Stalagmite stable isotope record of recent tropical cyclone events

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ABSTRACT

We present a 23 yr stalagmite record (1977–2000) of oxygen isotope variation, associated with 11 tropical cyclones (TCs), from Actun Tunichil Muknal cave in central Belize. High-resolution microsampling yielded a record of monthly to weekly temporal resolution that contains abrupt decreases (negative excursions) in calcite $\delta^{18}O$ values that correspond with recent TC rain events nearby. A logistic discriminant model reliably identified TC proxy signals using the measurable parameters $\delta^{18}O$ and $\delta^{13}C$ values, and single point changes in $\delta^{18}O$ value. The logistic model correctly identified 80% of excursions as TC events and incorrectly classified only 1 of nearly 1200 nonstorm sampling points. In addition to enabling high-resolution TC frequency reconstruction, this geologic proxy also provides information about the intensity of individual TCs. A multiple regression predicted TC intensity ($R^2 = 0.465$, $p = 0.034$) using sampling frequency and excursion amplitude. Consistent with previous low-resolution studies, we found that the decadal average $\delta^{18}O$ value was lower during the 1990s when several TCs produced rainfall in the area, but higher during the 1980s when only one TC struck. Longer, accurately dated, high-resolution speleothem stable isotope records may be a useful new tool for paleotempestology, to clarify associations between highly variable TC activity and the dynamic range of Quaternary climate.

Keywords: speleothems, stable isotopes, paleotempestology, hurricanes, paleoclimatology, Central America.

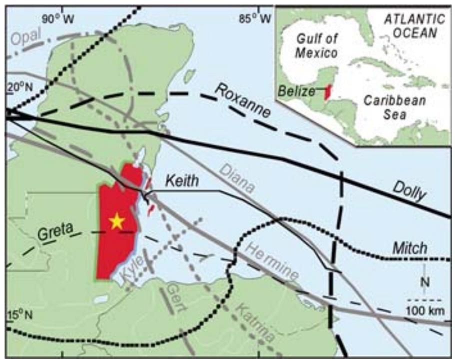

Figure 1. Location map indicating stalagmite source, Actun Tunichil Muknal cave (star), and nearby tropical cyclone (TC) storm tracks (1978–2001). Storm tracks for hurricanes are shown in black, tropical storms in gray.

INTRODUCTION

Tropical cyclones (TCs), including hurricanes, cyclones, and typhoons, are among the most deadly and costly natural hazards. TC intensity, frequency, spatial distribution, and economic damage are highly variable and depend on an array of global and regional climatic factors, including the El Niño–Southern Oscillation System, or ENSO (e.g., Klotzbach and Gray, 2004, and references therein; Landsea, 2000; Pielke and Landsea, 1999; Tartaglione et al., 2003; Tourre and White, 2005). Conversely, TCs may play a critical yet poorly understood role in controlling thermohaline circulation rates (Emanuel, 2001). Despite the ongoing research to understand Earth's climate system, associations between TC activity and overall climatic conditions are controversial (Emanuel, 2005; Giorgi et al., 2001; Henderson-Sellers et al., 1998; Landsea et al., 2006; Pielke et al., 2005; Walsh, 2004). Historical records from TC regions contain few examples of the most catastrophic storms. Paleotempestological evidence preserved in coastal sedimentary archives has illuminated centennial to millennial variations in late Holocene TC activity (Donnelly et al., 2001a, 2001b; Elsner and Liu, 2003; Elsner et al., 2000; Liu and Fearn, 1993, 2000, 2002; Nott, 2003, 2004; Nott and Hayne, 2001). Annual to decadal paleotempest proxies could clarify the controversial problem of TC hazard climatology and offer an independent test of posited feedbacks among the climate system, thermohaline circulation, and TC activity (Emanuel, 2005). Toward that end, we present a new high-resolution tool for paleotempestology that employs the proxy record of past TC rainfall preserved in a rapidly growing calcite stalagmite from Belize. The proxy is demonstrated for a recent 23 yr period for which the history of nearby storm tracks and intensity is known (Fig. 1; GSA Data Repository Table DR1[1]).

TC STABLE ISOTOPE VALUES AND CAVE DEPOSITIONAL SETTINGS

The average $\delta^{18}O$ value of TC precipitation is ~6‰ lower than other summer season rainwater (Lawrence and Gedzelman, 1996; Gedzelman et al., 2003), and perturbs the stable isotopic composition of groundwater and streams in the storm's wake (Lawrence, 1998; Pedersen et al., 2005). For individual TCs, precipitation $\delta^{18}O$ values decrease toward the eyewall, and more intense TCs are associated with lower $\delta^{18}O$ values (Lawrence and Gedzelman, 1996; Lawrence et al., 1998). A TC rainfall event over a cave results in a short-lived pulse of low $\delta^{18}O$ value water that behaves as a natural isotopic tracer spike, infiltrating through soil and karst bedrock overburden. Interstorm meteoric water with more typical higher $\delta^{18}O$ values provides isotopic contrast. Ultimately, infiltrating TC waters can produce a short-lived decrease, or negative excursion, in cave dripwater and calcite $\delta^{18}O$ values. In contrast, TCs are unlikely to substantially perturb calcite $\delta^{13}C$ values. Recognition of an isotopic TC rainfall tracer led to exploration of potential paleo-TC archives in corals (Cohen, 2001), otoliths (Patterson, 1998), tree rings (Miller, 2005; Miller et al., 2006), and speleothems (Malmquist, 1997; Schwehr, 1998). Early attempts to develop a speleothem TC proxy were frustrated by low sampling frequency (approximately annual). Nevertheless, these studies established significant decadal and/or multidecadal anticorrelations between TC frequency and average speleothem calcite $\delta^{18}O$ values, indicating that enhanced TC rainfall can depress speleothem $\delta^{18}O$ values on decadal time scales.

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[1]GSA Data Repository item 2007032, Table DR1 (storm characteristics of nearby tropical cyclone events [1978–2001]), Table DR2 (multiple linear regression results for excursion amplitude-storm intensity analysis), and Appendices 1–5 (site description, analytical methodology, dating and age model, statistical analyses, and archival 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.

To record a measurable TC-derived, or cyclogenic, isotopic excursion in speleothem calcite, the hydrologic pathway through the epikarst must (1) allow infiltrating cyclogenic water to reach supersaturation with calcite, and (2) avoid excessive homogenization of cyclogenic water with other soil water and groundwater. Even absent excessive mixing, diffusion and dispersion during infiltration cause some cyclogenic water to be released slowly, affecting the oxygen isotopic composition of dripwater and calcite for some time after the primary isotopic spike passes through the conduit system. A high-resolution speleothem isotope-based paleotempest proxy would add complementary advantages to established coastal paleotempest proxies, including relative ease of radiometric dating, high temporal resolution, relatively continuous interstorm deposition, storm intensity indicators, detailed background climatic records, and a stable depositional environment independent of Quaternary sea-level variations. Advances in microsampling technology for isotopic analysis of carbonates (Carpenter, 1996) now enable us to examine the speleothem record at sufficient resolution to detect proxy evidence of individual TCs.

METHODS

In January 2001 actively growing stalagmites were collected from Actun Tunichil Muknal, a cave in central Belize (Appendix 1; see footnote 1). Stalagmites with field characteristics suggesting sensitivity to large precipitation events were selected (Frappier, 2006). Stalagmite ATM7 was sectioned longitudinally, polished, and dated using both radiometric (^{137}Cs) and layer counting techniques (Frappier et al., 2002; Appendix 3 [see footnote 1]).

Microsampling and Stable Isotope Analyses

Microsampling and stable isotope analyses were performed at the University of Iowa's Paul H. Nelson Stable Isotope Laboratory. Microsamples of stalagmite calcite (~0.02–0.05 mg of $CaCO_3$) were milled along the growth axis continuously at 20 μm resolution (Fig. 2) using a CM-1 computer-controlled microsampling device (Carpenter, 1996; Frappier et al., 2002; Appendix 2 [see footnote 1]). Powdered carbonate samples were analyzed using a Kiel III automated carbonate device coupled with a Finnigan-MAT 252 gas isotope ratio mass spectrometer (IRMS). Daily analysis of National Institute of Standards and Technology and in-house carbonate standards yielded analytical precision of better than ±0.1‰ for both $\delta^{18}O$ and $\delta^{13}C$ values. All results are reported in per mil (‰) relative to Vienna Peedee belemnite (VPDB).

Identifying and Dating Isotopic Excursions

The largest short-lived negative $\delta^{18}O$ value excursions not associated with substantial decreases in $\delta^{13}C$ values were identified in the ATM7 record (Appendix 4; see footnote 1). Accounting for covariation between $\delta^{18}O$ and $\delta^{13}C$ values in this record made it possible to distinguish brief cyclogenic decreases in $\delta^{18}O$ values from sustained decreases in both $\delta^{13}C$ and $\delta^{18}O$ values related to ENSO variability (Frappier et al., 2002). After a previously developed age model (Frappier et al., 2002) was updated to reflect new recognition of subannual layers (Appendix 3; see footnote 1), the year of deposition was identified for each excursion.

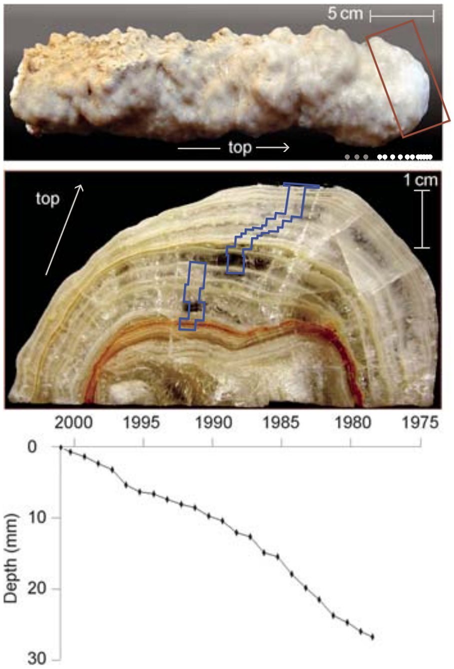

Figure 2. Photograph of stalagmite ATM7 showing depth of radiometric dating samples, micromilling track across approximately annually laminated couplets, and age-depth curve. White (gray) circles denote stratigraphic position of γ-activity samples with positive (undetectable) ^{137}Cs activity. We interpret onset of ^{137}Cs γ-activity to indicate local deposition of global fallout from post-1953 atmospheric thermonuclear detonations. Polished cross section shows continuous micromilling track (blue outline), which we positioned to maintain perpendicularity to growth axis throughout sampling.

To test the suitability of high-resolution stalagmite stable isotope records for detecting unknown prehistoric TCs, a binary logistic regression was applied to distinguish the proxy record of cyclogenic excursions from background variability. Within the 11 historical excursions we identified as cyclogenic, the sampling point with the lowest $\delta^{18}O$ value was coded as a storm event (1); all other sampling points were coded as nonstorm (0). During Hurricane Mitch's long traverse across this region, it made landfall in both Honduras and Yucatán; thus, we coded the two largest excursions in 1998 as storms. Predictor variables were $\delta^{18}O_d$ (the difference in $\delta^{18}O$ value between adjacent samples), $\delta^{18}O$ value, and $\delta^{13}C$ value. Because of two adjacent missing data points, an excursion in 1993 was not included in this model because the $\delta^{18}O_d$ could not be calculated.

RESULTS AND DISCUSSION

The ATM7 oxygen isotope record contains 11 negative excursions in $\delta^{18}O$ values (≥0.48‰) that are not coupled with similar decreases in $\delta^{13}C$ values (≤0.2‰) and are correlated with historical TCs near the cave (Figs. 3A, 3B). No similar excursions are evident during years lacking nearby TCs. Excursions are associated with historical TCs ranging in intensity from tropical storm to catastrophic hurricane, and with storm tracks whose eyes passed the cave at 40–370 km. ATM7 also reflects interstorm deposition, enabling accurate estimates of between-storm intervals (Figs. 3A, 3B, 3E). Multiple excursions occurred in years with multiple TC strikes and in 1998, when Hurricane Mitch reintensified as it passed the site a second time (Fig. 1). In 1996, when Dolly and Kyle struck two months apart, two excursions are separated by several samples (Fig. 3E). A single point separates two excursions in 1995, when Opal and Roxanne struck two weeks apart (Fig. 3E).

Consistent with previous studies (Malmquist, 1997; Schwehr, 1998), decadal average $\delta^{18}O$ values in ATM7 were lower by 1.87‰ ± 0.19‰ during the 1990s when many TCs affected the region. In contrast, average $\delta^{18}O$ values in ATM7 were higher during the 1980s when only one TC affected the area (Fig. 3B). Given the fidelity of this stalagmite proxy record of nearby TC events, the lack of any excursion from Hurricane Keith in 2000 provides a constraint on the transport time required for meteoric water to reach the cave. ATM7 was collected only three months after Hurricane Keith made landfall, suggesting that the storm water was still infiltrating through the epikarst at that time, and that the residence time for this stalagmite is at least three months.

The binary logistic regression resulted in a probability function to quantify the likelihood that any sample represents a TC event:

$$\text{probability} = -11.01 * \delta^{18}O_d - 1.85 * \delta^{18}O + 0.51 * \delta^{13}C - 12.86. \quad (1)$$

Using equation 1, logistic probability values >0.5 captured excursions related to 8 of the 10 TC events included in the model (Fig. 3D). Of more than 1200 nonstorm data points, the logistic probability model identified as a cyclogenic signal only one sample that we coded as nonstorm. This model-identified excursion in 1998

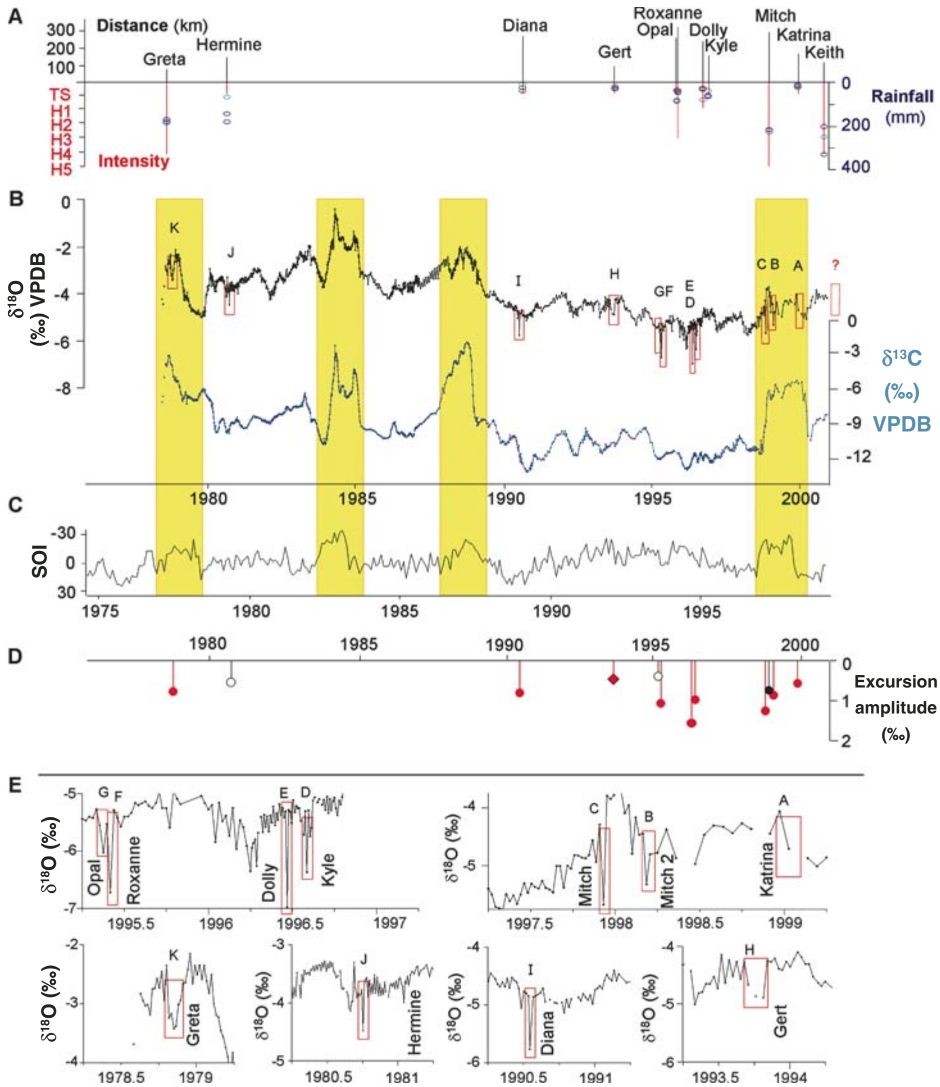

Figure 3. Recent tropical cyclones (TCs) near Belize with stalagmite $\delta^{18}O$, $\delta^{13}C$ value time series with Southern Oscillation Index (SOI), and TC proxy model results. Horizontal axes are identical (1978–2001), except for C, offset by 1.5 yr lead (Appendix 3; see footnote 1). Dating uncertainty for stalagmite ATM7 is weeks to months; thus, storm events in A and B should not be expected to match exactly. A: Historical records of distance (black bars, from cave to nearby storm tracks) and local maximum storm intensity (red bars indicate Saffir-Simpson intensity categories tropical storm [TS] to category 5 hurricane [C5]). Blue circles denote TC rainfall totals from three nearby weather stations. B: ATM7 $\delta^{18}O$ and $\delta^{13}C$ values are shown in black and blue, respectively; note different vertical scales. Cyclogenic excursions (A–K) are highlighted. VPDB—Vienna Peedee belemnite. C: SOI is inverted. Major El Niño events (vertical tan bars) are associated with elevated $\delta^{13}C$ and $\delta^{18}O$ values in ATM7. D: Logistic regression model discriminated cyclogenic excursions of differing amplitude from background isotopic variation. Red circles denote excursions classified correctly as cyclogenic. Black circles denote excursions classified incorrectly by model as noncyclogenic (open) or cyclogenic (closed). The new model-identified cyclogenic point was associated with Hurricane Mitch. E: For locally active hurricane seasons, $\delta^{18}O$ value detail highlights cyclogenic excursions across corresponding annual couplets.

was associated with Hurricane Mitch. Thus, we infer that multiple excursions can be produced by a single TC system that produces distinct local rainfall events. Overall, this model reliably identified TC signals in an isotopic record with substantial background variability, and will serve as a testable model for future speleothem paleotempestology records.

Investigating Potential TC Intensity Indicators

We examined relations between the proxy (negative $\delta^{18}O$ value excursion amplitude) and characteristics of recorded TC events, postulating that annual sampling frequency S (number of stable isotope samples per year) could be an important secondary control on measured excursion amplitude as a result of interannual growth rate fluctuations (Appendix 4; see footnote 1). A standard multiple regression using the independent variables maximum storm intensity (I), proximal storm track distance (D), and S explained 65.4% of variation in excursion amplitude ($p < 0.030$; Appendix 4; Table DR2 [see footnote 1]). The most important predictors of excursion amplitude were I (semipartial $R^2 = 0.352$) and S (semipartial $R^2 = 0.383$), suggesting that this application is limited by microsampling technology. TC intensity was a better predictor of excursion amplitude than local precipitation amount (Appendix 4; see footnote 1). Surprisingly, excursion amplitude was not substantially related to D (semipartial $R^2 = 0.029$).

We interpret these results to indicate that in this data set, excursion amplitude was primarily related to TC intensity and was not substantially confounded by storm track distance. Although surprising, this finding is consistent with the observation that a TC rainfall $\delta^{18}O$ value is an integrated gauge of the storm's history (Lawrence et al., 1998). Toward reconstructing TC intensity from measurable predictor variables (S and excursion amplitude), we performed a linear regression that explained 46.5% of variance in storm intensity ($p < 0.034$). High-resolution prehistoric speleothem proxy data sets (Appendix 5; see footnote 1) can thus provide the basis for accurately reconstructing paleohurricane intensities. A robust test of the models presented here for reconstructing paleotempest incidence and intensity was precluded by the absence of an independent data set of similar quality. A longer record of historical TC events will be required to assess the sensitivity of this stable isotope proxy to storm characteristics identified by Lawrence et al. (1998; e.g., assorted storm track distance and intensity measures, storm duration or short-term intensity changes, storm radius, storm quadrant affecting the site).

CONCLUSIONS

The low $\delta^{18}O$ value excursions measured in the rapidly growing ATM7 stalagmite represent an accurate, detailed proxy for past TC rainfall events. The statistical models presented here open the door to developing highly resolute speleothem records of prehistoric TC frequency and intensity. New independent stable isotope records and longer calibration period records are needed to test these TC activity proxies. Close agreement between the speleothem proxy and historical records suggests that this tool can bridge the gap between historical and meteorological TC observations (synoptic to multidecadal scale) and coastal paleotempest proxies (centennial to millennial scale). The speleothem proxy complements existing coastal paleotempestology tools, providing advantages related to ease of dating, independence from Holocene sea-level changes, and potential applicability throughout the Quaternary. The proxy is limited by the availability of storm-sensitive speleothems, stable isotope sampling frequency, and potential snow-melt interference in temperate regions (Dansgaard, 1964). Only TCs that produce significant rain in karst regions could be recorded. Between 1851 and 2004, this cave site was affected by 6% of major hurricanes and 8% of all named landfalling TCs in the Atlantic Basin. Thus, several cave sites from karst regions across the basin may yield a representative record that reflects seasonal to centennial variation in overall Atlantic paleotempest activity during Quaternary intervals of interest. A spatially and temporally distributed network of high-resolution paleotempest proxy records in multiple TC basins may ultimately contribute to risk assessment and climate change impact detection and/or attribution programs (Nott, 2004).

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REFERENCES CITED

Carpenter, S.J., 1996, A new microsampling device for extracting high-resolution isotope data from geologic and biologic materials: Geological Society of America Abstracts with Programs, v. 28, no. 7, p. 360.

Cohen, A., 2001, Hurricane tracking with chemistry: Exploring the coral archive: Workshop on Atlantic Basin paleohurricane reconstructions from high resolution records, March 25–27, 2001: Columbia, South Carolina, University of South Carolina.

Dansgaard, W., 1964, Stable isotopes in precipitation: Tellus, v. 16, p. 436–468.

Donnelly, J.P., Bryant, S.S., Butler, J., Dowling, J., Fan, L., Hausmann, N., Newby, P., Shuman, B., Stern, J., Westover, K., and Webb III, T., 2001a, 700 yr sedimentary record of intense hurricane landfalls in southern New England: Geological Society of America Bulletin, v. 113, p. 714–727.

Donnelly, J.P., Roll, S., Wengren, M., Butler, J., Lederer, R., and Webb, T., III, 2001b, Sedimentary evidence of intense hurricane strikes from New Jersey: Geology, v. 29, p. 615–618, doi: 10.1130/0091–7613(2001)029<0615:SEOIHS>2.0.CO;2.

Elsner, J.B., and Liu, K.B., 2003, Examining the ENSO-typhoon hypothesis: Climate Research, v. 25, p. 43–54.

Elsner, J.B., Liu, K.B., and Kocher, B., 2000, Spatial variations in major US hurricane activity: Statistics and a physical mechanism: Journal of Climate, v. 13, p. 2293–2305, doi: 10.1175/1520–0442(2000)013<2293:SVIMUS>2.0.CO;2.

Emanuel, K., 2001, Contribution of tropical cyclones to meridional heat transport by the oceans: Journal of Geophysical Research–Atmospheres, v. 106, p. 14,771–14,781, doi: 10.1029/2000JD900641.

Emanuel, K., 2005, Increasing destructiveness of tropical cyclones over the past 30 years: Nature, v. 436, p. 686–688, doi: 10.1038/nature03906.

Frappier, A.B., 2006, Recent extreme events in a tropical stalagmite: Multi-proxy records and analysis of ecosystem $\delta^{13}C$ value sensitivity to weak climate forcing [Ph.D. thesis]: Durham, University of New Hampshire, 133 p.

Frappier, A., Sahagian, D., Gonzalez, L.A., and Carpenter, S.J., 2002, El Niño events recorded by stalagmite carbon isotopes: Science, v. 298, p. 565, doi: 10.1126/science.1076446.

Gedzelman, S., Lawrence, J., Gamache, J., Black, M., Hindman, E., Black, R., Dunion, J., Willoughby, H., and Xiaoping Zhang, 2003, Probing hurricanes with stable isotopes of rain and water vapor: Monthly Weather Review, v. 131, p. 1112–1127.

Giorgi, F., Hewitson, B., Christensen, J., Hulme, M., Storch, H.V., Whetton, P., Jones, R., Mearns, L., and Fu, C., 2001, Regional climate change information—Evaluation and projections, *in* Houghton, J.T., et al., eds., Climate change 2001—The scientific basis: Cambridge, UK, Cambridge University Press, p. 583–638.

Henderson-Sellers, A., Zhang, H., Berz, G., Emanuel, K., Gray, W., Landsea, C., Holland, G., Lighthill, J., Shieh, S.L., Webster, P., and McGuffie, K., 1998, Tropical cyclones and global climate change: A post-IPCC assessment: American Meteorological Society Bulletin, v. 79, p. 19–38, doi: 10.1175/1520–0477(1998)079<0019:TCAGCC>2.0.CO;2.

Klotzbach, P.J., and Gray, W.M., 2004, Updated 6–11-month prediction of Atlantic basin seasonal hurricane activity: Weather and Forecasting, v. 19, p. 917–934, doi: 10.1175/1520–0434(2004)019<0917:UMPOAB>2.0.CO;2.

Landsea, C.W., 2000, El Niño–Southern Oscillation and the seasonal predictability of tropical cyclones, *in* Diaz, H.F., and Markgraf, V., eds., El Niño and the Southern Oscillation: Multiscale variability and global and regional impacts: Cambridge, UK, Cambridge University Press, p. 149–181.

Landsea, C.W., Harper, B.A., Hoarau, K., and Knaff, J.A., 2006, Can we detect trends in extreme tropical cyclones?: Science, v. 313, p. 452–454.

Lawrence, J.R., 1998, Isotopic spikes from tropical cyclones in surface waters: Opportunities in hydrology and paleoclimatology: Chemical Geology, v. 144, p. 153–160, doi: 10.1016/S0009–2541(97)00090–9.

Lawrence, J.R., and Gedzelman, S.D., 1996, Low stable isotope ratios of tropical cyclone rains: Geophysical Research Letters, v. 23, p. 527–530, doi: 10.1029/96GL00425.

Lawrence, J.R., Gedzelman, S.D., Zhang, X.P., and Arnold, R., 1998, Stable isotope ratios of rain and vapor in 1995 hurricanes: Journal of Geophysical Research–Atmospheres, v. 103, p. 11,381–11,400, doi: 10.1029/97JD03627.

Liu, K.B., and Fearn, M.L., 1993, Lake-sediment record of late Holocene hurricane activities from coastal Alabama: Geology, v. 21, p. 793–796, doi: 10.1130/0091–7613(1993)021<0793:LSROLH>2.3.CO;2.

Liu, K.B., and Fearn, M.L., 2000, Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records: Quaternary Research, v. 54, p. 238–245, doi: 10.1006/qres.2000.2166.

Liu, K.B., and Fearn, M.L., 2002, Lake sediment evidence of coastal geologic evolution and hurricane history from Western Lake, Florida: Reply: Quaternary Research, v. 57, p. 429–431, doi: 10.1006/qres.2002.2334.

Malmquist, D.L., 1997, Oxygen isotopes in cave stalagmites as a proxy record of past tropical cyclone activity, *in* Proceedings of the 22nd Conference on Hurricanes and Tropical Meteorology: Fort Collins, Colorado, American Meteorological Society, p. 393–394.

Miller, D.L., 2005, A tree-ring oxygen isotope record of tropical cyclone activity, moisture stress, and long-term climate oscillations for the Southeastern U.S. [Ph.D. thesis]: Knoxville, University of Tennessee, 169 p.

Miller, D.L., Mora, C.I., Grissino-Mayer, H.D., Mock, C.J., Uhle, M.E., and Sharp, Z., 2006, Tree-ring isotope records of tropical cyclone activity: Proceedings of the National Academy of Sciences, v. 103, p. 14294–14297, doi: 10.1073/pnas.0606549103.

Nott, J., 2003, Intensity of prehistoric tropical cyclones: Journal of Geophysical Research, v. 108, p. 4212, doi: 10.1029/2002JD002726.

Nott, J.F., 2004, Palaeotempestology—A review and implications for risk assessment: Environment International, v. 30, p. 433–447, doi: 10.1016/j.envint.2003.09.010.

Nott, J., and Hayne, M., 2001, High frequency of 'super-cyclones' along the Great Barrier Reef over the past 5,000 years: Nature, v. 413, p. 508–512, doi: 10.1038/35097055.

Patterson, W.P., 1998, North American continental seasonality during the last millennium: High-resolution analysis of sagittal otoliths: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 138, p. 271–303, doi: 10.1016/S0031–0182(97)00137–5.

Pedersen, B., Booth, C., and Perry, E., 2005, Hurricane precipitation isotope signature as a calibration tool and recharge flux marker for modeling a tropical karstic aquifer: Geological Society of America Abstracts with Programs, v. 37, n. 7, p. 174.

Pielke, R.A., Jr., and Landsea, C.N., 1999, La Nina, El Nino, and Atlantic hurricane damages in the United States: American Meteorological Society Bulletin, v. 80, p. 2027–2033, doi: 10.1175/1520–0477(1999)080<2027:LNAENO>2.0.CO;2.

Pielke, R.A., Jr., Landsea, C., Emanuel, K., Mayfield, M., Laver, J., and Pasch, R., 2005, Hurricanes and global warming: American Meteorological Society Bulletin, v. 86, p. 1571–1575, doi: 10.1175/BAMS-86–11–1571.

Schwehr, K.A., 1998, Oxygen isotopic variations of soda straw cave deposits from the Yucatan Peninsula: A test of their use as a paleoprecipitation tool [M.S. thesis]: Houston, Texas, University of Houston.

Tartaglione, C.A., Smith, S.R., and O'Brien, J.J., 2003, ENSO impact on hurricane landfall probabilities for the Caribbean: Journal of Climate, v. 16, p. 2925–2931, doi: 10.1175/1520–0442(2003)016<2925:EIOHLP>2.0.CO;2.

Tourre, Y.M., and White, W.B., 2005, Evolution of the ENSO signal over the tropical Pacific-Atlantic domain: Geophysical Research Letters, v. 32, p. L07605, doi: 10.1029/2004GL022128.

Walsh, K., 2004, Tropical cyclones and climate change: Unresolved issues: Climate Research, v. 27, p. 77–83.

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