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Solar forcing of Holocene droughts in a stalagmite record from West Virginia in east-central North America

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[1] Elevated Sr/Ca ratios and $\delta^{13}C$ values in Holocene-age stalagmite BCC-002 from east-central North America record six centennial-scale droughts during the last five North Atlantic Ocean ice-rafted debris (IRD) episodes, previously ascribed to solar irradiance minima. Spectral and cross-spectral analyses of the multi-decadal resolution Sr/Ca and $\delta^{13}C$ time series yield coherent ~200 and ~500 years periodicities. The former is consistent with the de Vries solar irradiance cycle. Cross-spectral analysis of the Sr/Ca and IRD time series yields coherent periodicities of 715- and 455-years, which are harmonics of the 1,450 ± 500 year IRD periodicity. These coherencies corroborate strong visual correlations and provide convincing evidence for solar forcing of east-central North American droughts and strengthen the case for solar modulation of mid-continent climates. Moisture transport across North America may have lessened during droughts because of weakened north-south temperature and pressure gradients caused by cooling of the tropical Pacific and Atlantic Oceans. **Citation:** Springer, G. S., H. D. Rowe, B. Hardt, R. L. Edwards, and H. Cheng (2008), Solar forcing of Holocene droughts in a stalagmite record from West Virginia in east-central North America, *Geophys. Res. Lett.*, *35*, L17703, doi:10.1029/2008GL034971.

1. Introduction

[2] Given its proximity to the well-studied North Atlantic Ocean (AO), surprisingly little is known about how eastern North American hydroclimates responded to purported solar-forcing of North Atlantic sea-surface temperatures (SSTs) during the Holocene [*Willard et al.*, 2005; *Li et al.*, 2007]. East-central North America (NA) lies at the seasonal juncture of Northern Hemisphere westerlies with low-level jets and moist air masses originating from the subtropical Gulf of Mexico. As a result, local climate is very sensitive to the north-south contrast in pressure over the North AO and eastern NA. Specifically, weak N-S pressure gradients suppress northeastward moisture transport across eastern NA [*Enfield et al.*, 2001], as does the position of the polar jet, which determines the trajectories and northward penetrations of moist, subtropical air masses across the region throughout much of the year. As such, hydroclimates of eastern NA are dually sensitive to the climate state of the North AO and mid-latitude transcontinental teleconnections linking the Pacific and North Atlantic oceans [*McCabe et al.*, 2004; *Seager*, 2007]. Herein, we demonstrate that this dual dependency allowed an east-central NA paleoclimate archive (speleothem) to directly record solar-forcing of Mid- to Late Holocene droughts that were caused by weakening of moisture transport over east-central NA in response to cooling of the Pacific and Atlantic Oceans.

2. Methodology

[3] We present a multi-decadal scale record of east-central NA hydroclimatology using stalagmite BCC-002 from Buckeye Creek Cave (BCC), West Virginia (37°58.57′N, 80°23.98′W, 600 m amsl)(Figure S1 of the auxiliary material[1]). BCC-002 was collected from a humid, upper-level cave passage from beneath a soda straw, which has a constant, but slow drip rate. BCC-002 grew continuously from ~7,000 years B.P. to ~800 years B.P., when a very brief hiatus occurred, marked by a break in sample growth structure at 10.5 mm depth from the stalagmite tip (Figure S2). BCC-002 then grew continuously from ~800 years B.P. until its collection in 2002. Fourteen $^{234}U/^{230}Th$ age estimates were obtained along the growth axis of the 200 mm-tall stalagmite using U/Th dating techniques developed for carbonates and adapted for measurement on a mass spectrometer [*Edwards et al.*, 1987]. Ages and radiometric data are provided in the auxiliary material (Table S1). Sample ages were assigned by linear interpolation between individual $^{234}U/^{230}Th$ ages and are reported as calendar years before present (years B.P.), where present is defined as 1950 A.D.

[4] BCC-002 was contiguously sampled at mm-scale resolution down the growth axis to obtain 200 samples for stable isotopic ($\delta^{18}O$, $\delta^{13}C$) and elemental abundance (Ca, Sr) analyses (Data Set S1). Stable isotope samples were analyzed using a GasBench II coupled to a ThermoFinnigan Delta*Plus*XP isotope ratio mass spectrometer. Values were standardized to V-PDB using NBS-19, with precisions of 0.1‰ for both $\delta^{18}O$ and $\delta^{13}C$. Trace metal analyses were performed by inductive couple plasma mass spectrometry using standard methods and were reproducible to a precision of 0.05%.

[5] We focused on developing proxies for drought conditions using the $\delta^{13}C$ and Sr/Ca ratios in BCC-002 calcite. Stalagmitic $\delta^{13}C$ values reflect the degree of water-rock interactions above the speleothem, but the isotopic ratios can be used as proxies for relative moisture abundance in

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[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2008gl034971. Other auxiliary material files are in the HTML.

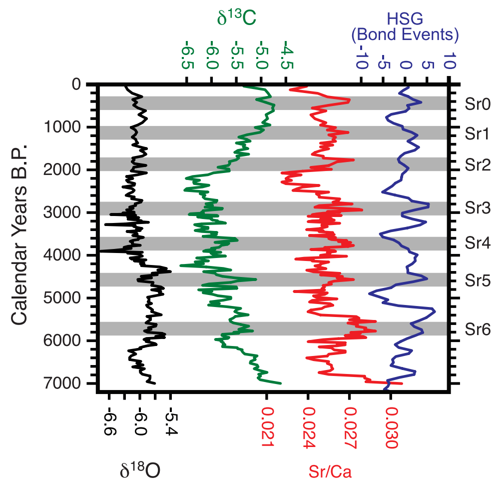

Figure 1. δ^{18}O, δ^{13}C, and Sr/Ca ratio data from stalagmite BCC-002 plotted against normalized abundance of hematite-stained grains (HSG) in North Atlantic Ocean core MC52-VM29-191 [*Bond et al.*, 2001]. The two comparatively stable time periods (pre- and post-4,200 years B.P.) in the δ^{18}O time series contrast with a general downward trend in δ^{13}C values, which is abruptly reversed ~2,100 years B.P. due to land disturbances (see text). Local maxima of the δ^{13}C and Sr/Ca time series are well correlated, but do not show consistent relationships with the δ^{18}O time series. Seven peaks are readily discernable in the Sr/Ca time series, highlighted in gray, and six of these droughts are reached during or close to North Atlantic IRD events recorded by greater abundances of HSG. The gray boxes are for illustrative purposes only.

overlying soils and epikarst because soil respiration rates and plant productivity help define the carbon isotopic compositions of speleothem-forming drip waters. δ^{13}C values are more depleted (enriched) when climate is comparatively moist (dry), due to increased (decreased) soil respiration [*McDermott*, 2004]. Sr/Ca ratios can be used to reconstruct relative rates of epikarstic moisture transport because low moisture levels can cause 1) increased drip water residence times, leading to 2) Ca drawdown *via* calcite precipitation in the overlying epikarst, which increases Sr/Ca ratios in the residual drip waters and their dependent speleothems. A positive correlation can exist between speleothem δ^{13}C and Sr/Ca ratios because decreased moisture abundances result in precipitation of calcite in the vadose zone, leaving the residual solution enriched in ^{13}C and Sr [*Musgrove and Banner*, 2004], although the strength of correlation is presumably weakened by differences in biotic (δ^{13}C) *versus* abiotic (Sr/Ca) responses to changes in moisture abundance.

[6] A detailed discussion of the δ^{18}O record will be provided elsewhere (Rowe et al., manuscript in preparation, 2008). Herein, we note that δ^{18}O values in speleothem calcite can be an archive of local mean atmospheric temperature and precipitation sources [*McDermott*, 2004]. BCC-002 δ^{18}O values are not well correlated with δ^{13}C values (R^2 = 0.04) and local δ^{13}C maxima, interpreted to reflect relatively dry conditions, are not always coincident with local δ^{18}O minima (Figure 1), which could be interpreted to reflect cooling.

3. Results

3.1. Sr/Ca Ratios and δ^{13}C

[7] The stalagmite δ^{13}C record (Figure 1) reveals a multimillennial-scale decreasing trend from −4.6 to −6.5‰ between ~7,000 to 2,100 years B.P., superimposed by several multicentennial-scale ^{13}C-enrichment episodes. These ^{13}C-enrichment episodes correlate with well-defined episodes of increased Sr/Ca ratios (Figure 1) and can be attributed to decreased hydrologic head caused by increased aridity [*Musgrove and Banner*, 2004]. Because the Sr/Ca record does not possess a multimillennial-scale trend like δ^{13}C, seven episodes of increased epikarstic water-rock interaction are defined on the basis of elevated Sr/Ca ratios (Figure 1, Sr0-Sr6 denoted in gray). However, the post-2,100 years B.P. records of δ^{13}C and Sr/Ca ratios are partially affected by watershed-scale landscape disturbance from Native American land-use practices, which were tied to native settlement(s) near BCC [*McBride and Sherwood*, 2006; *White*, 2007]. The disturbances most affected the local ecosystem [*White*, 2007] and we do not utilize post-2,100 years B.P. values of δ^{13}C because any changes in C3 and C4 plant abundances [*Denniston et al.*, 2007] or intentional forest fires would have affected δ^{13}C. We do interpret the entirety of the largely abiotically-derived Sr/Ca record, including Sr0-Sr2.

[8] Interestingly, six of the seven dry intervals (Sr0-Sr3, Sr5, Sr6) correlate with episodes of increased drift-ice in the North AO that are hypothesized to be forced by solar variability and possess a periodicity of 1,450 ± 500 years [*Bond et al.*, 2001]. Additional stable isotopic evidence from speleothem and lake-level records from the North American mid-continent further support an association between NA aridity and North AO ice rafting, suggesting that these relatively low-frequency drought cycles are also driven by solar variability [*Viau et al.*, 2002; *Denniston et al.*, 2007].

3.2. Spectral Analysis

[9] Spectral analysis of the Sr/Ca ratio and δ^{13}C time series was performed using ARAND software [*Howell et al.*, 2006] to determine whether the inferred droughts display periodicity (Figure 2). The average time resolution for BCC-002 is 35 years, but decreasing growth rates reduce resolution to 75 years after 835 years B.P and we disregard all spectral peaks below the Nyquist period of 150 years (0.0067 yr^{-1}). The Sr/Ca spectral analysis included all BCC-002 data (37 to 6,945 years B.P.), but only the time period 2,100 to 6,945 years B.P. was used for the spectral analyses involving δ^{13}C values (Figures 2b and 2c).

[10] The Sr/Ca and δ^{13}C records both have statistically significant periodicities of ~200 and ~500 years (Figures 2a and 2b), which have coherencies of >0.90 (Figure 2c). Spectral periodicity and cross-spectral coherency at the 210-yr band is consistent with the 205-yr de Vries (Suess) solar cycle [*Wagner et al.*, 2001]. The ~500-yr spectral and coherency peaks may be the result of coupled solar-secular forcings described by *Emile-Geay et al.* [2007] or a harmonic of IRD event periodicities, as discussed below.

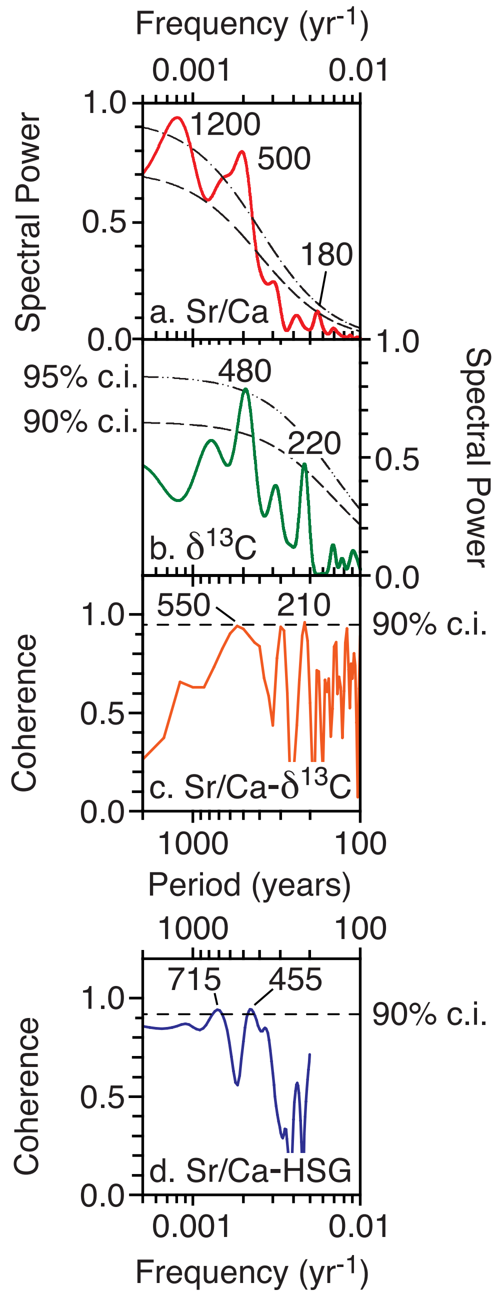

Figure 2. Normalized spectral power densities for unsmoothed (a) Sr/Ca ratios and (b) δ^{13}C time series. Data were linearly detrended. Bandwidths are 0.0038 yr^{-1}. (c) Results of cross-spectral analysis for coherence between the Sr/Ca and δ^{13}C records. Periods exceeding the 90% significance level (lower dashed line) in spectral analyses are labeled in years (Figures 2a and 2b). Among the labeled coherence peaks, only the 210 yr period exceeds the 90% significance level. The 300 and 550 yr periods are significant at levels of ≥88%. (d) Results of cross-spectral analysis for coherence between the BCC Sr/Ca time series and HSG abundance in North Atlantic Ocean core MC52-VM29-191 [*Bond et al.*, 2001]. Bandwidth is 0.0038 yr^{-1}.

[11] A broad spectral peak in the Sr/Ca time series is centered on the 1,200-year band (Figure 2a), which is consistent with six of the seven peaks in the Sr/Ca time series (Sr0-Sr3, Sr5-Sr6) having been reached contemporaneously with peak periods of ice-rafting in the North AO (Figure 1) [*Bond et al.*, 2001]. Cross-spectral analysis of the Sr/Ca ratios and IRD time series yield statistically significant coherencies at periodicities of 455 and 715 years (Figure 2d), which are approximately equal to the second and third harmonics of the Bond's eponymous 1,450 ± 500 year cycle (725 and 480 years, respectively).

[12] The abridged δ^{13}C time series displays local maxima correlative to Sr/Ca ratio peaks Sr3-Sr6 (Figure 1), but spectral analysis does not yield a statistically significant millennial-scale periodicity (Figure 2b). Absence of the low-frequency periodicity in the δ^{13}C time series probably reflects: (i) poor resolution at low frequencies created by record abridgement, (ii) differing responses of the abiotic and biotic pathways to the low frequency oscillation, or (iii) masking by significant, largely unidirectional changes in forest composition that began at the end of the Pleistocene and continued until anthropogenic forest management began in the Late Holocene [*Delcourt and Delcourt*, 2004].

4. Continental Droughts and Solar Forcing

[13] Historically, SST anomalies (SSTA) in the North AO have been a strong predictor of drought in east-central NA and the BCC region. Low annual mean daily discharges (Q_m) in the Greenbrier River near BCC (Figure S1) have been associated with the warm phase of the Atlantic Multidecadal Oscillation (+AMO) during which the North AO was comparatively warm (Figures 3a and 3c). However, numerous studies have established that SSTA in the tropical and north Pacific Ocean are good predictors of NA drought, especially west of the Mississippi River [*Hoerling and Kumar*, 2003; *McCabe et al.*, 2004; *Booth et al.*, 2006; *Cook et al.*, 2007]. Historically, extended La Niña-like conditions (cool tropical Pacific Ocean SST) have resulted in reduced evaporation and weakening of atmospheric

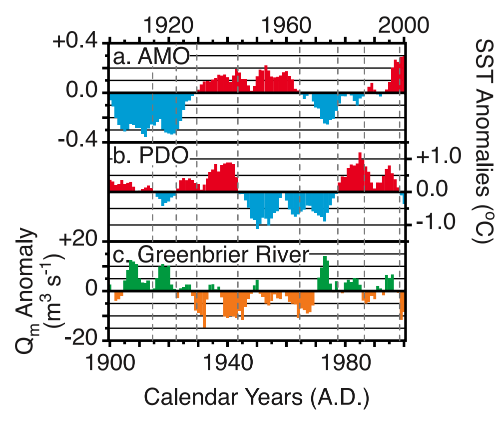

Figure 3. Differences between the long-term average of annual mean daily discharge (Q_m = 57.0 m^3 s^{-1}) in the (c) Greenbrier River and values for individual years plotted against SSTA in the (a) North Atlantic and (b) North Pacific oceans. Each time series was smoothed using a 5-year moving average. Q_m data is for gaging station 03183500 at Alderson, WV (U.S. Geological Survey, National Water Information System database, http://waterdata.usgs.gov/nwis/sw?), which is located 35 km south of BCC.

circulation across the NA interior [*Booth et al.*, 2006; *Cook et al.*, 2007]. Migration of stationary Rossby waves over NA is favored during extended La-Niña events, which induces anomalous anticyclonal activity over the southern United States and further enhances drought conditions [*Cook et al.*, 2007], which can themselves be magnified by reductions in winter flow convergence over NA [*Seager*, 2007].

[14] Negative phases of the Pacific Decadal Oscillation (-PDO), during which North Pacific SSTs are anomalously warm and eastern tropical Pacific SSTs are anomalously cool, resemble La Niña-like climatic conditions with northward migration of the Pacific jet stream and decreased precipitation in east-central NA [*Livezey et al.*, 1997]. Low annual mean daily discharges (Q_m) in the Greenbrier River near BCC were associated with -PDO from 1944 to 1970 (Figure 3). Both the AMO and PDO were negative from 1965 to 1970, a period characterized by below average Q_m in the Greenbrier River (Figure 3c). However, the AMO was only slightly negative and Q_m was significantly above average after 1970 as the -AMO phase strengthened (Figure 3).

[15] The 210-year period coherency in the BCC-002 Sr/Ca and δ^{13}C time series is evidence that the de Vries solar irradiance cycle has significant effects upon moisture levels in east-central NA. The drought-SIC association is particularly striking when Sr/Ca ratios and δ^{13}C values are compared visually to cool North AO episodes and enhanced ice-rafting (Figure 1). This qualitative observation is supported by the 1,200-year periodicity in the Sr/Ca time series and coherency of the Sr/Ca time series with prominent IRD harmonics (Figure 2d). However, cool episodes in the North AO (-AMO) are generally associated with enhanced runoff in the Greenbrier River and not drought (Figure 3). This observation suggests that different climate regimes operate during -AMO periods *versus* episodes of enhanced ice-rafting and IRD deposition.

[16] The difference may lie in the states of the tropical Atlantic Ocean. SSTs in the tropical AO decreased by 1.5°C during the Little Ice Age and Maunder solar minimum with the most pronounced drop in SSTs coinciding with the apex of the Maunder solar minimum [*Black et al.*, 2007]. This cooling of the tropical AO coincided with significant changes in circulation over the North AO and drying in eastern NA [*Shindell et al.*, 2001; *Willard et al.*, 2005]. In contrast, the lack of significant tropical cooling during recent -AMO periods favored enhanced circulation and precipitation over east-central NA (Figure 3) by creating strong N-S temperature and pressure gradients.

[17] With regard to Pacific Ocean forcing, tree ring and glacier advance studies from western North America and Alaska record a persistent -PDO mode during the three most recent solar minima [*Wiles et al.*, 2004]. This cooling of the North Pacific Ocean caused changes in transcontinental meridional flow and, thereby, cooling and drying in eastern NA [*Willard et al.*, 2005]. Thus, the combination of SST-driven changes in transcontinental meridional circulation caused a decrease in flow convergence, increased drought frequencies, and cooling in east-central NA [cf. *McCabe et al.*, 2004; *Willard et al.*, 2005]. This scenario corroborates previously published studies that attribute simultaneous droughts and vegetation changes in the Midwestern United States to changes in atmospheric circulation that were forced by decreased solar irradiance during IRD events [*Viau et al.*, 2002; *Denniston et al.*, 2007].

5. Conclusions

[18] Seven significant Mid- to Late Holocene droughts are recorded in West Virginia stalagmite BCC-002 as elevated Sr/Ca ratios and δ^{13}C values. Six droughts correlate with cooling of the Atlantic and Pacific Oceans as part of the North Atlantic Ocean ice-rafted debris cycle, which has been linked to the solar irradiance cycle. The Sr/Ca and δ^{13}C time series display periodicities of $\sim$200 and $\sim$500 years and are coherent in those frequency bands. The $\sim$200-year periodicity is consistent with the de Vries (Suess) solar irradiance cycle. We interpret the $\sim$500-year periodicity to be a harmonic of the IRD oscillations. Visually, the Sr/Ca and IRD time series show strong correlations and cross-spectral analysis of the Sr/Ca and IRD time series yields statistically significant coherencies at periodicities of 455 and 715 years. These latter values are very similar to the second (725-years) and third (480-years) harmonics of the 1450 ± 500-years IRD periodicity [*Bond et al.*, 2001]. Collectively, these findings and a 1,200-year periodicity in the Sr/Ca time series, demonstrates solar forcing of droughts in east-central North America on multiple time scales. Droughts typically occur during solar minima when SST in the Atlantic and Pacific Oceans are comparatively cool. These SST anomalies cause migration of the jet stream away from east-central NA, yielding decreased meridional moisture transport and reduced convergence over east-central NA. Our findings appear to corroborate works indicating that millennial-scale solar-forcing is responsible for droughts and ecosystem changes in central and eastern North America [*Viau et al.*, 2002; *Willard et al.*, 2005; *Denniston et al.*, 2007], but our high-resolution time series provide much stronger evidence in favor of solar-forcing of North American drought by yielding unambiguous spectral analysis results.

[19] **Acknowledgments.** We thank Gene Turner for permission to collect BCC speleothems. Insightful reviews by Greg Wiles and two anonymous reviewers improved the manuscript.

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