the correlations were not strong enough to warrant corrections for multicollinearity, however this effect does slightly increase uncertainties of the model results.

Finally, we compare the results of our multiple regression model with those of simple linear regression models to test whether the more complex model successfully explains more of the variance in the data than the simpler models.

3. Results

The deuterium excess values, mean annual values of temperature (MAT) and precipitation (MAP), and the precipitation weighted annual means of $\delta^{18}O_p$ and δD for the period 1988–1990 are shown in Table 1 for the 10 GNIP sites used in this study. A plot of $\delta^{18}O_p$–T and $\delta^{18}O_p$–P illustrates the lack of a significant relationship between $\delta^{18}O_p$ and T or P (Fig. 5a,b). Thus, it is evident that the $\delta^{18}O_p$–P–T systematics are much more complex than those at higher latitudes where a clear spatial relationship between $\delta^{18}O_p$ and T is seen. $\delta^{18}O_p$ time series from sites in China, however, show very strong seasonal patterns, suggesting that $\delta^{18}O_p$ is indeed responding to changes in T and P. To illustrate this point, we plotted monthly $\delta^{18}O_p$ values for 1988–1990 (Fig. 6) for three of the GNIP sites: Hong Kong, which is dominated by the summer monsoon, Hetian, which is dominated by the winter monsoon, and Baotou, which is near the northern boundary of the summer monsoon.

The seasonal $\delta^{18}O_p$ pattern in Hong Kong consists of lower $\delta^{18}O_p$ values in the summer and higher values in the winter (ranging from about −10‰ to about 0‰, respectively), suggesting that the dominant factor influencing stable isotopes in precipitation here is the amount effect. In contrast, the highest $\delta^{18}O_p$ values in Hetian occur in the summer and the lowest in the winter, suggesting that temperature is the dominant factor controlling stable isotopes in precipitation at

Table 1
General characteristics of modern climate and precipitation at 10 IAEA/GNIP sites in China

City name	Latitude (°)	Longitude (°)	Elevation (m)	MAP (mm)	MAT (°C)	Mean $\delta^{18}O_p$ (‰)	Mean δD (‰)	d-excess (1σ) (‰)
Baotou	40.67	109.85	1067	354	7.5	−8.08	−57.9	−6.9 (2.7)
Fuzhou	26.05	119.17	16	1423	19.6	−7.20	−47.5	16.5 (1.8)
Guilin	25.07	110.08	170	1487	19.2	−6.70	−38.2	15.1 (1.4)
Guiyang	26.35	106.43	1071	910	15.2	−9.08	−57.6	21.7 (1.4)
Hetian	37.08	79.56	1375	238	7.9	−5.66	−33.8	10.7 (2.3)
Hong Kong	22.32	114.17	66	1893	22.9	−6.25	−38.9	13.1(1.2)
Lhasa	29.42	91.08	3649	480	8.0	−17.16	−126.5	4.5 (1.7)
Yantai	37.53	121.40	47	568	13.1	−6.93	−48.4	−0.7 (3.5)
Zhangye	38.93	100.43	1483	135	7.5	−5.91	−38.0	4.4 (2.7)
Zunyi	27.70	106.88	844	958	15.4	−8.96	−59.0	11.3 (2.2)

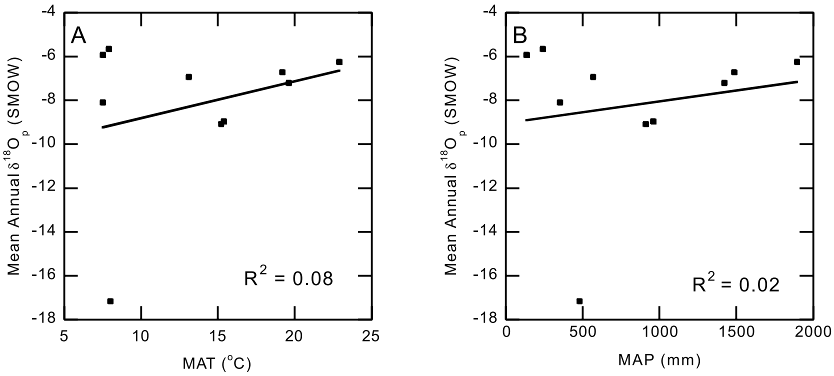

Fig. 5. Weighted means of $\delta^{18}O_p$ versus MAT and MAP for the 10 IAEA/GNIP sites.

this site. The range in $\delta^{18}O_p$ in Hetian is much larger than Hong Kong, with a maximum value of approximately 3‰ in the summer and a minimum of −25‰ in the winter. The seasonal $\delta^{18}O_p$ pattern in Baotou is less clearly defined, with summer values falling around −5 to −10‰, while the annual range is approximately −20‰ to 0‰. This suggests that in this region, near the northern boundary of the summer monsoon, both the temperature effect and the amount effect play an important role in the stable isotope systematics of precipitation.

Based on the results of the multiple regression of $\delta^{18}O_p$ against T and log P (Fig. 7), the 10 GNIP sites can be divided into four general regions: Southern China (Fuzhou, Guilin, Guiyang, Hong Kong, and Zunyi), Northeastern China (Baotou and Yantai), Northcentral China (Zhangye), and Western China (Hetian and Lhasa). The $\delta^{18}O_p$ values at sites within each region exhibit similar dependence on temperature and the amount of precipitation (Table 2), due to the dominance of common atmospheric circulation patterns.

3.1. Southern China

The sites in this region are strongly influenced by summer monsoon precipitation. The dominant air mass source for these five sites is the Western Equatorial Pacific, due primarily to the southern location, south of the intertropical convergence zone for much of the year [21]. The multiple regression model results show that $\delta^{18}O_p$ is negatively correlated to both T and log P at these sites (Fig. 7), although the slopes and statistical significance vary. The fact that the partial regression slope of the $\delta^{18}O_p$–T relationship is negative, even after the precipitation effect has been removed, is an artifact of the correlation between T and P. Since this artifact masks any underlying positive $\delta^{18}O_p$–T relationship, we assume that $\delta^{18}O_p$ at these sites is most strongly related to the amount of precipitation.

Araguas-Araguas et al. [22] also reported the dominance of the amount effect at sites in this region; however, the estimates of the slopes may be improved through use of a multiple regression model as opposed to a simple linear regression model. For example, in Hong Kong, Araguas-Araguas et al. reported a $\delta^{18}O_p$–P slope of −0.01 ($R^2 = 0.76$) and a $\delta^{18}O_p$–T slope of −0.39 ($R^2 = 0.89$), while the multiple regression model yields partial regression slopes of −1.78 and −0.19 for β_{logP} and β_T respectively ($R^2 = 0.55$), suggesting a greater influence of P on $\delta^{18}O_p$. While the R^2 for the multiple regression model is lower than for the linear regression models, the slopes are likely to be more accurate due to the separation of the confounding effects of T and P. The difference between the model results may also be due somewhat to the different time periods used in the two studies.

3.2. Northeastern China

The sites in Northeastern China are located near the northern limit of the summer monsoon

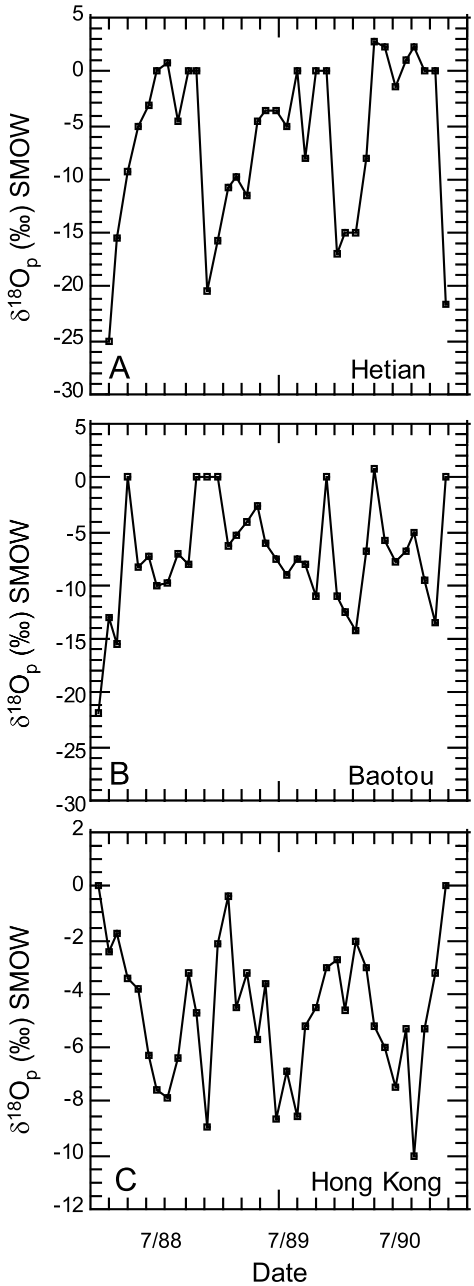

Fig. 6. Mean monthly $\delta^{18}O_p$ plotted over the 1988–1990 time period for (A) Hetian, (B) Baotou, and (C) Hong Kong, illustrating the high spatial variability of seasonal $\delta^{18}O_p$ patterns in China.

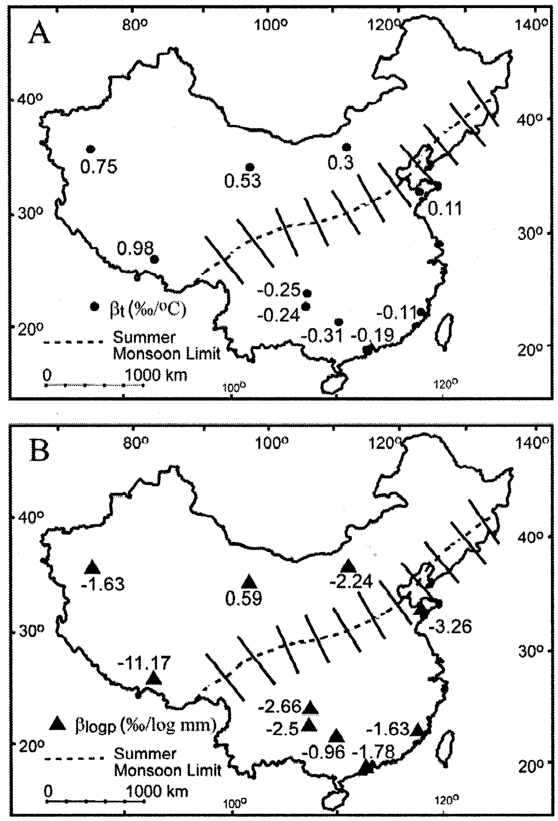

Fig. 7. Maps showing partial regression slopes (A) β_t (‰/°C) and (B) β_{logP} (‰/log mm) for the 10 IAEA/GNIP sites.

precipitation. Although most of the rain falls during the summer months, it is far less than in the south, and a larger proportion of precipitation may be due to small, locally derived convective storms as opposed to the summer monsoon circulation. The multiple regression models for these sites all show positive correlations of $\delta^{18}O_p$ with T (Fig. 7), suggesting that temperature is an important control on $\delta^{18}O_p$. $\delta^{18}O_p$ is negatively correlated with log P at these sites, however, suggesting that the stable isotopic composition of precipitation is also related to the amount of precipitation in this region.

3.3. Northcentral China

The site in Northcentral China, Zhangye, is located north of the summer monsoon limit. $\delta^{18}O_p$

Table 2
Summary of multiple regression results

Site name	β_0 (‰)	s.e. β_0 (‰)	β_t (‰/°C)	s.e. β_t (‰/°C)	Prob > F	β_{logP} (‰/log mm)	s.e. β_{logP} (‰/log mm)	Prob > F	R^2
Southern China									
Fuzhou	−0.77	1.95	−0.11	0.06	0.1017	−1.63	0.88	0.0733	0.21
Guilin	1.98	1.69	−0.31	0.05	< 0.0001	−0.96	0.82	0.2544	0.60
Guiyang	1.00	3.06	−0.24	0.11	0.0464	−2.50	2.33	0.2914	0.39
Hong Kong	3.16	1.38	−0.19	0.07	0.0171	−1.78	0.69	0.0158	0.55
Zunyi	1.62	2.12	−0.25	0.09	0.0094	−2.66	1.54	0.0948	0.46
Northeastern China									
Baotou	−8.80	1.94	0.30	0.10	0.0097	−2.24	2.10	0.2953	0.32
Yantai	−3.40	2.19	0.11	0.08	0.1926	−3.26	1.73	0.07	0.12
Northcentral China									
Zhangye	−14.76	1.36	0.53	0.07	< 0.0001	0.59	1.76	0.7399	0.81
Western China									
Hetian	−13.32	1.20	0.75	0.07	< 0.0001	−1.63	1.12	0.1573	0.83
Lhasa	−7.93	6.17	0.98	0.73	0.1964	−11.17	4.34	0.0192	0.29

at Zhangye is positively correlated with both T and log P. This suggests that the $\delta^{18}O$ of precipitation in this region is strongly related to temperature. The positive $\delta^{18}O_p$–P relationship at Zhangye suggests that the multicollinearity artifact is larger than the amount effect at this site.

3.4. Western China

The majority of the annual precipitation at the two sites in Western China falls during the summer monsoon months. Precipitation at Hetian does not originate from the monsoon, while precipitation at Lhasa does. While these two sites are both characterized by very strong positive relationships between $\delta^{18}O_p$ and temperature and negative relationships between $\delta^{18}O_p$ and precipitation (Fig. 7), these common relationships are reflecting different controls on $\delta^{18}O_p$. The large positive β_T (0.75) at Hetian is highly significant ($1\sigma = 0.07$), while β_{logP} is only slightly significant. The majority of precipitation at Hetian is derived during the summer from small convective storms, with temperature being the dominant control on $\delta^{18}O_p$. In Lhasa, where the annual $\delta^{18}O_p$ pattern is similar to that of Hong Kong (Fig. 6), and β_{logP} is much more significant than β_T (Table 2), $\delta^{18}O_p$ is controlled largely by the amount effect. This suggests that the dominant moisture source for Lhasa is the summer monsoon precipitation. The $\delta^{18}O_p$ systematics at Lhasa may be further complicated by interaction of the Southeast Asian monsoon and the Indian monsoon circulation.

3.5. Deuterium excess

The D-excess values are also somewhat distinct within each region. In Southern China, D-excess values are all greater than the global value of 10‰, and range from 11.3‰ at Zunyi to 21.7‰ at Guiyang. In Northeastern China, D-excess values are negative, with values of −6.9‰ at Baotou and −0.7‰ at Yantai. The value in Northcentral China at Zhangye is 4.4‰. Values in Western China range from 4.5‰ at Lhasa to 10.7‰ at Hetian. This spatial variability of D-excess in China suggests that the stable isotope systematics here are affected by factors other than T and P. The D-excess values may reflect site-to-site variations in the origin of atmospheric moisture (e.g. Indian monsoon vs. Southeast Asian monsoon precipitation), the relative humidity in the oceanic source areas, and secondary processes, such as the re-evaporation of raindrops below the cloud base [22].

3.6. Multiple regression versus mean $\delta^{18}O_p$

$\delta^{18}O_p$ values were calculated for the 10 GNIP sites using the multiple regression model (Eq. 3) and the β_0, β_T and β_{logP} values from Table 2. Fig. 8 shows the relation between modeled $\delta^{18}O_p$ and

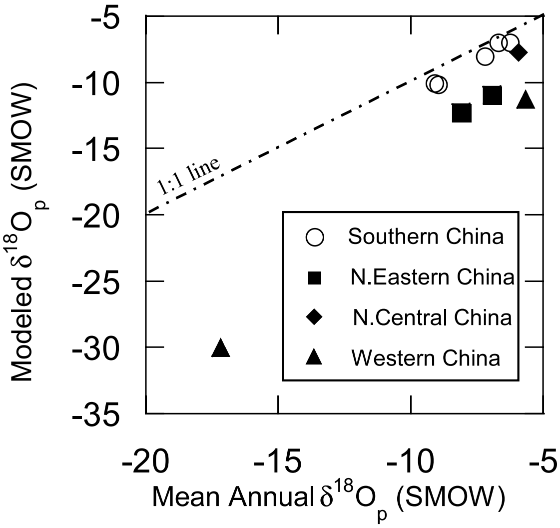

Fig. 8. Modeled $\delta^{18}O_p$ versus mean annual $\delta^{18}O_p$. Sites in the Northeastern China and Western China regions exhibit a greater offset from the 1:1 line, illustrating that the model performs best for the southern sites, which are greatly influenced by the summer monsoon.

the 1988–1990 weighted mean $\delta^{18}O_p$. The standard errors of the modeled values were calculated using Gaussian error propagation (Table 3). The 1988–1990 means and the model results agree within error for all sites, except for Hetian. The model performs especially well for the Southern China sites, the ones most influenced by the summer monsoon. The difference between the mean and the calculated $\delta^{18}O_p$ ($\Delta_{\text{mean}-\text{model}}$) is less than 1.2‰ for all five sites in this region. This difference results from the use of this simplified multiple regression model. A comprehensive model that included all parameters that affect $\delta^{18}O_p$ would come closer to reproducing the true mean values. The model performs less well for the Northeastern, Northcentral, and Western China regions.

3.7. Multiple regression versus simple linear regression models

To test whether a simpler model is more appropriate, we performed linear regressions of $\delta^{18}O_p$ versus T and P for each site (Fig. 9), as in Araguas-Araguas et al. [22]. The $d\delta^{18}O_p/dT$ slopes (β_T) and the $d\delta^{18}O_p/d\log P$ ($\beta_{\log P}$) slopes for all sites in Southern China exhibit the same sign as the partial regression slopes, β_T and $\beta_{\log P}$, although the magnitudes vary significantly. The $\beta_{\log P}$ values have opposite signs for Baotou and Hetian, while β_T has the opposite sign for Lhasa. Table 3 shows the difference between the 1988–1990 mean $\delta^{18}O_p$ for the 10 sites and the $\delta^{18}O_p$ values modeled only as a function of temperature ($\Delta_{\text{mean}-T\text{ model}}$) and only as a function of precipitation ($\Delta_{\text{mean}-P\text{ model}}$). If these values are compared to the $\Delta_{\text{mean}-\text{model}}$ values in Table 3, it is evident that the multiple regression model does a better job of predicting $\delta^{18}O_p$ in the Southern China sites, which are most heavily influenced by the summer monsoon precipitation. This suggests

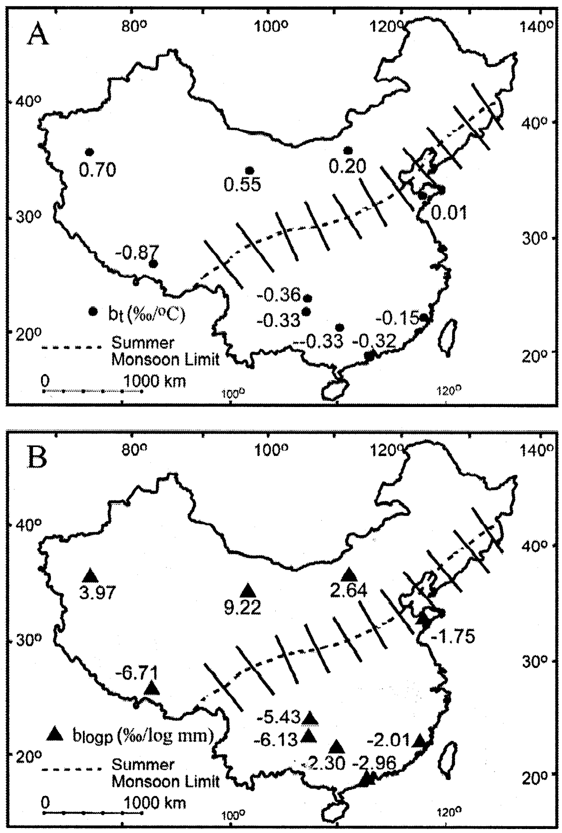

Fig. 9. Maps showing linear regression slopes (A) β_T and (B) $\beta_{\log P}$ for the 10 IAEA/GNIP sites. Comparison with Fig. 7 suggests that with a simple linear model, the dependence of $\delta^{18}O_p$ on temperature may be overestimated while dependence on precipitation amount may be underestimated, especially for sites in Southern China.

Table 3
Comparison of mean $\delta^{18}O_p$ with $\delta^{18}O_p$ calculated with the multiple regression model, a geographic model, and linear P and T models

Site name	Mean $\delta^{18}O_p$ (‰)	Multiple regression model $\delta^{18}O_p$ (‰)	S.E.M. (‰)	Δ_{MR} [a] (‰)	Geog. model $\delta^{18}O_p$ (‰)	Δ_G [b] (‰)	P model $\delta^{18}O_p$ (‰)	Δ_P [c] (‰)	T model $\delta^{18}O_p$ (‰)	Δ_T [d] (‰)
Southern China										
Fuzhou	−7.20	−8.07	3.59	0.87	−4.04	−3.16	−8.86	1.66	−6.08	−1.12
Guilin	−6.70	−7.02	3.25	0.32	−4.27	−2.43	−8.99	2.29	−5.90	−0.80
Guiyang	−9.08	−10.05	7.73	0.97	−6.17	−2.91	−14.55	5.47	−6.96	−2.12
Hong Kong	−6.25	−7.02	3.10	0.77	−3.89	−2.36	−8.79	2.54	−4.60	−1.65
Zunyi	−8.96	−10.16	5.24	1.20	−5.85	−3.11	−13.77	4.81	−6.89	−2.07
Northeastern China										
Baotou	−8.08	−12.26	5.74	4.18	−8.48	0.40	−5.22	−2.86	−9.15	1.07
Yantai	−6.93	−10.94	5.35	4.01	−5.75	−1.18	−8.81	1.88	−6.83	−0.10
Northcentral China										
Zhangye	−5.91	−9.53	4.02	3.62	−8.92	3.01	1.59	−7.50	−10.26	4.35
Western China										
Hetian	−5.66	−11.27	2.97	5.61	−8.32	2.66	−2.69	−2.97	−9.04	3.38
Lhasa	−17.16	−30.04	14.41	12.88	−11.65	−5.51	−20.38	3.22	−7.58	−9.58

[a] $\Delta_{\text{mean−multiple regression model}}$.
[b] $\Delta_{\text{mean−geographic model}}$.
[c] $\Delta_{\text{mean−linear } P \text{ model}}$.
[d] $\Delta_{\text{mean−linear } T \text{ model}}$.

that $\delta^{18}O_p$ variations in precipitation in the Asian monsoon region cannot be used solely as a paleothermometer or a paleomonsoon proxy, but must be used as a combination of these.

3.8. *Geographic model vs. multiple regression model*

Bowen and Wilkinson [23] demonstrated that $\delta^{18}O_p$ can be modeled quite accurately as a function of solely latitude and elevation. We compare the $\delta^{18}O_p$ values calculated using this geographic model with those from the multiple regression model (Table 3). The multiple regression model more accurately predicts $\delta^{18}O_p$ for all five sites in the Southern China Region, while the simple latitude/altitude model is best in the other three regions, which are less affected by the Asian Monsoon. Bowen and Wilkinson point out, however, that regional characteristics of the atmospheric circulation affect $\delta^{18}O_p$ patterns and hence, $\delta^{18}O_p$ can be better represented via inclusion of an interpolated field of latitude/altitude model residuals. This significantly improves the geographic model's performance in Southern China.

4. Conclusions

Records of past variations of $\delta^{18}O$ and δD in precipitation, whether preserved in ice cores or fluid inclusions, or inferred from proxy data from geologic materials, such as speleothem calcite, can provide a wealth of useful information about paleotemperatures, paleoprecipitation, and paleocirculation patterns. The Asian monsoon region has one of the most interesting and complex climatic histories in the world; unfortunately, it is this very complexity that presents major obstacles to paleoclimatologists and climate modelers alike. A thorough understanding of the stable isotope systematics in this region is key for improving interpretations of multiple paleoenvironmental records. The simple multiple regression model presented here, which interprets $\delta^{18}O_p$ as a function of only T and P, provides some useful insights.

The multiple regression results demonstrate the high degree of spatial variability in $\delta^{18}O_p$–T–P relationships in this region. The signs of β_T and $\beta_{\log P}$ are clearly related to the dominant atmospheric circulation patterns at any given site, although the magnitude of these slopes is more difficult to interpret. $\delta^{18}O_p$ values at sites in Southern China, which are greatly affected by the summer monsoon precipitation, are somewhat dependent on the amount of precipitation. Inclusion of temperature in the model, however, greatly improves our ability to reproduce the modern mean $\delta^{18}O_p$ values. Sites in Northern and Western China may not be affected as much by the amount effect, yet inclusion of precipitation in the model may also improve the accuracy of the calculated slopes.

This high degree of spatial variability, which is somewhat related to the intensity of the summer monsoon, suggests that caution should be used in any quantitative, or even qualitative, interpretation of $\delta^{18}O_p$ or δD paleorecords. It is well known that the intensity of the summer monsoon has varied greatly between glacial and interglacial periods, and also exhibits high-frequency decadal to annual variations in intensity. The fact that the degree of dependence of $\delta^{18}O_p$ on T and P is related to monsoon intensity, which is highly variable, leads to the conclusion that the β_T and $\beta_{\log P}$ values at any given site may vary as monsoon intensity varies, and thus it may not be justified to use modern values in interpretation of paleorecords. Interpretation of paleorecords which lie near the northern limit of the summer monsoon may be especially difficult, since the dominant control on $\delta^{18}O_p$ may switch back and forth between P and T as the strength of the monsoon increases and decreases, respectively.

The site-to-site variability of the partial regression slopes may be reflecting more complex factors such as the dependence of $\delta^{18}O_p$ on elevation, latitude, source of moisture, topography, degree of water vapor recycling, and atmospheric transport pathways. The relatively low R^2 values for the fit of the multiple regression model to the data (Table 2) suggest a large portion of the variance is unexplained by either T or P and may be attributed to one or more of these factors. The model could be significantly improved through inclusion of some of these variables, although this is obviously better accomplished using a GCM. This study is also intrinsically limited by the short duration of the data set, which is characteristic of the GNIP database in China. Inclusion of all the available data may slightly improve the fit of the model, but the use of discontinuous time series could lead to systematic biases in the resulting model, for example, through inclusion of only summer precipitation.

Uncertainty may also arise when these modeled seasonal $\delta^{18}O_p$–T–P trends are applied to interannual trends that are observed in the paleorecord. Unfortunately, the short duration of the GNIP data set makes direct multiple regression analysis of interannual trends impossible. Therefore, we assume that the best estimate of how $\delta^{18}O_p$ varies as a function of MAT and MAP is derived through our investigation of how $\delta^{18}O_p$ varies throughout the year as a function of mean monthly temperature and precipitation. A change in the relative dominance of the precipitation amount effect and the temperature effect on $\delta^{18}O_p$ in the seasonal cycle would lead to a similar change on the interannual cycle.

The complex stable isotope systematics in China certainly present many challenges to isotope paleoclimatologists. If caution is used in interpreting the paleorecords, however, there is still great potential to obtain high-resolution records of monsoon variability over the last several glacial–interglacial cycles, as well as further increase our understanding of the systematics of stable isotopes in precipitation in the Asian monsoon region. For example, seasonally or annually resolved ice core or speleothem $\delta^{18}O$ records may be useful for extending the record of $\delta^{18}O$ in precipitation. If independent records of temperature and/or the amount of precipitation are available, multiple regression analyses can be performed to investigate $\delta^{18}O_p$–T–P relationships over longer timescales than is possible from the GNIP database alone. Speleothems in particular hold great potential for providing high-resolution continental records of monsoon variability. They preserve multiple types of paleoclimate proxy data ($\delta^{18}O_p$, trace elements, growth band thickness, etc.) in highly resolvable growth bands and therefore, interpretation of past $\delta^{18}O$ variations can be checked against independent proxy data within individual samples. Studies such as this could significantly improve our understanding of stable isotopes in precipitation, as well as improving the paleomonsoon record.

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