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Spatial analysis of the intra-annual variation of precipitation isotope ratios and its climatological corollaries

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[1] Intra-annual variation in the stable isotope ratios of precipitation imparts a time-dependent isotopic signal to continental hydrological and ecological systems. This variation is forced by seasonal climate cycles, with temperature and precipitation intensity each driving isotopic seasonality in different parts of the globe. In order to better characterize and understand the isotopic seasonality of precipitation and to advance applications such as the inversion of isotope/climate relationships for paleoclimate seasonality reconstruction, these relationships are analyzed using a database of precipitation isotope ratio observations and gridded maps. The results confirm the overwhelming dominance of temperature- and precipitation amount–related isotopic seasonality within specific, well-defined geographic zones and indicate that these zones encompass most of Earth's continental land surface. Analysis of global maps of precipitation isotopic seasonality, however, indicates spatially patterned variation in isotope/climate relationships, including patterns related to continentality in temperature-dominated regions and meridional trends in amount-dominated areas. These features reflect more complex climatological controls on isotope seasonality and suggest limitations and opportunities for paleoclimate reconstruction using isotopic archives.

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1. Introduction

[2] In many parts of the world the stable H- and O-isotopic compositions of precipitation (rain and snow) vary across the seasonal climate cycle. This water enters continental hydrosystems and ecosystems, propagating the seasonal signal to these systems where it can be measured to gain information on climatological, hydrological, or ecological processes. A wide range of geoscience applications are enabled by the natural seasonality of precipitation isotope ratios, including hydrograph separation [*Kendall and McDonnell*, 1996], estimation of water residence time in aquifers or catchments [*Fredrickson and Criss*, 1999; *Reddy et al.*, 2006; *Rodgers et al.*, 2005], and reconstruction of paleoclimate seasonality [*Dettman and Lohmann*, 1993; *Higgins and MacFadden*, 2004; *Kohn et al.*, 1998].

[3] The stable isotopic composition of precipitation is affected by a number of factors which affect the mass-dependent fractionation of ^{2}H- and ^{18}O-substituted water molecules relative to nonsubstituted forms at various points in the hydrological cycle [*Dansgaard*, 1964; *Ingraham and Taylor*, 1991; *Rozanski et al.*, 1993]. The temperature and atmospheric humidity over oceanic vapor source regions set the fractionation between ocean surface water and atmospheric vapor, and together with the isotopic composition of surface water control the initial isotopic composition of vapor arriving at the continental margins and oceanic islands. As air masses traverse the continents, they loose water to condensation and precipitation with a temperature-dependent isotopic fractionation. This "rainout" leads to a progressive depletion of the heavy isotopes in vapor and subsequent precipitation events, leading to a general tendency for precipitation isotope ratios to decrease along trajectories of atmospheric vapor transport, with decreasing temperature, and with increasing altitude. Vapor is also added to air masses through moisture recycling from the continents, with the effect of damping or even completely countering rainout-driven changes in precipitation isotope ratios [*Ingraham and Taylor*, 1991].

[4] The seasonality of precipitation isotope ratios (hereafter "isotopic seasonality") has been the subject of study based on time series generated by individual investigators [*Fredrickson and Criss*, 1999; *Harvey and Welker*, 2000; *Jacob and Sonntag*, 1991; *Peng et al.*, 2004] and the global database of the Global Network of Isotopes in Precipitation (GNIP [*Alley and Cuffey*, 2001; *Rozanski et al.*, 1992, 1993]). This work has lead to a classification of climatological factors influencing isotopic seasonality, primary among them the seasonality of temperature (temperature effect, a positive correlation generally observed at middle to high latitudes) and precipitation event intensity (amount effect, a negative correlation observed in the tropics [*Dansgaard*, 1964]). Seasonal temperature change is related to precipitation isotopic composition through its effect on the saturation vapor pressure of air masses and thus on the degree of

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rainout from air following its equilibration with ocean water masses having relatively constant temperature (compared to the continents). The precipitation amount effect can be largely attributed to seasonal changes in the intensity of convective storms that rainout a large fraction of air mass moisture, producing ^{2}H- and ^{18}O-depleted precipitation.

[5] Although previous work has clearly demonstrated that isotopic seasonality and the dominant climatological controls on isotopic seasonality are different for different regions, thus far there has been no study characterizing global spatial distribution of these values and synthesizing information on the strength and uniformity of seasonal isotope/climate relationships. Here, statistical analyses of global monitoring station and gridded isotopic data are used to document and map the relationships between seasonal climatic and isotopic variability. The results provide an improved characterization of isotopic seasonality and its relation to climate variables, with implications for a range of applications including the reconstruction of paleoclimate seasonality from isotopic archives.

2. Data and Analysis

[6] Precipitation isotope data generated at monthly or submonthly intervals was compiled from primary sources [*Kurita et al.*, 2004; *Peng et al.*, 2004] (see also http://www.nrel.colostate.edu/projects/usnip/, unpublished data for Saskatoon, CA, from L. Wassenaar (personal communication, 2006), and the IAEA/WMO GNIP database, available at http://isohis.iaea.org) and reduced to obtain calendar month values. All data were reported as δ values referenced to the VSMOW-VSLAP standard scale, where $\delta = (R_{smpl} - R_{std})/R_{std} - 1$, R indicates the ratio ^{2}H/^{1}H or ^{18}O/^{16}O in a sample (smpl) or the VSMOW standard (std), and values are given as parts per thousand (per mil, ‰). The analysis reported here focuses on δ^{18}O values, for which 37,173 values were obtained representing the period between 1960 and 2006. Because the rainout-driven isotopic fractionation underlying the patterns discussed here partitions ^{2}H- and ^{18}O-substituted molecules proportionally [*Craig*, 1961], the main results can be generalized to δ^2H values as well. The spatiotemporal distribution of these data are highly uneven [e.g., *Bowen and Revenaugh*, 2003], and to facilitate global analysis data for individual months were reduced to 5,295 unweighted long-term monthly average values from 500 stations. These were screened to remove stations where isotopic data was available for <90% of the average annual precipitation by volume or <4 months, leaving 469 stations. The data were used to produce a series of 12 long-term monthly average precipitation δ^{18}O grids at 10' spatial resolution over the continents following the methodology of *Bowen et al.* [2005], which applies coupled regression and geostatistical modeling to predict isotopic compositions between data stations.

[7] Climatological station data (long-term monthly average temperature and precipitation amount) were obtained from observations reported by the primary isotope data sources. Precipitation amount data were available for all stations, whereas temperature data were available for 339 stations. Long-term monthly average gridded climate data at 10' spatial resolution were obtained from the Climate Research Unit at the University of East Anglia (http://www.cru.uea.ac.uk/cru/data/).

[8] The data were analyzed using parametric (linear regression; described below) and nonparametric (Spearman rank-order correlation) tests for correlation. Two significance levels for the nonparametric test were calculated using the rank-order correlation coefficient (rocc) and the sum squared difference of ranks (ssdr). All nonparametric statistics were calculated using published computational routines [*Press et al.*, 2002]. Comparison of the parametric and nonparametric statistics were used to test the assumption that a linear regression function adequately represents the correlation of isotopic and climatic variables. Linear regression slopes (m), intercepts (b) and F statistics (F) were then calculated for the regression of long-term monthly average precipitation isotopic compositions (y) on climate variables (x) as:

$$m = \frac{n\sum(xy) - \sum x \sum y}{n\sum(x^2) - \left(\sum x\right)^2},$$

$$b = \frac{\sum y - m\sum x}{n},$$

and

$$F = \frac{Rss/_k}{\sum(y-\bar{y})^2 - Rss/_{n-k-1}},$$

where:

$$Rss = \sum(x-\bar{x})(y-\bar{y}) / \sum(x-\bar{x})^2,$$

n is the number of data, and k is the degrees of freedom for the regression and equal to 1. Calculations were performed in Microsoft Excel (for station data) and using a regression tool for ArcGIS 9.1 (for gridded data [*Naisbitt et al.*, 2005]). Statistical significance was evaluated at the 95% confidence level.

3. Results and Discussion

3.1. Intra-annual Precipitation Isotope Range

[9] Global maps depicting the intra-annual range of precipitation isotopic composition (Figure 1) were created by subtracting maximum and minimum monthly values for each map grid cell. These maps are the first of their kind, and document the spatial distribution of an important mode of isotopic variability in hydrological systems. They also provide a basis for the study of seasonal isotope-climate relationships at global to subcontinental spatial scales and provide baseline information for a range applications involving the spatiotemporal distribution and variability of water isotope ratios [*Hobson*, 2005; *Kreuzer-Martin et al.*, 2004; *Rossmann*, 2001; *Sharp et al.*, 2003]. Many factors contribute to the uncertainty of the calculations at any grid cell [*Bowen and Revenaugh*, 2003], significant among these the spatiotemporal unevenness in the data set. For example, even following our screening procedure 20% of all station months are represented by only a single measurement, and

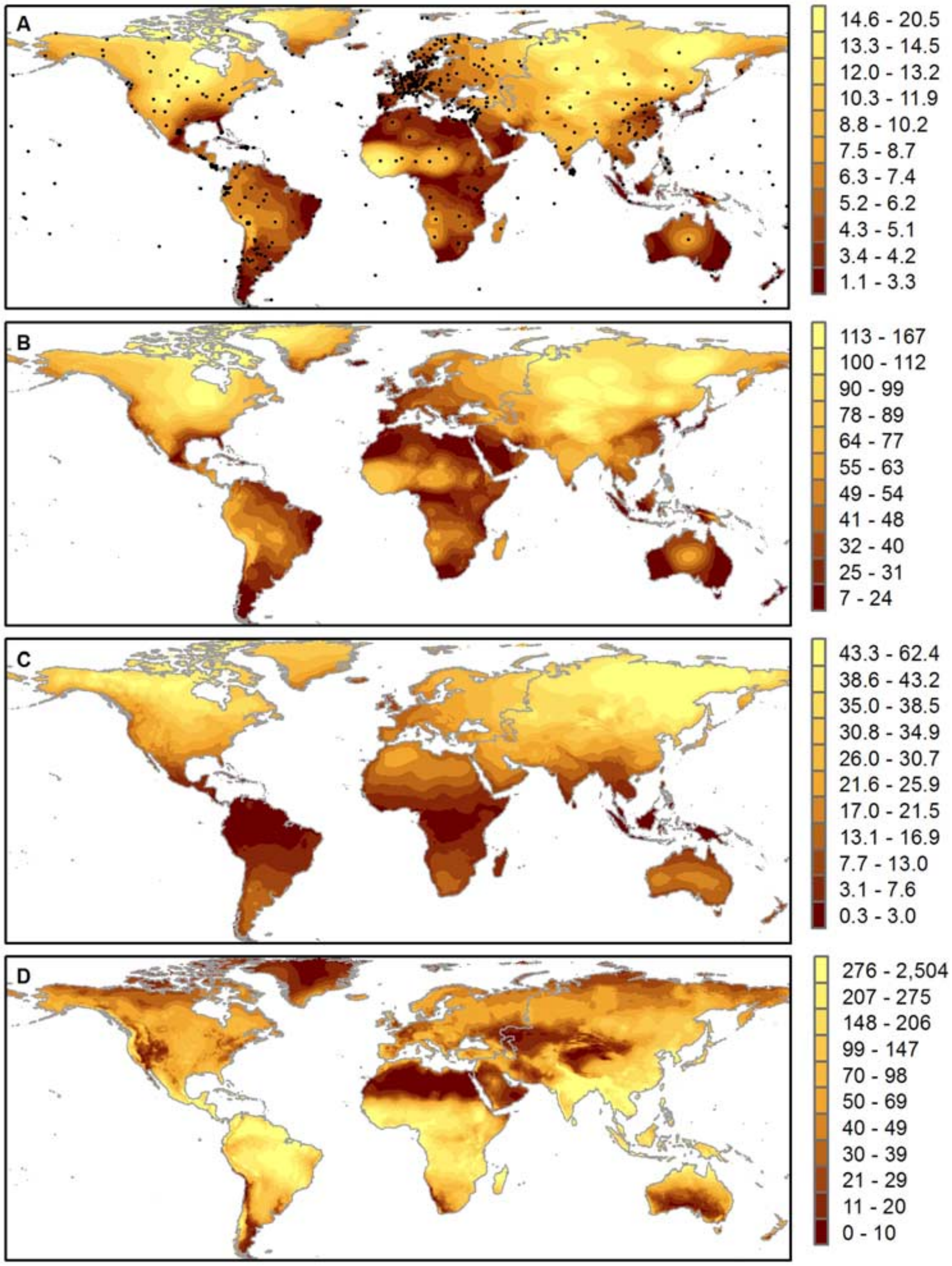

Figure 1. Mapped estimates of the intra-annual range of isotopic and climatological parameters. Color bands are classified as percentiles for (a) $\delta^{18}O$ values of long-term, monthly average precipitation (‰); (b) $\delta^{2}H$ values of long-term, monthly average precipitation (‰); (c) Monthly average temperature (°C); and (d) Precipitation amount (mm). Black dots in Figure 1a show the distribution of isotope monitoring stations used to create the map.

52% are calculated on the basis of 4 or fewer observations during the 47-year sampling window. This unevenness, which is inevitable given the nature of the data set, may in some cases compromise the comparability of stations with limited and contrasting temporal sampling. For the purposes of this study, however, we note that the data set documents strong, spatial trends supported by numerous stations in geographic proximity to each other, suggesting that the gross spatial patterns of interest are robust despite the uneven nature of the data. The mapping algorithm imparts additional uncertainty, and it is clear that the details of predicted isotopic seasonality patterns between individual monitoring stations are poorly constrained in many cases. For example, many ‘‘bull's-eye’’ features such as those in central Asia and Australia reflect the default pattern of influence that our mapping algorithm produces where data stations are sparse and do not clearly document the geometry of the true spatial pattern. However, even in such cases, the maps clearly define strong trends supported by the spatial juxtaposition of data from multiple stations, suggest-

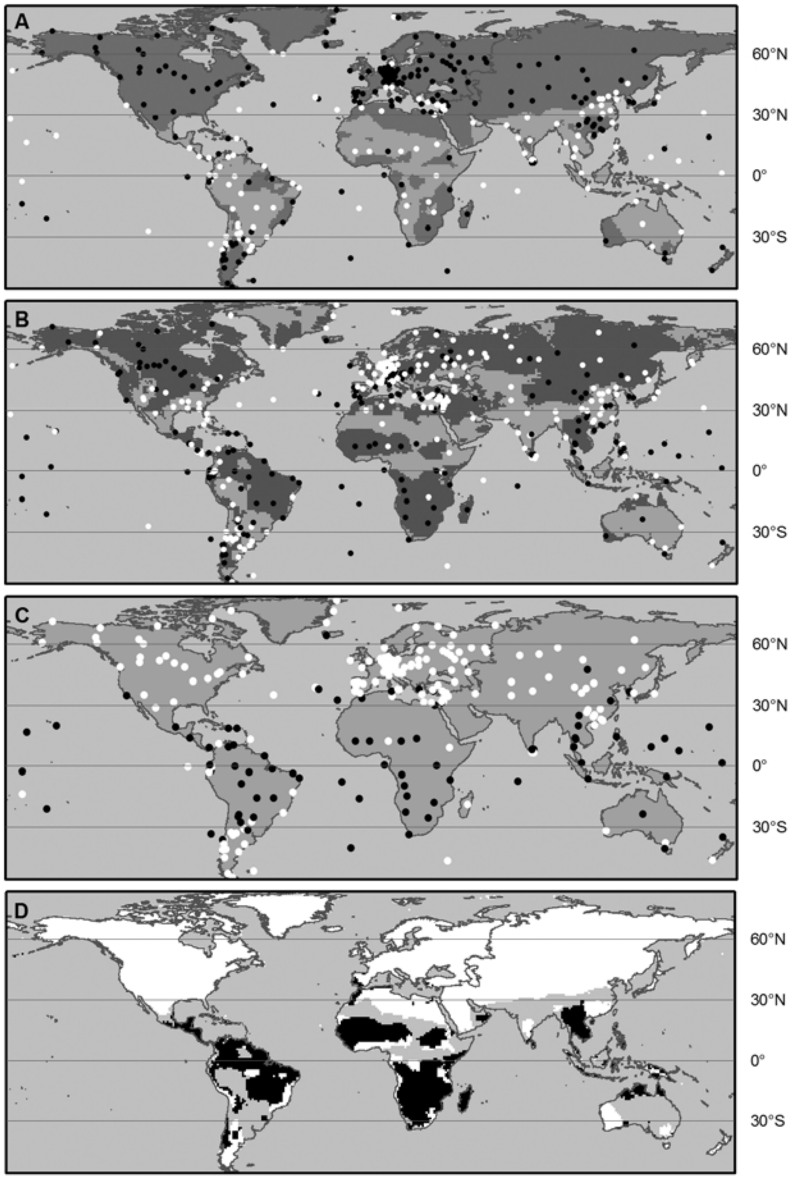

Figure 2. Significance level of correlation between long-term monthly average precipitation δ^{18}O and climatological parameters. (a and b) Stations and grid area with significant ($p < 0.05$; black dots and dark gray shading) and no significant (white dots, light gray shading) correlation between temperature (Figure 2a) or precipitation amount (Figure 2b) and δ^{18}O. (c and d) Mode (white indicates temperature; black indicates precipitation) of the strongest climatological correlation at all stations (Figure 2c) or grid points with one or more significant correlation (Figure 2d).

ing that the identification, if not the detailed geometry, of these features is accurate.

[10] The highest values of intra-annual isotopic range (e.g., >12‰ for δ^{18}O and >90‰ for δ^{2}H) are found across the middle- and high-latitude continental interiors of North America and Asia, extending to the Arctic coasts of each of these continents. In these regions intra-annual variation can be substantial relative to other modes of isotopic variability. For example, seasonal variability in these regions is equal to more than 40% of the total spatial variation in annual average precipitation δ^{18}O across the North American continent, where one of the strongest meridional gradients in precipitation isotope ratios is found (~28.5‰ [*Bowen and Revenaugh*, 2003]). Low values of intra-annual range (e.g., <5.0‰) at middle to high latitudes are restricted to the North American Gulf Coast and Western Europe. The map depicts strong coast-to-continent gradients in intra-annual isotopic range with zonal (Europe [*Rozanski et al.*, 1993] and western North America) and meridional (eastern North America) orientations. At tropical and subtropical latitudes ranges are generally low, with exceptions occurring in zonal bands at ~10–20°N and S in Africa and throughout the Andes and adjacent Amazon. A strong gradient in intra-

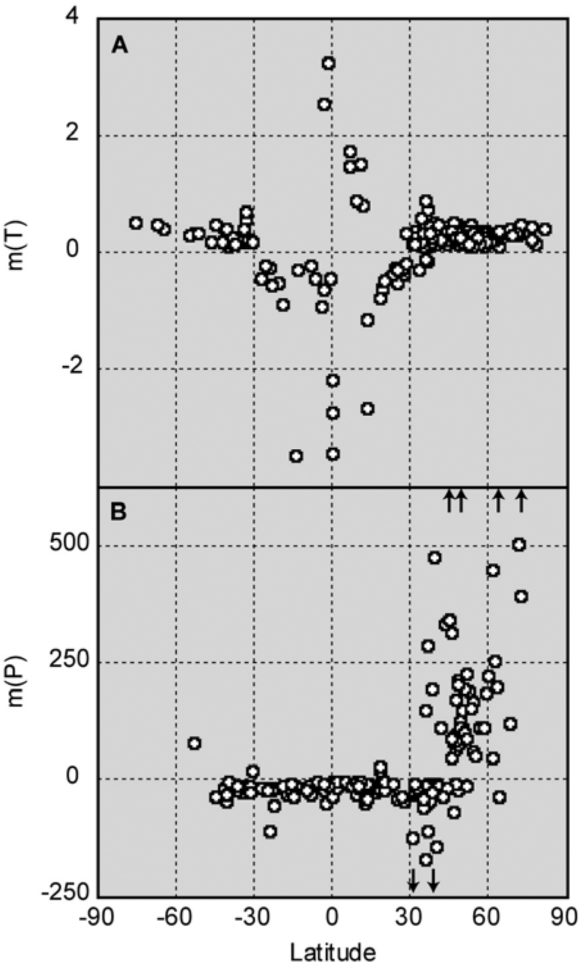

Figure 3. Slope coefficients of significant normal linear regressions between long-term mean monthly δ^{18}O values of precipitation and (a) monthly temperature (m(T); ‰/°) or (b) precipitation amount (m(P); ‰/m). Values of m(P) at six stations lie outside of the plotted range (arrows).

annual range extends from the Atlantic coast of South America to the Andes.

3.2. Spatial Extent of Isotope-Climate Relations

[11] A long-held dichotomy of temperature-controlled isotopic seasonality in temperate climates and precipitation amount-controlled isotopic seasonality in the tropics has been borne out through case studies and compilations of station data [*International Atomic Energy Agency*, 1992; *Rozanski et al.*, 1993]. However, a synthesis documenting the two-dimensional geographic extent and variability in these modes of isotope-climate correlation has been lacking. A recent assessment of data from ~80 monitoring stations suggested a limited influence (<50% of stations) of climate seasonality on intra-annual isotopic variation [*Alley and Cuffey*, 2001]. To further explore this issue regression statistics were used to test for significant, linear relationships between station or gridded isotope data and climate parameters and to map the spatial extent of this significance.

[12] This analysis is predicated on the assumption that a linear function adequately describes the relationships among climate variables and isotope ratios. To test this assumption, parametric (linear function) and nonparametric tests of correlation significance were compared. In general, parametric and nonparametric tests were in agreement with respect to the presence or absence of significant relationships between the isotope and climate variables. For example, for correlation of δ^{18}O with monthly average precipitation only 6.8% (for the ssdr statistic) or 10.4% (rocc) of stations were classified differently by the parametric and nonparametric tests. Of these, 23 stations (5% of total) were classified as significant by both nonparametric statistics but not significant by linear regression, perhaps suggesting that intra-annual isotopic variation at these stations is related to seasonal changes in precipitation by a more complex time-lagged or nonlinear function. In contrast, all of the stations for which the correlation was classified as significant by the parametric test were also classified as significant by one or both of the two nonparametric statistics, suggesting that the incidence of Type I errors is minimal in our linear regression-based analysis. Thus, the adoption of linear parametric statistics for the remainder of the analysis appears appropriate in most cases, though it may lead to a slight underestimate of the extent of isotope-climate correlation.

[13] Statistically significant linear correlation exists between long-term mean monthly temperature and precipitation isotopic composition at 212 stations (62.5%) and between precipitation amount and isotopic composition at 191 stations (40.7%). Although there is overlap between these groups (103 stations), our results suggest that significant seasonal correlation between climate variables and precipitation isotope ratios exists at more than 2/3 of these monitoring stations, and across more than 80% of the Earth's land surface (Figure 2d) including most areas where appreciable climate seasonality exists (Figures 1c and 1d).

[14] The areal distribution of isotope-climate correlation is consistently represented in station- and grid-based analyses (Figure 2). Both analysis indicate that significant correlation of precipitation δ^{18}O values with temperature is nearly ubiquitous above 30° N/S latitude, with exceptions at some maritime stations and in southeast Asia. These exceptions are generally limited to regions of low temperature seasonality and/or high monsoonal precipitation seasonality, where nontemperature factors might be expected to dominate intra-annual isotopic variation. Areas of temperature correlation also exist across some more restricted regions at low latitudes, for example in equatorial west Africa and the east coasts of subtropical south Africa and South America. Precipitation amount correlation occurs across much of the land area at <30°N/S, although both station-based and grid-based analyses suggest a number of exceptions including along the Andean corridor and southern Amazon, parts of equatorial, eastern, and Saharan Africa, and most of the Indian subcontinent. Patchy amount correlation does appear to exist poleward of 30°N/S, particularly in southern Europe, western North America, and central Asia. These sites are largely in areas of Mediterranean climate or other climate regimes where seasonal variation in temperature and precipitation are autocorrelated, and so the existence of both modes of correlation alone cannot be taken as strong evidence for a particular mechanistic control on isotope seasonality. Overall, temperature-correlated isotopic seasonality appears to be

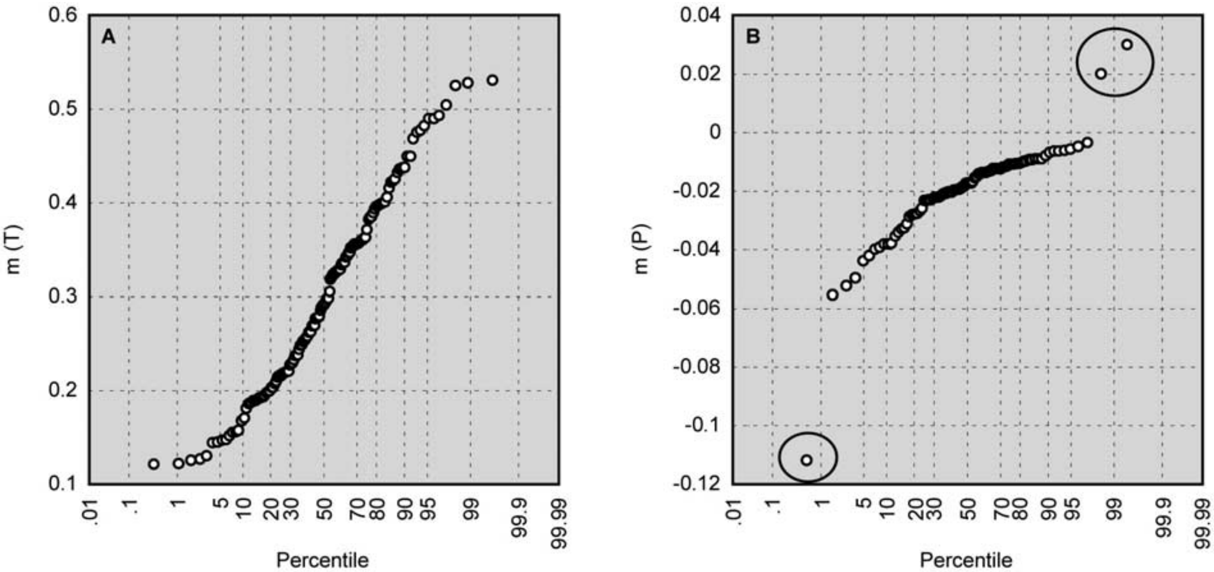

Figure 4. Probability distribution of slope coefficients for regressions between long-term monthly average δ^{18}O values of precipitation and (a) temperature (m(T)) or (b) precipitation (m(P)), for stations within the characteristic zones of correlation described in the text. Circled outliers in Figure 4b (two stations in India with high m(P) and one in Australia with low m(P)) were not included in the calculation of average regression coefficients presented in the text.

the norm poleward of 30°N/S but is inconsistent at lower latitudes, whereas precipitation amount-correlated isotopic seasonality is regionally prevalent at <30°N/S and a limited number of higher-latitude zones.

[15] Probability statistics for isotope/climate correlations suggest that the 30°N/S parallels mark a relatively sharp transition between precipitation amount-dominated to temperature-dominated isotopic seasonality. Temperature regressions are stronger (lower *p*) at almost all sites with significant correlations throughout North America, Europe, the midlatitudes of South America, and Asia excepting parts of southeast Asia (Figures 2c and 2d). Throughout much of southeast Asia and Indonesia, Africa, and tropical South and Central America correlation strength is greater for the precipitation amount regressions, although temperature correlations are stronger in some parts of equatorial and north Africa and coastal South America.

3.3. Spatial Stability of Isotope/Climate Relations

[16] The slope of the regression lines relating intra-annual precipitation isotope ratio variation to climate parameters provides another convenient and meaningful metric of these relationships. Isotope/climate slopes can be compared to the predictions of physical models to evaluate the climate processes leading to isotopic seasonality: for example, a simple first-order prediction based on our understanding of the temperature and amount effects is that these mechanisms should lead to positive covariation of isotope ratios and temperature and negative covariation with precipitation amount, respectively. Other practical applications of regression slopes include prediction of isotopic variability from climate observations, reconstruction of paleoclimate seasonality from isotopic records, and evaluation of the seasonal isotope/climate cycles produced by isotope-enabled general circulation models (GCMs).

[17] Slope coefficients for station-based regressions, although widely variable across all stations with significant correlation, are relatively invariant within well-defined latitudinal zones that closely match those of high significance for each mode of isotope/climate relation (Figures 3 and 4). Temperature (T, °C) coefficients are relatively uniform poleward of 30°N/S latitude and even more so at >38°N/S latitude, where they are normally distributed (Figure 4) about the average relationships:

$$\delta^{18}\mathrm{O} = 0.299(\pm 0.103)\ \mathrm{T} - 12.4(\pm 3.8),\ \text{and} \tag{1}$$

$$\mathrm{T} = 2.88(\pm 0.94)\delta^{18}\mathrm{O} + 35.8(\pm 10.3) \tag{2}$$

(1σ in parentheses). Similarly, for stations with significant isotope-precipitation (P, m) relationships located between 30°S and 30°N, the average relationships are:

$$\delta^{18}\mathrm{O} = -19.8(\pm 11.5)\ \mathrm{P} - 1.3(\pm 1.9),\ \text{and} \tag{3}$$

$$\mathrm{P} = -0.043(\pm 0.027)\delta^{18}\mathrm{O} - 0.014(\pm 0.133). \tag{4}$$

[18] This result reinforces the dichotomy described above, and suggests relatively uniform climatic controls force precipitation isotopic seasonality within these zonally bounded ‘‘characteristic zones’’ for the temperature and amount effects. The temperature slope coefficient calculated here is nearly identical to that derived in a previous analysis (0.28 ‰/° C [*Rozanski et al.*, 1992]), and the meridional distribution of coefficients is similar to that produced by isotope-enabled GCMs [*Jouzel et al.*, 2000]. As noted by those authors, however, this slope is much lower than those

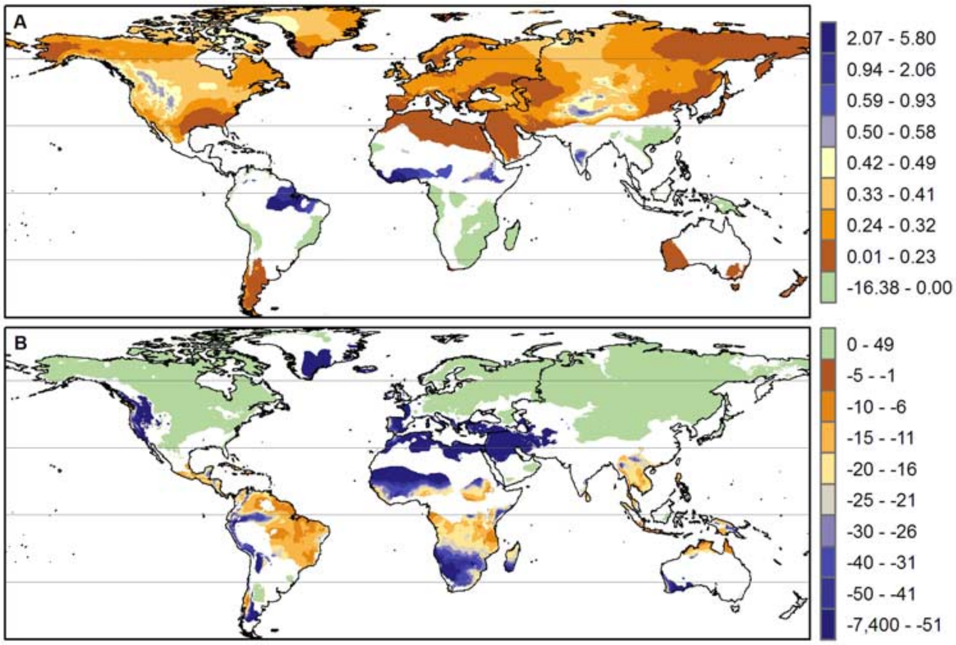

Figure 5. Slope coefficients for the regression of long-term monthly average precipitation δ^{18}O grid data on (a) temperature (‰/°) and (b) precipitation amount (‰/m). Color bands highlight variation within the ''characteristic'' zones for each mode of covariance; slopes of opposite sign to those typical of the temperature and amount effects appear in green.

relating mean annual temperature and δ^{18}O values of precipitation at spatially distributed monitoring sites across the middle and high latitudes. This difference has since been attributed to systematic differences in the seasonality of average climatological temperatures and condensation temperatures based on analysis of data from U.S. stations [*Kohn and Welker*, 2005].

[19] Outside the characteristic zones regression slopes are highly variable and of large magnitude and/or opposite sign relative to those typical of the temperature and amount effects (Figures 3 and 5), implying that these correlations may in many cases be artifacts rather than reflections of climatic forcing of isotopic seasonality in these regions. In the Northern Hemisphere Mediterranean climate zones, for example, monthly precipitation amount and temperature are strongly correlated and both climate variables are significantly correlated with monthly precipitation isotope ratios. However, temperature correlations are generally stronger and more uniform (Figure 2), and temperature slopes are more consistent with those of other characteristic zone locations than are the precipitation slopes, which are commonly an order of magnitude higher than tropical precipitation isotope/amount slopes (Figure 5). These results suggest that the precipitation amount effect does not represent a good model for seasonal changes in isotopic composition in Mediterranean climate regions, consistent with the fact that these systems are dominated by advection and frontal or orographic rather than convective precipitation.

[20] Grid-based regression slopes suggest additional spatial structure to the distribution of slope coefficients within the characteristic zones (Figure 5). Regression slopes for temperature-dominated seasonality exhibit a distinct continentality, and are largest at high elevation and across the continental interiors of North America and Asia. This heterogeneity cannot be attributed directly to the temperature-controlled distillation process, which should produce a near-linear dependence of precipitation isotopic composition on temperature during liquid-phase condensation and reduced slope nonlinear dependence for sites that receive snow during parts of the year [e.g., *Jouzel et al.*, 1997]. The one-dimensional modeling study of *Hendricks et al.* [2000] has provided theoretical evidence for the continentality of isotope/temperature slopes of Antarctic mean annual precipitation relative to long-term temperature change, and this effect is reproduced for parts of the Northern Hemisphere continents in GCM simulations [*Schmidt et al.*, 2007]. This is attributed to strong coupling between temperatures of coastal regions and the adjacent oceans where the isotopic composition and vapor pressure of air masses is set, leading to a relatively low temperature sensitivity of coastal and coast-proximal precipitation isotope ratios. A similar mechanism may underlie the pattern observed here for intra-annual isotope-climate regressions over the Northern Hemisphere continents, and may be accentuated by other factors including seasonal changes in atmospheric transport, as across the northern Great Plains of the USA, or continental water recycling through evapotranspiration.

[21] Regression slopes for precipitation amount correlation are relatively uniform throughout much of tropical South America, Africa, and Asia/Indonesia, but higher-magnitude slopes are found in a narrow equatorial band in western South America and at >10°N/15°S in Africa. These areas are characterized by relatively low seasonality of precipitation amount rather than atypically high isotopic seasonality, and in general lie just beyond the strongest influences of intertropical convergence zone (ITCZ) migra-

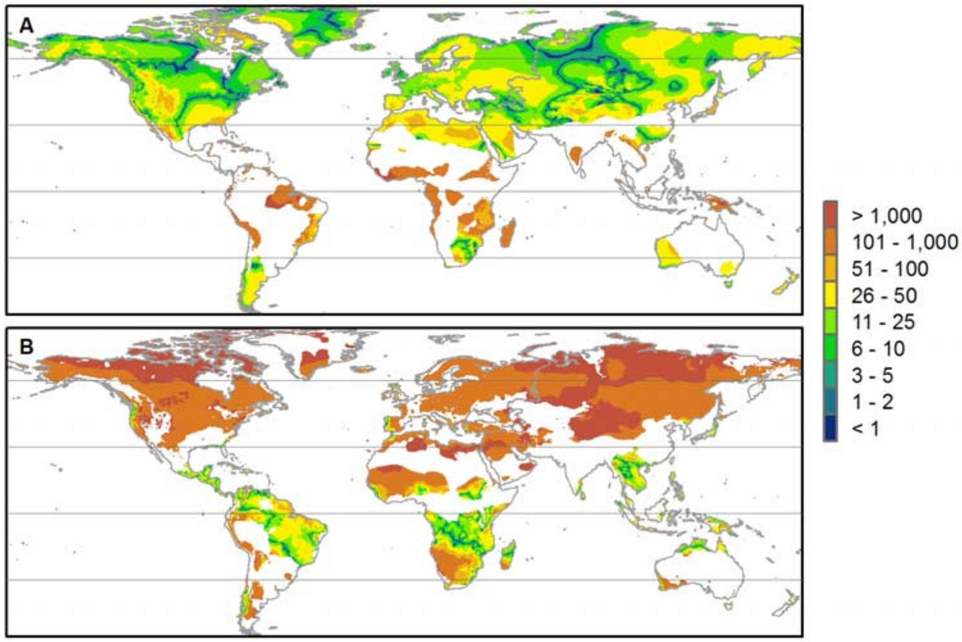

Figure 6. Prediction error for the reconstruction of intra-annual (a) temperature and (b) precipitation ranges using the average regression relationships for characteristic zone stations (equations (2) and (4)). Gridded predictions were made by applying the regression equations to grid cell δ^{18}O ranges (Figure 1). Errors are shown here as percentage, calculated by subtracting predictions from gridded climate parameter observations (Figure 1) and dividing by the observed values.

tion on seasonal precipitation patterns [*Waliser and Gautier*, 1993]. The enhanced isotopic seasonality in the high-slope areas may reflect the spatial propagation of isotopic variation through moisture transport from adjacent zones of higher precipitation amount seasonality. The principal mechanism underlying the amount effect is increased rainout of heavy isotopes during extreme seasonal rain events, and as the resulting ^{2}H- and ^{18}O-depleted air masses advect outward from zones of convergence they should propagate this isotopic signal to adjacent areas less strongly affected by convergence, enhancing the apparent magnitude of the amount effect in these locations. This suggests that powerful teleconnections exist between low-latitude zones of high seasonality and adjacent areas and implies that ITCZ intensity may be reflected in the seasonal variability of precipitation isotope ratios over large areas of the tropics and subtropics.

4. Conclusions and Implications for Paleoclimate Reconstruction

[22] Relationships between precipitation isotopic seasonality and climate underlie an important method for the reconstruction of paleoclimate seasonality from isotopic archives, and regardless of the many other factors impacting the seasonal isotopic signals in these archives a basic understanding of the isotopic seasonality of precipitation is prerequisite to the application of this method. Our work supports the validity of this method in that it confirms the strength of temperature- and amount-related seasonal variation in precipitation isotope ratios. Each of these effects is clearly dominant, if not ubiquitous, within well-defined geographic/climatological zones, and our analysis indicates that significant relationships between these climate variables and precipitation isotopic composition are much more common (in terms of number of stations or land area) than suggested in previous work.

[23] However, the results presented here suggest that reconstruction of paleoclimate seasonality using generalized climate/isotope response functions is a problematic approach because of the pronounced geographic variation in the slope of these relationships across the continents. As has been noted previously, the relationships between temperature or precipitation amount and precipitation isotopic composition are not purely mechanistic [e.g., *Alley and Cuffey*, 2001; *Kohn and Welker*, 2005], and their confident application for paleoclimate reconstruction depends on their stability over time and space. The analysis presented here has shown that, even within the characteristic zones for these isotope/climate relations, there is substantial variability in parameter values that could lead to large errors in paleoclimate reconstructions. Taking a simple case, application of the mean, characteristic zone climate/isotope relations (equations (2) and (4)) to predict modern temperature and precipitation ranges from gridded stable isotope data gives errors of 10–50% across much of the characteristic zone for temperature-dominated seasonality and >100% in some parts of the amount-dominated zone (Figure 6). These errors are independent of any uncertainty introduced by variations in isotope-climate response at different timescales or in response to different climatological forcing mechanisms [e.g., *Schmidt et al.*, 2007], which may further complicate such paleoclimatiological interpretations of water isotope proxy data. It is clear that generalized calibrations of seasonal isotope/climate relations, much like those describing isotope-climate change at inter-

annual and longer timescales [*Hendricks et al.*, 2000, and references therein], represent an extremely limited approach to the reconstruction of past climate variability.

[24] The maps presented here may advance the understanding of intra-annual isotope/climate relationships and paleoseasonality reconstruction using isotopes in at least two different ways. First, these maps illustrate for the first time that much of the variation in the intra-annual relationships between precipitation isotopic composition and climate variables is spatially coherent, and they may be useful for identifying region-specific response functions to improve paleoclimate seasonality reconstructions. Such application of the maps must be treated with caution, however, in that the stability of the spatial patterns and their corresponding regional response functions over time remains poorly known. For example, if the "continentality" of isotope/temperature regression slopes is in fact analogous to the spatial variation in interannual isotope/temperature slopes studied by *Hendricks et al.* [2000], then the stability of the local responses mapped in Figure 5 will be dependent on the spatial pattern of climate change. If coastal zones warm or cool at the same pace as the continental interiors the distribution of response slopes should remain approximately fixed (assuming no change in the seasonality of vapor transport trajectories), whereas spatially uneven warming or cooling would produce a geographic shift in isotope/temperature slopes. If adequate constraints can be brought to bear, this approach may facilitate improved estimates of paleoclimate seasonality from water isotope proxies, but significant challenges remain.

[25] Second, and more importantly, by describing the spatial patterning of the isotope/climate relationships the maps allow potential mechanisms for this variation to be proposed, which may ultimately lead to more sophisticated paleoclimatological interpretations of water isotope proxy data. For example, the observed patterns of isotope/amount relationships in the tropics and subtropics suggest that isotope seasonality over relatively large regions may be related to the strength of intra-annual precipitation variability in zones seasonally affected by the ITCZ, as controlled by the strength of convergence. This particular case may have important implications for the interpretation of paleoclimate records from many tropical ice cores that are located within or near the characteristic zone of precipitation amount-dominated seasonality as mapped here. At these sites, variation in the seasonal and mean isotopic composition of precipitation may be strongly influenced by teleconnections to high-seasonality tropical vapor source regions, complicating the interpretation of the ice core records in terms of temperature change. This scenario is supported by the results of a recent, isotope-enabled regional climate modeling study of South America and Andean glacier sites [*Sturm et al.*, 2007], and the general indication of these findings is that isotopic records within the low-latitude amount-dominated zones may be best suited for the reconstruction of regional, rather than local, aspects of climate change [e.g., *Schmidt et al.*, 2007].

[26] In summary, spatial analysis of the intra-annual variability in stable isotope ratios of precipitation provides insights into the limitations and potential for reconstruction of paleoclimatological seasonality using H and O isotopes. Seasonal isotope/climate relationships are found to be strong and nearly ubiquitous, but quantitatively they are spatially unstable. As a result, the inversion of generalized empirical response functions represents an extremely limited approach to paleoseasonality reconstruction, and future work should emphasize increased understanding of the mechanistic underpinnings of intra-annual isotopic variability, the conditions under which local or regional isotope/climate functions are likely to be stable, and robust relationships between isotopic seasonality and regional modes of climate variability. The maps and analysis presented here should motivate and facilitate this work, and provide additional context for the application of seasonal isotopic variability in hydrology, ecology, and other research fields.

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