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Inside:

Solar forcing of Holocene climate: New insights from a speleothem record, southwestern United States

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ABSTRACT

Holocene climate change has likely had a profound influence on ecosystems and culture. A link between solar forcing and Holocene climate, such as the Asian monsoon, has been shown for some regions, although no mechanism for this relationship has been suggested. Here we present the first high-resolution complete Holocene climate record for the North American monsoon region of the southwestern United States (southwest) in order to address the nature and causes of Holocene climate change. We show that periods of increased solar radiation correlate with decreased rainfall, the opposite to that observed in the Asian monsoon, and suggest that a solar link to Holocene climate is through changes in the Walker circulation and the Pacific Decadal Oscillation and El Niño–Southern Oscillation systems of the tropical Pacific Ocean. Given the link between increased warming and aridity in the southwest, additional warming due to greenhouse forcing could potentially lead to persistent hyperarid conditions, similar to those seen in our record during periods of high solar activity.

Keywords: Solar forcing, Holocene climate, monsoon, speothem, U-series, southwestern United States.

INTRODUCTION

The climate of the Holocene, while relatively stable in comparison to variability during the last glacial period, has varied enough to dramatically affect ecosystems and human development in many parts of the world. For example, the Holocene was a time of profound changes in the cultural landscape of the southwestern United States (herein southwest), including expansions and contractions of ancestral American communities that were in part responses to changes in climate (Polyak and Asmerom, 2001; Polyak et al., 2004). The causes of Holocene climate variation are not known with certainty, but three forcing mechanisms have been suggested as possible factors: ocean circulation, volcanic activity, and solar variability (Bianchi and McCave, 1999; Bond et al., 2001; Crowley, 2000). Recent studies have suggested a link between solar variability, expressed as changes in the carbon 14 content of the atmosphere ($\Delta^{14}C$), and North Atlantic climate (Bond et al., 2001) and the Asian monsoon (Neff et al., 2001; Fleitmann et al., 2003; Wang et al., 2005). It is still not clear how solar variability modulates climate changes in these regions and whether this link is global. In arid regions such as the southwest, the main challenge to identifying causes of Holocene climate variability has been the lack of high-resolution records that extend beyond the tree-ring chronology, which in the southwest only covers the past 2 k.y. (Grissino-Mayer, 1996). Speleothems provide a unique opportunity because it is possible to obtain absolute chronology at any interval, and they contain multiple chemical, physical, and isotopic proxies. Here we present the first complete high-resolution climate proxy for the southwest in the form of $\delta^{18}O$ variations in a speleothem covering the entire Holocene, to 12.3 ka. Our results show that periods of greater solar activity are associated with decreased moisture in the southwest. Over the same time period, the response of the Asian monsoons to solar variability was in the opposite direction. We suggest that these relationships may be explained if solar activity acts to modulate the El Niño–Southern Oscillation (ENSO) and or Pacific Decadal Oscillation (PDO), and in particular the Walker circulation, on decadal and centennial time scales.

CHRONOLOGY AND ISOTOPE GEOCHEMISTRY

Sample PP1, a 14-cm-long stalagmite, was collected from Pink Panther Cave in the Guadalupe Mountains, New Mexico (Fig. 1A). A series of 22 ^{230}Th-^{234}U dates demonstrates that the sample grew continuously but nonlinearly from ca. 12,330 yr B.P. to the present (Fig. 1B; Figs. DR1A and DR1B in the Data Repository[1]; complete uranium-series chronology data are in Table DR1). We measured oxygen stable isotope ratios at 200 μm intervals for a total of 681 samples, an average time resolution of 17 yr over the entire period. The $\delta^{18}O$ values vary from −5.81‰ to −2.66‰ (Fig. 2A; stable isotope data are available in Table DR2; see footnote 1). The time series of $\delta^{18}O$ does not show a clear trend through the Holocene, but displays rapid variations of (a few per mil) on millennial and centennial time scales. The variation due to temperature of calcite-water fractionation (~0.25‰/°C) probably does not contribute significantly to variation in the $\delta^{18}O$ values. Temperature variations of 4–5 °C would cause only 1‰ variation in $\delta^{18}O$, and there are no indicators of such large temperature changes during the Holocene. Variations in the O and C isotopic values could result from kinetic fractionation. In this case O and C values would covary. A plot of $\delta^{18}O$ versus $\delta^{13}C$ shows no overall signifi-

[1]GSA Data Repository item 2007010, Figures DR1A (photo of speleothem PP1), DR1B (photo of Pink Panther Cave) and DR1C ($\delta^{18}O$ vs. $\delta^{13}C$ figure), and Tables DR1 (complete data and methods for uranium-series chronology), and DR2, ($\delta^{18}O$ and $\delta^{13}C$ data), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

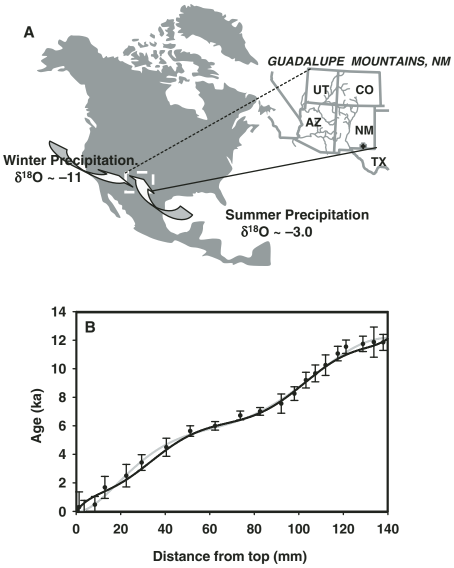

Figure 1. A: Guadalupe Mountains, New Mexico, site of Pink Panther Cave and typical of other parts of U.S. southwest, has two rainy seasons. Summer North American monsoon (NAM) rainfall (Adams and Comrie, 1997), derived from Gulf of Mexico, is characterized on average by heavy $\delta^{18}O$ values (~−3‰), while winter Pacific-derived precipitation is characterized by low $\delta^{18}O$ values (~−11‰) (Hoy and Gross, 1982; Yapp, 1985). B: Chronology of PP1, showing distance from top of stalagmite to bottom vs. U-Th ages. Solid curve is age model based on 9 degree polynomial fit of chronology data, covering entire period. Error bars reflect analytical errors, including uncertainties related to estimate of initial $^{230}Th/^{232}Th$ ratio (details on chronology, including analytical methods, are in Table DR1; see footnote 1).

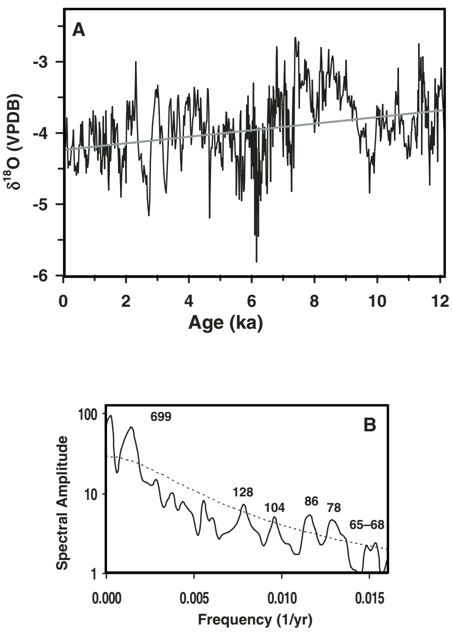

Figure 2. A: Raw (not detrended) $\delta^{18}O$ record for stalagmite PP1. For two segments where we have detailed speleothem growth data [between 0–4 ka (Polyak and Asmerom, 2001) and 9–12 ka (Polyak et al., 2004)], $\delta^{18}O$ variations correspond to variations in amount of precipitation. Overall, early Holocene, for which $\delta^{18}O$ values are highest, was driest segment of Holocene, characterized by desiccation of regional lakes (Anderson et al., 2002), after wet period that started after the beginning of Younger Dryas (Polyak et al., 2004). Large negative excursions during late Holocene, starting ca. 3.5 ka, such as at 3.3 and 2.7 ka, correspond to unusually wet periods, possibly initiating migration of agriculture into southwest (Polyak and Asmerom, 2001). Long-term trend from higher $\delta^{18}O$ in early Holocene to lower $\delta^{18}O$ values in late Holocene (calculated using simple linear fit to data) is opposite to trend observed in Asian monsoon (Wang et al., 2005) and is unlikely to represent strengthening of North American monsoon. B: Univariate spectra of entire raw $\delta^{18}O$ record estimated using computer program Redfit (Schulz and Mudelsee, 2002), which utilizes Lomb-Scargle Fourier transform for unevenly spaced data. Number of overlapping (50%) segments (n_{seg}) of 6 and Welch I type spectral window were used. Dashed line shows red-noise boundary (upper 90% χ^2 bound). Most significant peaks (above red-noise background) within 6 dB bandwidth frequency resolution (0.451 k.y.$^{-1}$) are 128, 104, 86, 78, and 65–68 yr, and are similar to peaks observed in $\Delta^{14}C$ spectra and have been attributed to solar variability (Sonnett and Finney, 1990; Stuiver and Braziunas, 1993). Resolution of our $\delta^{18}O$ data, on average, is 17 yr, thus peaks younger than 50 yr were disregarded. VPDB—Vienna Peedee belemnite.

cant fractionation trend (Fig. DR1C). Secular variation in $\delta^{18}O$ for a given speleothem, even in arid regions more arid than our sample site (Bar-Matthews et al., 2003; Neff et al., 2001), has been shown to primarily reflect variations in the isotopic composition of precipitation, the source of the cave drip water. We similarly attribute the great majority of the observed variability in PP-1 to be due to changes in the isotopic composition of rainfall through time.

DISCUSSION AND CONCLUSIONS

Typical of much of the southwest, rainfall in the study region is concentrated in two periods. From July through September, rainfall in the area is associated with the North American monsoon (NAM) (Adams and Comrie, 1997), moisture being derived primarily from the Gulf of Mexico. From December through March precipitation is derived from westerly low-pressure systems from the Pacific Ocean by the jet stream. On average these two seasons and sources of rainfall also have very distinct oxygen isotope ratios. Summer precipitation is much more enriched in the heavy isotope ($\delta^{18}O$ ~−3‰) compared to the Pacific-derived winter precipitation ($\delta^{18}O$ ~−11‰) (Fig. 1A) (Hoy and Gross, 1982; Yapp, 1985). Thus, the balance between winter and summer precipitation is one factor that may influence the $\delta^{18}O$ value of mean annual precipitation. In addition, the amount of rainfall in many monsoon regions is observed to be inversely correlated with the $\delta^{18}O$ value of precipitation (termed the amount effect) during the monsoon months (Dansgaard, 1964). Wright et al. (2001) documented amount effect in the North American monsoon. Analysis of instrumental data for the past 100 yr shows that, even though the annual moisture budget is dominated by summer precipitation, years with above-average annual precipitation are most often years with above-average winter precipitation (Liles, 1999; McCabe et al., 2004). To a first approximation, we interpret lower $\delta^{18}O$ values in sample PP1 as indicating an increase in either summer or winter precipitation, or an increase in both.

The high $\delta^{18}O$ values seen during the early Holocene and the early half of the middle Holocene are consistent with previous observations that these were very arid periods for the region (Anderson et al., 2002; Polyak et al., 2004). For the late Holocene (Polyak and Asmerom, 2001) and the Pleistocene-Holocene transition (Polyak et al., 2004), we have an independent, growth thickness–based record with which to compare our $\delta^{18}O$ data. The large negative excursions in the $\delta^{18}O$ record (Fig. 2A) ca. 3300 yr B.P. and in particular at 2700 yr B.P. correlate with increased stalagmite growth (high moisture) and are often the ages above hiatuses (initiation of growth after middle Holocene aridity) (Polyak and Asmerom, 2001). Conversely, the large positive excursion in $\delta^{18}O$ values ca. 10,000 yr B.P. represents the termination of growth for a number of speleothems and a period of desiccation for regional lakes (Anderson et al., 2002), marking the end of a wet period that started soon after the initiation of the Younger Dryas and lasted until ca. 10 ka (Polyak et al., 2004). We have virtually no speleothems (except for PP1) that show any growth during the period consistent with the high $\delta^{18}O$ values in PP1. This dry period persisted to ca. 7 ka. After 7 ka, lower $\delta^{18}O$ values suggest a return to wetter conditions. This is corroborated by the initiation of growth in a number of our speleothems, although not to the extent observed during the late Holocene (Polyak and Asmerom, 2001). The prominent negative $\delta^{18}O$ excursions ca. 6.2 ka likely represent a brief episode of greater than normal effective precipitation. Evidence for such an event is noted in the nearby Lake Estancia sediment record (Menking and Anderson, 2003) and a northern Mexico lake record (Castiglia and Fawcett, 2006).

To test for the presence of cyclical variation in our record, we performed spectral analysis of the raw $\delta^{18}O$ data using the program Redfit (Schulz and Mudelsee, 2002). Results show significant (above the red-noise curve) peaks centered at ~128, 104, 86, 78, and 65–68 yr. A number of these peaks closely match previously reported periodicities in the ^{14}C content of the atmosphere, which have been attributed to periodicities in the solar cycle (Stuiver and Braziunas, 1993). Shorter periods are not considered because our $\delta^{18}O$ record has an average 17 yr sampling resolution. Our $\delta^{18}O$ data and the detrended $\Delta^{14}C$ data (INTCAL 98; Stuiver et al., 1998) have a noticeable visual match (Fig. 3A). The chronology for the $\delta^{18}O$ data is tuned to the $\Delta^{14}C$ record using a polynomial curve (shown in Fig. 1B), taking into consideration and fitting within the 2 σ analytical errors, plus small errors associated with the $\Delta^{14}C$ chronology

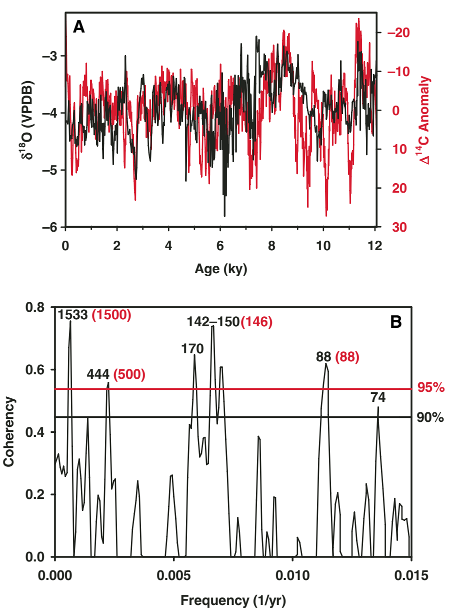

Figure 3. A: Covariation of raw $\delta^{18}O$ record (black line) and detrended $\Delta^{14}C$ data (INTCAL 98) (red line) (Stuiver et al., 1998). We detrended $\Delta^{14}C$ data by subtracting six degree polynomial long-term trend from data. Scales for two records are in opposite direction to each other to show negative correlation. In this case, higher $\delta^{18}O$ values correspond to lower $\Delta^{14}C$ values but higher solar intensity. Zero reference is A.D. 1955. Two records have excellent visual match. Correlation coefficient for two records for entire Holocene is R = –0.34 to –0.38 (20–50 yr interpolation). We do not know cause of mismatch ca. 7.2 ka. B: Cross-spectral analysis, using computer package SPECTRUM (Schulz and Stattegger, 1997), of raw $\delta^{18}O$ and raw $\Delta^{14}C$ time series. Parameters for coherency calculations were similar to those used for univariate spectral analysis (Fig. 2B). 95% and 90% false alarm limits are shown as solid and dashed lines, respectively. Significant peaks (in black) include 1533, 444, 170, 146, and 88 yr. Corresponding numbers in red are peaks previously associated with solar peaks (Sonnett and Finney, 1990; Stuiver and Braziunas, 1993). VPDB—Vienna Peedee belemnite.

(INTCAL 98; Stuiver et al., 1998). Periods of increased solar activity and likely higher irradiance (Stuiver and Braziunas, 1993), expressed as negative $\Delta^{14}C$, are well correlated with positive $\delta^{18}O$ anomalies. If our interpretation of the isotopic record is correct, greater solar activity results in decreased winter or summer precipitation (or both) and a drier climate in southern New Mexico. Our $\delta^{18}O$ record and the global $\Delta^{14}C$ record show a remarkable correlation, R = –0.34 to –0.38 (20–50 yr interpolation) for the entire record, considering that the proxies are so dissimilar.

Cross-spectral analysis of the $\Delta^{14}C$ data and $\delta^{18}O$ data (Fig. 3B) confirms that the two records have matching periodicities at 1533, 444, 170, 146, and 88 yr above the 95% confidence interval. The coherent peaks, within the bandwidth of the Welch window, are identical to the spectral peaks of the $\Delta^{14}C$ record, and some of these, including the 1533 (1500) yr (Bond), 440 (400–500) yr, the 146 yr, and the 88 yr (Gleissberg) cycles, have been attributed to solar variability (Bond et al., 2001; Sonnett and Finney, 1990; Stuiver and Braziunas, 1993). The coherence between our $\delta^{18}O$ and the $\Delta^{14}C$ data (Figs. 3A, 3B) suggests a link between southwest climate change and solar variability over the past 12 k.y.

Previous studies of the Asian monsoon show a relationship between rainfall and solar activity that is opposite in sign to the results of our study. In speleothem records from Oman and China, increased solar activity correlates with more negative stalagmite $\delta^{18}O$ values and greater monsoon rainfall. The variance in solar irradiance associated with historical solar cycles is estimated to be between 0.1% and 0.3% (1–2 mW/m^2) (Hoyt and Schatten, 1993; Lean et al., 1995), which seems too small to directly affect the sensible heating component of the Asian monsoon. It is not clear how such minor changes in irradiance are amplified by the ocean-atmosphere system so that they affect large-scale components of climate such as the monsoons. Nonetheless, if some direct (though amplified) solar forcing of the NAM was the dominant control on southwest precipitation, we would expect a positive relationship between solar activity and moisture (positive correlation between $\delta^{18}O$ and $\Delta^{14}C$), similar to the relationship observed with the Asian monsoon. Reanalysis of modern instrumental data shows some degree of intensification of the Asian monsoon and the NAM (van Loon et al., 2004). Thus we do not rule out a component in our record that reflects positive solar feedback on the NAM, especially on short time scales. What is clear from our record is that the dominant climate-solar relationship in the southwest is opposite to that observed in the Asian monsoon regions, and implies that any direct solar intensification of the two monsoons is overridden in the southwest by some other effect of solar forcing that results in a contrasting relationship between solar variability and moisture in the two regions.

One possible mechanism for the observed climate responses is that solar variability is affecting climate via the Pacific Ocean and the PDO–ENSO system, because PDO–ENSO affects rainfall in the Asian monsoon region and the southwest in opposite ways. Drier than normal winters in the southwest almost without exception follow a La Niña episode, while wet winters and less often wet summers typically occur during El Niño years, in particular during positive PDO years (Cook et al., 2004; Liles, 1999; McCabe et al., 2004). While the relationship between ENSO and the Asian monsoon is less clear, in the summers following an El Niño event the Asian monsoon is typically weakened and the area is often characterized by droughts (Chan and Zhou, 2005). Comparison of modern rainfall data from China and the southwest shows an opposite relationship (Rasmussen et al., 2006). If this relationship between the two regions holds true for the rest of the Holocene, then it suggests that solar forcing might be steering the PDO–ENSO system on millennial and centennial time scales via changes in the Walker circulation. If periods of increased solar activity lead to a stronger Walker circulation and generally more La Niña–like conditions (and vice versa), then the antiphase behavior of the responses of precipitation in the Asian monsoon and the southwest could be explained. Such a relationship between solar variability and the ENSO system has been observed in recent modeling studies (Mann et al., 2005).

This salient anticorrelation of the two climatic regimes, currently expressed in their seesaw responses to PDO–ENSO, suggests that solar forcing of continental climate is likely modulated through the Pacific Ocean. Temperature anomalies in the Pacific Ocean seem capable of inducing globally synchronous climate change (Clement et al., 1999). The link between southwest climate, Asian monsoon, and solar variability described here shows that the teleconnections observed in the modern climate regime may have operated throughout the Holocene and that solar forcing of the tropical Pacific may explain much of the variability observed in Holocene climate both in the southwest and elsewhere. A relationship between historical southwest precipitation and the Atlantic Multidecadal Oscillation (AMO) has been reported (McCabe et al., 2004). AMO variability is related to changes in sea surface temperature (SST) in the North Atlantic; Holocene paleoclimatic data also show strong modulation of North Atlantic climate (Bond et al., 2001). Moreover, Hoerling et al. (2001), based on climate data since 1950, has suggested that North Atlantic climate, including the AMO, may be forced by the tropical (Indian and Pacific) oceans. Thus, the relationship between the AMO and southwest climate may not be causal, and rather may be linked through their mutual response to solar forcing through the tropical oceans.

It is not clear how variations in solar output modulate ENSO–PDO in detail. If it is linked to small changes in heat, then based on our Holocene data, increased warming due to other causes, such as increases in greenhouse gases, is likely to lead to even more arid conditions in the desert southwest and wetter conditions in the monsoon regions of Asia.

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About the Cover:

Pueblo Bonito is the largest ruin at Chaco Canyon, New Mexico, USA. The Chaco complex was an important center of Pueblo culture that flourished sometime between 1200 to about 700 years before present. The abandonment of dwellings by ancestral Americans, such as those at Chaco, may have been caused by sudden shifts in climate. Although the cause of Holocene climate variability is not well understood, Asmerom et al. suggest that solar variability, via modulation of the tropical Pacific, may be the cause of Holocene climate change. See "Solar forcing of Holocene climate: New insights from a speleothem record, southwestern United States" by Asmerom et al., p. 1–4.

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