



## Amount-weighted annual isotopic ( $\delta^{18}\text{O}$ ) values are affected by the seasonality of precipitation: A sensitivity study

R. W. Vachon,<sup>1</sup> J. W. C. White,<sup>1</sup> E. Gutmann,<sup>2</sup> and J. M. Welker<sup>3</sup>

Received 1 May 2007; revised 23 July 2007; accepted 8 October 2007; published 15 November 2007.

[1] Year to year differences in the isotopes of precipitation ( $\delta^{18}\text{O}$ ) are typically attributed to corresponding interannual changes in mean annual temperature. However, changes in the seasonal distribution of precipitation are one of the main complicating factors in interpreting year to year variability of isotopes of precipitation. Using a five year dataset with 73 sites across the United States, we investigate the influence of changes in seasonal distribution of precipitation on annually averaged  $\delta^{18}\text{O}$ . Based on these  $\delta^{18}\text{O}$  measurements, and using multi-decadal records of variability of monthly precipitation amounts, we identify areas within the United States where records of isotopes in precipitation are susceptible to changes in the seasonal distribution of precipitation. For the three regions, Northern Great Plains, the Rocky Mountains, and the Southwest, seasonality effects could be misinterpreted as 1°C to 3°C temperature changes between years. These findings will improve and possibly change our interpretation of climate isotopic climate records and provide spatially explicit areas where classic interpretations require caution. **Citation:** Vachon, R. W., J. W. C. White, E. Gutmann, and J. M. Welker (2007), Amount-weighted annual isotopic ( $\delta^{18}\text{O}$ ) values are affected by the seasonality of precipitation: A sensitivity study, *Geophys. Res. Lett.*, *34*, L21707, doi:10.1029/2007GL030547.

### 1. Introduction

[2] Ice cores, tree rings, plant growth segments, lake sediments, and speleothems typically develop in annual increments that retain climate records [White *et al.*, 1997; Urban *et al.*, 2000; Welker *et al.*, 2005]. For many of these records, the stable isotopes of precipitation ( $\delta^{18}\text{O}$ ) are the primary proxies used to understand climate histories. Resolving the specific climate information contained in climate proxies does however require our understanding of the detailed processes controlling the modern variability in stable isotopic composition of precipitation [Dutton *et al.*, 2005; Kohn and Welker, 2005; Welker, 2000].

[3] For instance, the  $\delta^{18}\text{O}$  of an air mass is largely controlled by the amount of moisture that has been condensed along its trajectory, from source to sink. The degree of condensation is largely linked to the surface temperatures at the site of precipitation, which is reflected by the strong

correlation between  $\delta^{18}\text{O}$  and year-to-year variability in annual average temperatures [Dansgaard, 1964; White *et al.*, 1997]. For this reason, long-term records of isotopes in precipitation, such as ice cores, have been widely interpreted as records of local temperature.

[4] For a modern perspective, most places within the United States experience interannual temperature variability of approximately 0.5° to 1.5°C (National Climate Data Center, <http://www.ncdc.noaa.gov/oa/climate/stationlocator.html>). If these changes are translated into isotopic values using a global average transfer function of  $\sim 0.7\text{‰ } \delta^{18}\text{O}/\text{°C}$  [Dansgaard, 1964], average annual isotopic values would fluctuate by  $\sim 0.3\text{‰}$  to  $1\text{‰ } \delta^{18}\text{O}$ . There are however, other parameters that may result in interannual changes of similar magnitudes, such as changes in the year-to-year distribution patterns of precipitation. Accounting for shifts in the seasonal distribution of precipitation has not been adequately studied. We now possess a database that is spatially adequate to address the effects of changes in the seasonal patterns of precipitation on the annual average  $\delta^{18}\text{O}$  values at the continental scale [Welker, 2000].

[5] The isotope-temperature linkage typically causes  $\delta^{18}\text{O}$  to vary seasonally in a predictable manner [Rozanski *et al.*, 1993]. Precipitation is typically depleted (i.e. more negative  $\delta^{18}\text{O}$  values) during the colder months and more enriched (i.e. less negative  $\delta^{18}\text{O}$  values) during the warm months [Dansgaard, 1964; Rozanski *et al.*, 1993; Shuman *et al.*, 1995; White *et al.*, 1997]. The degree to which temperatures differ between seasons can be an order of magnitude greater than interannual temperature variability. Thus,  $\delta^{18}\text{O}$  can vary seasonally far more than interannually. Annual  $\delta^{18}\text{O}$  values mostly reflect the isotopic composition of the seasons during which the greatest amount of precipitation falls (e.g. winter for locations like California). Therefore, shifts in the seasonal patterns of precipitation can strongly influence annual  $\delta^{18}\text{O}$  values [Steig, 1994; Werner *et al.*, 2000; Denton *et al.*, 2005.]

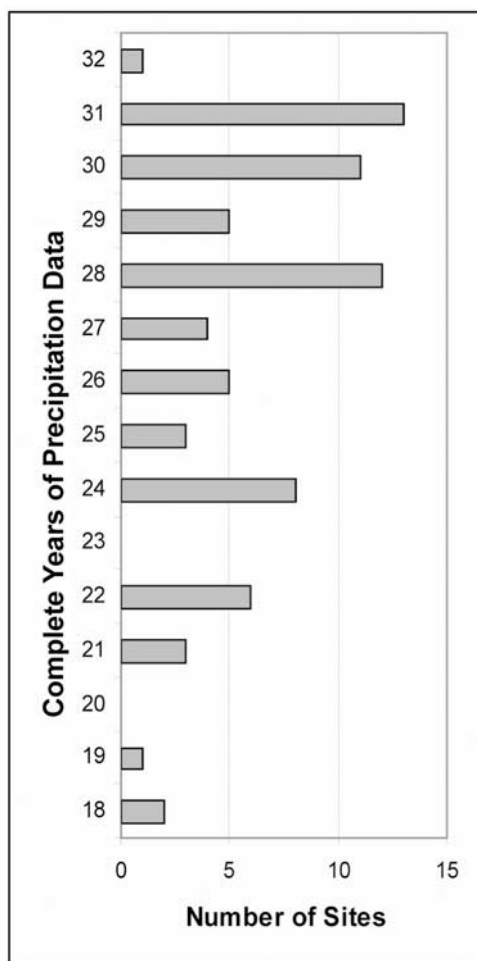
[6] Two conditions are required for the seasonal distribution of precipitation (SDP) to effect interannual variability in  $\delta^{18}\text{O}$  values for a given location. First, the location must experience some degree of year-to-year variability in the seasonality of precipitation. Second, large interseasonal differences in precipitation  $\delta^{18}\text{O}$  values must occur. For example, when both criteria exist, an increase in warm season precipitation would typically result in an enrichment in annual  $\delta^{18}\text{O}$  values.

[7] In this study, we conducted a sensitivity analysis that examines how changes in the SDP differentially affect annual  $\delta^{18}\text{O}$  values of precipitation across the United States. This is accomplished using our  $\delta^{18}\text{O}$  values of precipitation from 73 locations across the U. S. (United States Network

<sup>1</sup>Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado, USA.

<sup>2</sup>Center for the Study of Earth from Space and Cooperative Institute for Research in Environmental Science, University of Colorado, Boulder, Colorado, USA.

<sup>3</sup>Environment and Natural Resources Institute and Biology Department, University of Alaska Anchorage, Alaska, USA.



**Figure 1.** The histogram illustrates the number of complete years of precipitation that were used to calculate the time-series of amount-weighted annual SIP values, for all USNIP sites included in this study.

for Isotopes in Precipitation (USNIP)) in conjunction with companion monthly precipitation amounts [Welker, 2000].

## 2. Methods

### 2.1. Interannual Variability in Precipitation Amounts

[8] 25 to 32 years of monthly precipitation measurements ( $\text{Ppt}_{\text{Monthly}}$ ) for each USNIP site were provided by the National Climate Data Center (NCDC). The locations of the meteorological stations were within 50 km (half a degree) of each station where precipitation was collected for isotopic analysis ([www.ncdc.noaa.gov](http://www.ncdc.noaa.gov)). Because the calculation of a single  $\delta^{18}\text{O}_{\text{Annual}}$  value requires precipitation measurements for all twelve months of the year (even if no precipitation occurred), small gaps in the NCDC climate archive required that we omit certain years from our  $\delta^{18}\text{O}_{\text{Annual}}$  time-series. Figure 1 outlines the distribution of number of complete years of precipitation data per number of sites.

[9] We calculated the long-term (20 to 30 years) variance and standard deviations of precipitation amounts for each month. Based on these we then derived two standard deviations ( $2\sigma$ ) of the monthly precipitation (95.45% con-

fidence). We then divided the  $2\sigma$  values by the average monthly precipitation over these same periods. This provided a normalized monthly precipitation variance index. These variance index values were then averaged over the entire year, for each site. Because this is a comparison of proportions, absolute precipitation measurements are not of consequence. Thus, precipitation variability within regions of high precipitation can be compared impartially against regions of low precipitation.

### 2.2. SDPs Effect on Composite Annual $\delta^{18}\text{O}$

[10] It was our goal to approximate the degree to which SDP could effect the  $\delta^{18}\text{O}$ -values of precipitation from various regions across the continental United States. Time-series of composite-annual isotopic values ( $\delta^{18}\text{O}_{\text{Annual}}$ ), were calculated, for each site, using two data sets (1) multiyear time-series of monthly precipitation amount ( $\text{Ppt}_{\text{Monthly}}$ ) taken from the NCDC data base and (2) average monthly isotopic ( $\delta^{18}\text{O}_{\text{Avg Monthly}}$ ) values.  $\delta^{18}\text{O}_{\text{Annual}}$  values were calculated using equation 1 [Rozanski *et al.*, 1993].

$$\delta_{\text{Annual}} = \sum_{\text{December}}^{\text{January}} \delta_{\text{Each Month}} \times \frac{\text{Ppt}_{\text{Each Month}}}{\text{Ppt}_{\text{Annual Total}}} \quad (1)$$

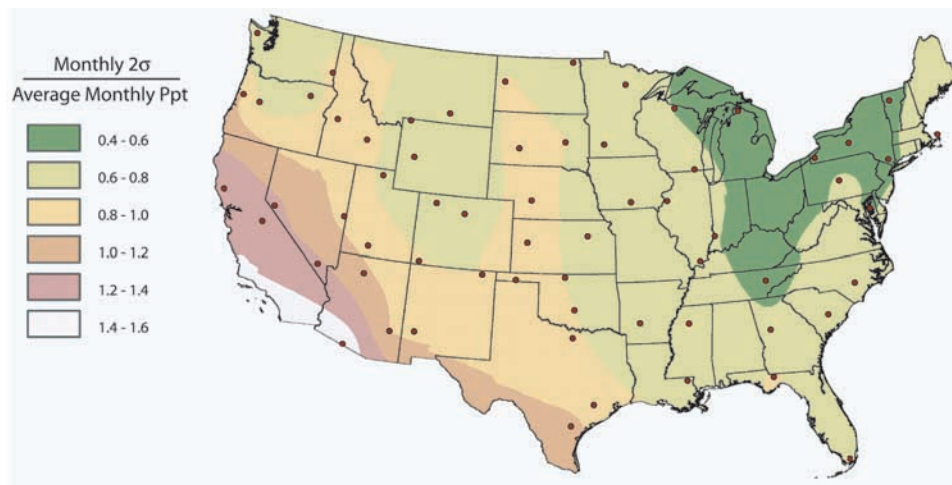
[11]  $\text{Ppt}_{\text{Annual}}$  refers to total precipitation measurements for a complete year.

[12] Seasonal trends  $\delta^{18}\text{O}$  were derived from the USNIP database. The USNIP database containing monthly isotope data for 73 sites within the contiguous United States [Lynch *et al.*, 1995; Welker, 2000]. The USNIP isotopic measurements (monthly samples) used in this study were primarily for the period of January 1989 to December 1994, however for 5 sites samples spanned from January 1989 to the end of 2001 (CA99, CO01, VT99, FL11 and WA14). Approximately one third of all samples were analyzed for both  $\delta^{18}\text{O}$  and  $\delta\text{D}$ . Due to the tight linkages between  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values for most USNIP sites, the monthly  $\delta^{18}\text{O}$  data was enhanced by additional points, where by  $\delta\text{D}$  were translated into additional  $\delta^{18}\text{O}$  values through the Local Meteoric Water Lines. This increased the number of monthly isotopic values from 1,900 to 3,373. We thus used 30 to 120 monthly  $\delta^{18}\text{O}$  measurements for each site. Although these datasets are not continuous enough to produce long-term (20–30 year) records of monthly  $\delta^{18}\text{O}$  variability, they are well suited for calculating average monthly  $\delta^{18}\text{O}$  values. These values can then be fitted to a sine curve, defining an average annual  $\delta^{18}\text{O}$  cycle. We use sine curves here as they are the best-suited for describing the seasonal patterns of  $\delta^{18}\text{O}$  values in precipitation.

## 3. Results

### 3.1. Interannual Variability in Precipitation Amounts

[13] Our normalized index ( $2\sigma$ /average monthly precipitation) vary spatially across the United States (Figure 2). The Desert Southwest, i.e. Southern California and Arizona, exhibit the largest precipitation variance index values (1.4 to 1.6). Such large ranges are indicative of the large changes in year to year precipitation that we typically find in parts of California and Arizona. The smallest precipitation variance index values were found in the Great Lakes, Ohio River Valley and in portions of the Northeast (0.4–0.5). The entire



**Figure 2.** The map shows the average monthly variability in monthly precipitation from one year to the next divided into the precipitation amount experienced during those months. Areas with large values suggest that the amount of seasonal precipitation received at a given region varies more from one year to the next than areas with low values.

central United States, including the Rocky Mountains and the Great Plains are intermediate values.

### 3.2. SDPs Effect on Composite Annual $\delta^{18}\text{O}$

[14] The seasonal patterns (the timing of increased or decreased  $\delta^{18}\text{O}$  values) is very similar for the USNIP sites. Typically the lowest  $\delta^{18}\text{O}$  values occur in February while the highest  $\delta^{18}\text{O}$  values occur in July (Figure 3a). The skill of the sine curves to reproduce the observed monthly  $\delta^{18}\text{O}$  values is most powerful in the Rocky Mountains and the Midwest, and decrease rapidly with proximity to the coast and with lower latitudes. Coefficients of determinations between sine curves and  $\delta^{18}\text{O}$  values are outlined in the auxiliary material.<sup>1</sup>

[15] Additionally, the seasonal  $\delta^{18}\text{O}$  ranges ( $\delta^{18}\text{O}_{\text{Ranges}}$ ) are spatially variable across the United States (Figure 3b). The largest  $\delta^{18}\text{O}_{\text{Ranges}}$  are found in the Rocky Mountains and the Great Lakes Region. Most coastal areas have the smallest  $\delta^{18}\text{O}_{\text{Ranges}}$ . Coastal areas in the Eastern United States are intermediate in their  $\delta^{18}\text{O}_{\text{Ranges}}$  compared to the Great Lakes Region and the Gulf Coast.

[16] The multi-decadal time-series of  $\delta^{18}\text{O}_{\text{Annual}}$ , derived from time-series of precipitation amount and sine curves (defining seasonal patterns of isotopes), were calculated through Equation 1 (Figure 4a). The degree of interannual variability of  $\delta^{18}\text{O}_{\text{Annual}}$  for each site was expressed as two standard deviations of each  $\delta^{18}\text{O}_{\text{Annual}}$  time-series ( $2\sigma\delta^{18}\text{O}_{\text{Annual}}$ ) (Figure 4b). The degree to which  $\delta^{18}\text{O}_{\text{Annual}}$  values vary interannually ultimately defines the potential effect that SDP has on long-term isotopic archives. The lowest  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  values (between 0.25 and 0.75‰  $\delta^{18}\text{O}$ ) dominantly occur in a region surrounding the Gulf of Mexico and the most northerly reaches of the Northeast. The low  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  values around the Gulf of Mexico can be attributed to low  $\delta^{18}\text{O}_{\text{Ranges}}$ , which make it impossible to produce large  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  values despite moderate precipitation variability. The opposite is true in the North-

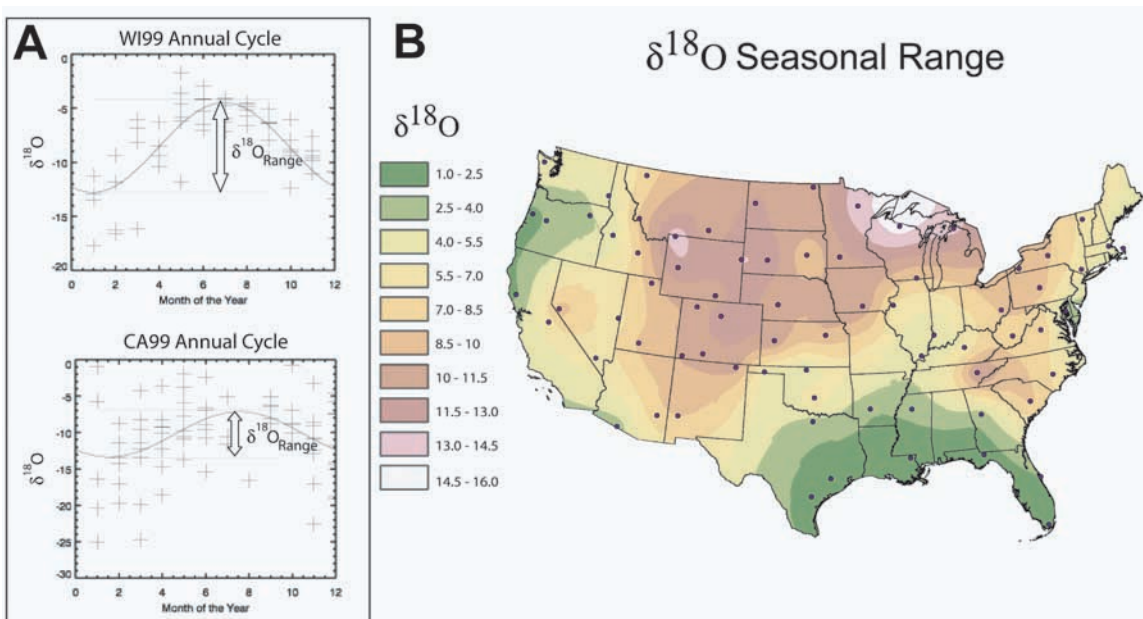
east where  $\delta^{18}\text{O}_{\text{Ranges}}$  are moderate, yet very little seasonal precipitation variability is noted.

[17] The interannual  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  values increase uniformly westward from the Southeast to CO, UT, NM and AZ. Although centered on the Four Corner States, this area of greatest  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  variability (1.25 to 1.75‰  $\delta^{18}\text{O}$ ) runs diagonally from the Four Corner to North Dakota. Strikingly, the Four Corners region does not have the largest  $\delta^{18}\text{O}_{\text{Ranges}}$ . The high  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  variability is attributed to the highly variable SDP as observed in Figure 2. Marginally weaker  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  signals ( $\sim 1.0$  to 1.25‰  $\delta^{18}\text{O}$ ) are observed in the Northern Rocky Mountains, Northern Great Plains regions and Southern Great Plains regions of the country. Similar factors as identified in the Four Corners region likely control the  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  within the Southern Great Plains region, however seasonal variability in precipitation is less significant within the Northern Great Plains and Northern Rocky Mountains. Here, subtle shifts in SDP are powerfully transmitted into the  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  trends through the steep seasonal cycle of  $\delta^{18}\text{O}$ . The extent of  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  within the Northeast, Midwest and Central Atlantic States is approximately 0.5 to 1.25‰  $\delta^{18}\text{O}$ . Low degrees of interannual variability in precipitation amount, results in very little change in interannual isotopic values, despite the  $\delta^{18}\text{O}_{\text{Ranges}}$  being quite sizeable.  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  values within the Southeast and Pacific Northwest are comparable to the Midwest and Northeast, however quite the opposite situation exists. Moderate interannual variability of precipitation cannot be communicated into  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  because the seasonal range in isotopes is very small.

## 4. Discussion

[18] Our study highlights the regions across the United States where SDP has the potential to translate into substantial changes in  $\delta^{18}\text{O}_{\text{Annual}}$  values. The area of large  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  values, in the Southwest extending into the Northern Great Plains, reflects the large  $\delta^{18}\text{O}_{\text{Ranges}}$  in these areas. Precipitation in areas such as the Southwest is influenced by ENSO [D'Odorico *et al.*, 2001]; thus it seems

<sup>1</sup>Auxiliary materials are available at <ftp://ftp.agu.org/apend/gl/2007gl030547>.

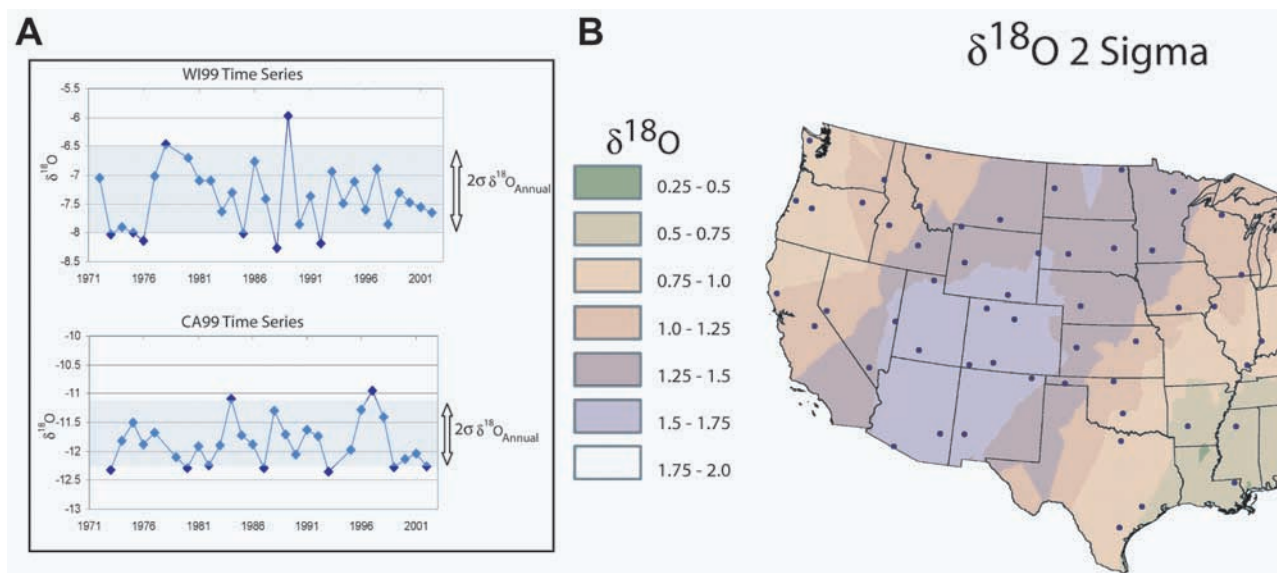


**Figure 3.** (a) Examples of best-fit sine curve for two USNIP sites (WI99 and CA99). These curves were calculated iteratively, changing the various variables of the sine curve equation until the coefficients of determination were smallest. (b) Seasonal ranges of  $\delta^{18}\text{O}$ . Like other studies have shown [e.g., Dansgaard, 1964; Rozanski et al., 1993], the greatest ranges occur in continental regions of the United States, where seasonal temperature ranges are likewise greatest.

reasonable that ENSO could be recorded in paleoclimate records in this region. For the regions where the  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  is above  $\sim 1.0\text{‰}$   $\delta^{18}\text{O}$ , signals of such magnitudes could be misinterpreted as 1.5 to 3.0°C fluctuations in annual average temperatures (using the isotope/temperature transfer function of  $\sim 0.7\text{‰}$   $\delta^{18}\text{O}/\text{°C}$ ) [Dansgaard, 1964]. There is new evidence suggesting that isotope-temperature transfer functions are closer to 0.3 to 0.5 within the United States [Vachon, 1996].

[19] Conversely, the low  $\delta^{18}\text{O}_{\text{Ranges}}$  observed in most coastal regions may result in low coefficients of determination of seasonal patterns of precipitation isotopes and a suppressed potential effect of SDP on  $\delta^{18}\text{O}$  values. For this reason isotopic variability in paleoarchives from such regions do not likely reflect changes in the SDP. Instead, temperature and or the amount of precipitation may be the primary factors effecting  $\delta^{18}\text{O}_{\text{Annual}}$ .

[20] For perspective, during the transition from the Last glacial Maximum to the Holocene, isotope-based paleocli-



**Figure 4.** (a) Two examples of time-series of amount-weighted  $\delta^{18}\text{O}$  values derived from our calculations. The gray/blue bars illustrate 2 sigma ranges of these values. (b) The map illustrates two sigma of the amount-weighted time-series of annual  $\delta^{18}\text{O}$  values.

mate records show an isotopic change of  $\sim 6\%$   $\delta^{18}\text{O}$  at GISP2 [Grootes et al., 1993],  $\sim 6.5\%$   $\delta^{18}\text{O}$  at Huascaran, Peru [Thompson et al., 1995] and Byrd, Antarctica,  $\sim 2\%$   $\delta^{18}\text{O}$  at Devil's Hole, Nevada [Winograd et al., 1992], and  $\sim 5\%$   $\delta^{18}\text{O}$  in Southwestern Alaska [Hu and Shemesh, 2003]. The largest  $2\sigma\delta^{18}\text{O}_{\text{Annual}}$  values ( $1.75\%$ ) derived from our study equate to the entire range for Devil's Hole record and approximately one half of isotopic range between glacial and interglacial conditions seen in these ice cores. Indeed, Figure 2 identifies considerable year-to-year variability in SDP within the United States. However, we note that in order to effect long-term paleoclimate records to the degrees observed between stadial and interstadial conditions, shifts in the timing of precipitation would need to be sustained for decades.

## 5. Conclusions

[21] This research highlights the extent to which changes in the seasonal distribution of precipitation can effect interannual isotopic values of precipitation in the United States. We show that a region's sensitivity to the seasonal distribution of precipitation are the result of: (1) seasonal values of the isotopic composition of precipitation, and (2) the variability in the seasonal amounts of precipitation. In regions where seasonal isotopic amplitudes are low (i.e. Florida), a large seasonal fluctuation in precipitation amount may result in undetectable interannual isotopic signals.

[22] However, in regions where the interannual isotopic values fluctuate dramatically (e.g. Wyoming), seasonal distributions of precipitation can significantly alter the annual isotopic values. Thus, interpretations of climate proxies, need to consider that significant changes in the  $\delta^{18}\text{O}$  values of annual ice core layers, tree rings, speleothems or paleosols can not be strictly attributed to changes in temperature.

[23] **Acknowledgments.** This research was supported by the National Science Foundation, Earth System History program (ESH 01223344, 01654433). We acknowledge the support and cooperation of the National Atmospheric Deposition Program and all of the site managers who made the samples available.

## References

- Dansgaard, W. (1964), Stable isotopes in precipitation, *Tellus*, *16*, 436–468.
- Denton, H. D., R. B. Alley, G. C. Comer, and W. S. Broecker (2005), The role of seasonality in abrupt climate change, *Quat. Sci. Rev.*, *24*, 1159–1182.
- D'Odorico, P., J. C. Yoo, and T. M. Over (2001), An assessment of ENSO-induced patterns of rainfall erosivity in the southwestern United States, *J. Clim.*, *14*(21), 4230–4242.
- Dutton, A., B. H. Wilkinson, J. M. Welker, G. J. Bowen, and K. C. Lohmann (2005), Spatial distribution and seasonal variation in  $18\text{O}/16\text{O}$  of modern precipitation and river water across the conterminous USA, *Hydrol. Processes*, *19*, 4121–4146.
- Grootes, P. M., M. Stuiver, J. W. C. White, S. Johnsen, and J. Jouzel (1993), Comparing of oxygen isotope records from the GISP2 and GRIP Greenland ice cores, *Nature*, *266*, 552–554.
- Hu, F. S., and A. Shemesh (2003), A biogenic-silica  $\delta^{18}\text{O}$  record of climatic change during the last glacial-interglacial transition in southwestern Alaska, *Quat. Res.*, *59*, 379–385.
- Kohn, M., and J. M. Welker (2005), Precipitation and  $\text{d}18\text{O}$ -temperature relations: A reexamination, *Earth Planet. Sci. Lett.*, *231*, 78–96.
- Lynch, J. A., J. W. Gimm, and V. C. Bowersox (1995), Trends in precipitation chemistry in the United States: A national perspective, 1980–1990, *Atmos. Environ.*, *29*, 1231–1246.
- Rozanski, K., L. Araguas-Araguas, and R. Gonfiantini (1993), Isotopic patterns in modern global precipitation, in *Climate Change in Continental Isotopic Records*, *Geophys. Monogr. Ser.*, vol. 78, pp. 1–36, AGU, Washington, D. C.
- Shuman, C. A., R. B. Alley, S. Anandkrishnan, J. W. C. White, P. M. Grootes, and C. R. Stearns (1995), Temperature and accumulation at the Greenland Summit: Comparison of high-resolution isotope profiles and satellite passive microwave brightness temperature trends, *J. Geophys. Res.*, *100*, 9165–9177.
- Steig, E. (1994), Seasonal precipitation timing and ice core records, *Science*, *266*, 1885–1886.
- Thompson, L. G., E. Mosley-Thompson, M. E. Davis, P. N. Lin, K. A. Henderson, J. Cole-Dai, J. F. Bolzan, and K. B. Liu (1995), Late glacial stage and Holocene tropical ice core records from Huascaran, Peru, *Science*, *269*, 46–50.
- Urban, F. E., J. E. Cole, and J. T. Overpeck (2000), Influence of mean climate change on climate variability from a 155-year tropical Pacific coral record, *Nature*, *407*, 989–993.
- Vachon, R. W. (1996), Using a new network of isotopes of precipitation within the United States (USNIP) to better understand mid-latitude isotope-climate relationships, Ph.D. dissertation, Univ. of Colo., Boulder.
- Welker, J. M. (2000), Isotopic ( $18\text{O}$ ) characteristics of weekly precipitation collected across the USA: An initial analysis with application to water source studies, *Hydrol. Processes*, *14*, 1449–1464.
- Welker, J. M., S. Rayback, and G. R. Henry (2005), Arctic and North Atlantic Oscillation phase changes are recorded in the isotopes ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ) of Cassiope tetragona plants, *Global Change Biol.*, *11*, 1–6.
- Werner, M., U. Mikolajewicz, M. Heimann, and G. Hoffmann (2000), Borehole versus isotope temperatures on Greenland: Seasonality does matter, *Geophys. Res. Lett.*, *27*(5), 723–726, doi:10.1029/1999GL006075.
- White, J. W. C., L. K. Barlow, D. Fisher, P. Grootes, J. Jouzel, S. J. Johnsen, M. Stuiver, and H. Clausen (1997), The climate signal in the stable isotopes of snow from Summit, Greenland: Results of comparisons with modern climate observations, *J. Geophys. Res.*, *102*, 26,425–26,440.
- Winograd, I. J., T. B. Coplen, J. M. Landwehr, A. C. Riggs, K. R. Ludwig, B. J. Szabo, P. T. Kolesar, and K. M. Revesz (1992), Continuous 500,000-year climate record from vein calcite in Devils Hole, Nevada, *Science*, *258*, 255–260.

E. Gutmann, Center for the Study of Earth from Space and Cooperative Institute for Research in Environmental Science, University of Colorado, 216 UCB, Boulder, CO 80309, USA.

R. W. Vachon and J. W. C. White, Institute of Arctic and Alpine Research, University of Colorado, Campus Box 450, Boulder, CO 80309, USA. (ryan.vachon@colorado.edu)

J. M. Welker, Environment and Natural Resources Institute and Biology Department, University of Alaska Anchorage, Anchorage, AK 99508, USA.