A multitree perspective of the tree ring tropical cyclone record from longleaf pine (*Pinus palustris* Mill.), Big Thicket National Preserve, Texas, United States

Daniel B. Lewis,[1,2] David B. Finkelstein,[1,3] Henri D. Grissino-Mayer,[4] Claudia I. Mora,[5] and Edmund Perfect[1]

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[1] Tree rings afford the temporal resolution needed to characterize extreme weather events such as tropical cyclones, their frequency and variability. External factors such as soil water isotopic variability, soil heterogeneity, and/or stand disturbance affect the isotopic composition of individual trees in a stand, resulting in inaccuracies in the record. Single-tree isotope chronologies should be tested against multiple-tree chronologies to determine whether individual trees sufficiently characterize tropical cyclone variability. Eight individual trees from two sites in Big Thicket National Preserve were analyzed to evaluate whether they synchronously record tropical cyclone events. The ability of individual isotope models to capture an event was low (≤50%), and individual trees did not always record similar events. A composite chronology from the Turkey Creek Unit identified 5 false positive years and missed five storms. The composite chronology from the Big Sandy Creek Unit identified 5 false positives and missed four storms. All but 3 false positive years were characterized by above average precipitation that followed below average precipitation in the previous year. This mimics the negative isotopic excursion expected from tropical cyclones. Another year (1991) was coincident with a strong El Niño event, resulting in a shift in the dominant moisture source for the Texas Gulf Coast. Drought conditions occurred in years where storms were missed, which dampened the ^{18}O-depleted signal associated with tropical cyclones. These data show that the number of trees is critical for properly characterizing tropical cyclone frequency through time, especially for periods prior to reliable instrumental records.

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1. Introduction

[2] Tree rings can provide high-resolution records of regional climate reaching well beyond instrumental records. The oxygen isotope composition of tree ring α-cellulose in part reflects the oxygen isotope composition of the source water taken up by tree roots [*Anderson et al.*, 1998; *Tang and Feng*, 2001; *Anderson et al.*, 2002; *Waterhouse et al.*, 2002; *Helle and Schleser*, 2004; *McCarroll and Loader*, 2004]. Soil water $\delta^{18}O$ is related to the $\delta^{18}O$ of precipitation, and variability depends on frequency of rainfall events (e.g., droughts and deluges) and soil hydrological characteristics [*Tang and Feng*, 2001; *Darling*, 2004]. Tropical cyclone rainfall can be 10–20‰ depleted in ^{18}O compared to normal meteoric precipitation [*Gedzelman and Arnold*, 1994; *Lawrence and Gedzelman*, 1996; *Lawrence*, 1998]. This ^{18}O-depleted rainfall can remain in the soil for several weeks until it is dampened by evaporative enrichment or isotopic mixing [*Tang and Feng*, 2001]. Large negative excursions in tree ring α-cellulose can reflect rainfall from tropical cyclones [*Miller et al.*, 2006; *Nelson*, 2008].

[3] Tree ring $\delta^{18}O$ also has proven useful for characterizing tropical cyclone frequency and variability along the Gulf and Atlantic Coasts of the southeastern United States [*Miller et al.*, 2006; *Nelson*, 2008]. *Miller et al.* [2006] developed a 221 year record of tropical cyclone events from southern Georgia, while *Nelson* [2008] developed two short records from coastal South Carolina and a 294 year record from Pensacola, Florida. Each of these studies utilized only one tree for any portion of the time series to

[1]Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, Tennessee, USA.
[2]Now at ExxonMobil Exploration Company, Houston, Texas, USA.
[3]Now at Department of Geosciences, University of Massachusetts Amherst, Amherst, Massachusetts, USA.
[4]Department of Geography, University of Tennessee, Knoxville, Tennessee, USA.
[5]Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, New Mexico, USA.

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characterize tropical cyclones. What remains unclear is whether individual trees in a stand synchronously record the same tropical cyclone events. Single-tree isotope chronologies may be problematic for interpreting climate variability and tropical cyclone activity. The isotopic composition of soil water being used by trees for photosynthesis may not be homogeneous across a stand. The amount of ^{18}O-depleted rainwater characteristic of tropical cyclone events may not uniformly replace the existing soil moisture across a stand. Last, internal and external stand disturbances may affect an individual tree rendering it incapable of capturing enough of the common climate signal to characterize the regional climate signature.

[4] Two issues can complicate the tree ring hurricane record, false positives and missed storm events. A false positive is a negative isotopic anomaly in the δ^{18}O of tree ring cellulose not associated with a tropical cyclone event. The δ^{18}O of cellulose may not record tropical cyclone events known to have rained on the site (using local precipitation records). Both circumstances will reduce the effectiveness of the record. The purpose of this paper is to use latewood (LW) δ^{18}O of multiple longleaf pine (*Pinus palustris* Mill.) trees from two sites in close proximity to determine if incorporating multiple trees provides a more comprehensive analysis of tropical cyclone frequency and variability. We also evaluate possible mechanisms for generating false positives and missed storm events in the tree ring record.

2. Oxygen Isotopes in Tree Rings

[5] The oxygen isotope ratio of tree ring cellulose is primarily controlled by the isotopic composition of source water (rain, soil water), evaporative enrichment of water in the leaves, and biochemical fractionations [*Anderson et al.*, 2002; *Helle and Schleser*, 2004; *McCarroll and Loader*, 2004]. No fractionation occurs during uptake of water through the roots. Large fractionations can occur in the leaves due to transpiration, leaving leaf water enriched in δ^{18}O with respect to source water [*Anderson et al.*, 2002]. The oxygen isotopic composition of sucrose synthesized in the leaves is further modified via exchange with stem water (source water) prior to formation of cellulose [*Sternberg et al.*, 1986; *Farquhar et al.*, 1998; *Anderson et al.*, 2002]. These fractionations are relatively constant for trees of the same species growing in close proximity to one another, so that the year-to-year variability in cellulose δ^{18}O likely reflects isotopic changes in source water [*Anderson et al.*, 2002].

[6] The δ^{18}O of water in the upper portion of the soil column is related to the isotopic composition of meteoric precipitation [*Tang and Feng*, 2001; *Anderson et al.*, 2002]. The degree to which soil water δ^{18}O reflects meteoric precipitation depends on the frequency of rainfall events and the hydrological characteristics of the soil [*Tang and Feng*, 2001]. Soil water δ^{18}O becomes increasingly enriched in the upper soil column through evapoconcentration as residence time increases [*Tang and Feng*, 2001]. Therefore, the interannual variability in cellulose δ^{18}O should reflect available moisture.

[7] Tropical cyclones are capable of producing precipitation 10–20‰ depleted in ^{18}O with respect to normal precipitation [*Gedzelman and Arnold*, 1994; *Lawrence and Gedzelman*, 1996; *Lawrence*, 1998]. This rainfall signal is capable of remaining in the soil for several weeks after the event before is it dampened through evaporative enrichment or mixing with subsequent rainfall events [*Tang and Feng*, 2001]. As a result, large depletions in the oxygen isotope composition of tree ring α-cellulose can reflect rainfall from tropical cyclone events.

3. Site Description

[8] The Big Thicket National Preserve (BTNP) in southeastern Texas was established in 1974 and consists of numerous land units, typically located along creeks and rivers. The preserve is located along the southeastern Texas Coastal Plain, and has been affected by numerous tropical cyclone systems. Two land units, Turkey Creek (TC) (30.59°N, 94.33°W) and Big Sandy Creek (BSC) (30.65°N, 94.67°W), were sampled for this study. The majority (85%) of the soils in BSC were Pinetucky fine sandy loam (hydrologic soil group B, moderately well drained) (National Resources Conservation Service, http://websoilsurvey.nrcs.usda.gov/app/, 2009). The other 15% were Pinetucky and Conroe (hydrologic soil group C, moderately well drained). Soils in TC were the Kirbyville-Nirwana Complex (hydrologic soil group B, moderately well drained). Sand content was 45–65% at both sites. Depth to water table was >2 m at BSC, and approximately 80 cm at TC (National Resources Conservation Service, http://websoilsurvey.nrcs.usda.gov/app/, 2009).

[9] The stands consisted of young and mature (60–160 years) longleaf pine and young (50–70 years) loblolly pine (*Pinus taeda* L.). Understory vegetation was sparse at the time of sampling because both stands are frequently burned. Significant tree mortality resulted from Hurricane Rita (2005) and Hurricane Ike (2008). Several canopy trees had been either uprooted or snapped off up the stem. This, combined with low vegetation cover, significantly increased sun exposure at the soil surface.

4. Methods

[10] Ten longleaf pine trees were sampled at TC, and twenty at BSC, using a 12 mm increment borer. Annual growth rings were crossdated using standard dendrochronological techniques [*Stokes and Smiley*, 1996], and dating was statistically verified using the computer program COFECHA [*Holmes*, 1983; *Grissino-Mayer*, 2001]. Four of these trees were randomly selected from both sites for isotopic analysis over a 25 year period (1982–2006). Annual rings were separated into their seasonal components (earlywood and latewood) and sliced into thin (50 μm) slivers using a scalpel. Alpha-cellulose was extracted using soxhlet extraction techniques [*Loader et al.*, 1997; *Rinne et al.*, 2005]. Approximately 100 μg of latewood α-cellulose was weighed and placed into silver capsules. Oxygen isotope data were collected on a Finnigan Thermochemolysis/Elemental Analyzer (TC/EA) connected to a Finnigan Delta XL Plus mass spectrometer. All samples were run in duplicate. Results are reported VSMOW in per mil (‰) notation where $\delta = (R_{sample}/R_{standard} - 1)1000$. Standards were placed every six samples throughout each run (sd < 0.2‰, n = 130).

Table 1. Tropical Cyclone Events Within a 250 km Radius of Kountze, Texas[a]

Year	Storm Name	Category at Site
1983	**Alicia**	Hurricane Category 2
1985	Danny	Hurricane Category 1
	Juan	Hurricane Category 1
1986	**Bonnie**	Hurricane Category 1
1987	**No Name**	Tropical Storm
1988	**Beryl**	Tropical Depression
1989	**Allison**	Tropical Storm
	Chantal	Hurricane Category 1
	Jerry	Hurricane Category 1
1995	**Dean**	Tropical Storm
1998	**Frances**	Tropical Depression
2001	***Allison**	Tropical Storm
2002	Lili	Hurricane Category 1
2003	**Grace**	Tropical Storm
2004	**Ivan**	Tropical Depression
2005	**Rita**	Hurricane Category 2

[a]Bold names were confirmed with precipitation in local climate records. An asterisk indicates the storm occurred in the earlywood portion of the growing season, and was not included in these analyses. Category is the category of the storm over the sample area.

[11] Each individual latewood isotope series was analyzed to determine their agreement in identifying tropical cyclone events. Hurricane track data were obtained from NOAA Coastal Services and Unisys Weather for all storms within 250 km of Kountze, Texas (closest town to BTNP) (NOAA Coastal Services Center, http://maps.csc.noaa.gov/hurricanes/viewer.html, 2009; Unisys Weather, http://weather.unisys.com/hurricane/index.html, 2009). The 250 km radius is an arbitrary distance that was used in previous studies [*Miller et al.*, 2006; *Nelson*, 2008]. The storm track data were verified against daily precipitation logs from Kountze, Texas (National Climatic Data Center, http://www.ncdc.noaa.gov/oa/ncdc.html, 2009) to determine if precipitation from the storm event was recorded.

[12] An autoregressive model (AR-1) was applied to each individual isotope series to highlight the isotopic anomalies associated with tropical cyclone events [*Miller et al.*, 2006; *Nelson*, 2008]. The predicted values (model) were then subtracted from the observed values (isotope time series) to obtain a residual chronology. Using this method, Miller et al. found that most negative residuals ≤ -1.0 indicated anomalously light isotope values associated with confirmed storm events. Additionally, many years with negative residuals between -0.5 and -1.0 were also affected by storm events. This study uses the same criteria for identifying tropical cyclone events for comparison purposes.

[13] Five AR-1 models were developed for each site, one for each individual LW δ^{18}O series (four) and one for the average LW δ^{18}O chronology. A composite tropical cyclone chronology was developed for each site by combining all predictions from the individual trees. The composite records were then compared to the records obtained from the average δ^{18}O chronologies to characterize the differences between the two techniques.

5. Results

[14] Twelve years were identified as being affected by one or more tropical cyclone events based on best track data and local precipitation records during the 25 year period (Table 1). A 2001 storm (TS Allison) was confirmed to have dropped precipitation near the site, but the storm occurred on 6 June, prior to LW production. It is unlikely that rainwater from this event would have persisted in the soil long enough to be utilized for LW production by trees. Hurricane Lili (2002) was not confirmed to have dropped precipitation at the Kountze, Texas climate station, but was recorded as a negative anomaly by five of the eight trees.

[15] The individual trees at both sites exhibited variability identifying tropical cyclone events (Figure 1). Three events (1986, Hurricane Bonnie Category 1; 1998, Tropical Storm Frances; 2002, Hurricane Lili) were identified by all four trees at TC. TC1 recorded 2003, 2002, 1998, 1989, 1986, and 1983. TC2 recorded 2003, 2002, 1998, 1989, 1986, and 1985. TC3 recorded 2002, 1998, 1988, 1986, and 1985. TC4 recorded 2003, 2002, 1998, 1986, and 1985. Four events (1987, Tropical Storm (no name); 1988, Tropical Storm Beryl; 1995, Tropical Storm Dean; 2005, Hurricane Rita) were not detected by any of the trees. Hurricane Rita was a Category 5 hurricane that passed directly over the Turkey Creek Unit (as a Category 3), dropping over 16 cm of precipitation.

[16] Only one event (1986, Hurricane Bonnie) was recorded by all four trees at BSC (Figure 1). BSC1 recorded 1983, 1986, 1998, 2002, 2003, and 2004. BSC2 identified 1983, 1986, 1998, and 2003. BSC3 recorded 1986, 1989, 1998, and 2004. BSC4 recorded 1985 and1986. The same four events missed at TC were also missed by all four trees at BSC.

[17] When the AR-1 model was applied to the average isotope chronology from TC, it identified 5 of the 12 storm events (42%) (Figure 1). The AR-1 model developed the BSC average isotope chronology identified 4 of the 12 storm events (33%) (Figure 1). To provide a comprehensive characterization of tropical cyclone events during the 25 year period, we combined the predictions from the eight individual models into one composite tropical cyclone chronology. This practice is commonly used when developing fire history chronologies from multiple tree ring samples [e.g., *Baisan and Swetnam*, 1990; *Grissino-Mayer*, 1995; *Lewis*, 2003]. If a single tree in a stand records the event, then the event is confirmed to have affected the stand, even if multiple trees in the stand fail to record it. The composite tropical cyclone chronology identified 8 of the 12 total events in the 25 year period (67%).

[18] A number of "false positives," years with negative isotopic anomalies not related to known tropical cyclone events, were found at both sites (2001, 1996, 1994, 1993, 1991, and 1984) using the individual AR-1 models. One year, 1996, was systematically recorded among six of the eight series. False positives were also identified by more than two trees in 1991 and 2001 (Figure 1). These false positives indicate either another climatic mechanism is capable of producing significantly depleted rainfall, or the AR-1 model is not appropriate for short time series.

6. Discussion

6.1. Composite Chronologies Versus Average Chronologies

[19] The best result obtained by individual trees at either site was 50% (6 out of 12 events). The three average δ^{18}O

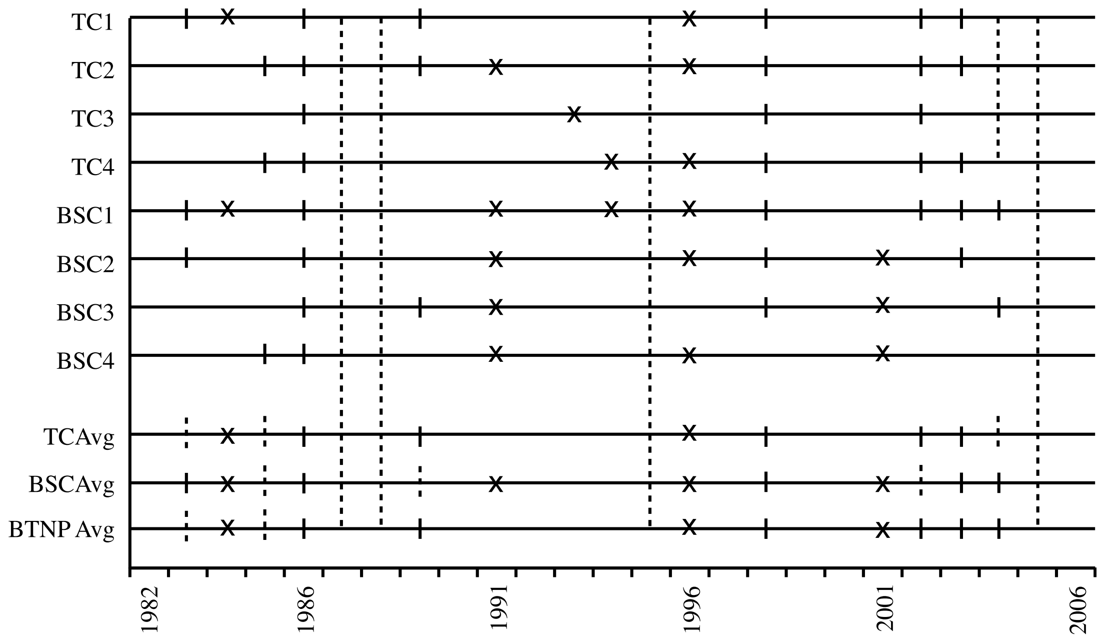

Figure 1. Individual and average tropical cyclone chronologies for the Turkey Creek Unit (TC) and Big Sandy Creek Unit (BSC) at Big Thicket National Preserve. A vertical tic mark indicates a true positive, a cross indicates a false positive, and the dashed lines indicate missed storms in the record. TC average, BSC average, and BTNP average are the AR-1 models applied to the average LW δ^{18}O series. All residuals represent those ≤ -0.5.

chronologies identified a maximum of 50% of the events. A composite (summed predictions) chronology developed from all eight trees identified 8 out of 12 tropical cyclone events (67%). The drawback to the composite chronologies is the higher number of false positives in the record, since the predictions are summed for all samples. Both TC and BSC identified five false positive events, nearly equal to identified storm events. The opposite was apparent using the average δ^{18}O series. Each average isotope series identified a lower number of known storms (five) over the composite chronology, but exhibited fewer false positives (two at TC, four at BSC). These results are not unexpected. Negative isotopic anomalies recorded by only one tree in the stand will be smoothed out using the average isotope series.

[20] The −0.5 residual worked well as a lower threshold of the previous tree ring hurricane records. However, these records were developed using only a single tree for any portion of the time series. The models developed from individual trees at both of these sites exhibited higher standard deviation than the average isotope models. If variability in the model is reduced using the average isotope series, then the −0.5 AR-1 residual may not prove to be a useful threshold level. Lowering the threshold level to −0.3 residual resulted in improved effectiveness of the average models at TC (6 of 12) and BSC (7 of 12) with no increase in false positive events at either site (Table 2). Although the average site models still record slightly fewer storms than the composite chronology, they prove a more conservative approach with respect to error from false positive events.

[21] This methodology was also applied to the BTNP average δ^{18}O chronology (developed from all eight trees) (Table 1). Using an AR-1 threshold of −0.3, the BTNP average AR-1 model correctly identified 8 of 12 known storms (67%), and included only 3 false positive years. The effectiveness of this model is equivalent to the composite chronology developed from the eight trees, but contains fewer false positives. It is difficult to ascertain whether these patterns hold true for other sites or are specific to this study.

Table 2. Table of True and False Positives and Missed Storms[a]

	True Positive Years	False Positive Years	Missed Storm Years
		−0.5 AR-1 Residual	
TC average	1986, 1989, 1998, 2002, 2003	1984, 1986	1983, 1985, 1987, 1988, 1995, 2004, 2005
BSC average	1983, 1986, 1998, 2002, 2003, 2004	1984, 1991, 1996, 2001	1985, 1987, 1988, 1989, 1995, 2002, 2005
BTNP average	1986, 1989, 1998, 2002, 2003, 2004	1984, 1996, 2001	1983, 1985, 1987, 1988, 1995, 2005
		−0.3 AR-1 Residual	
TC average	1985, 1986, 1989, 1998, 2002, 2003	1984, 1986	1987, 1988, 1995, 2004, 2005
BSC average	1983, 1985, 1989, 1998, 2002, 2003, 2004	1984, 1991, 1996, 2001	1987, 1988, 1995, 2005
BTNP average	1983, 1985, 1986, 1989, 1998, 2002, 2003, 2004	1984, 1996, 2001	1987, 1988, 1995, 2005

[a]Using −0.3 instead of −0.5 as the AR-1 model threshold, the effectiveness of the models was improved without an increase in false positives. The BTNP average record exhibited the best result.

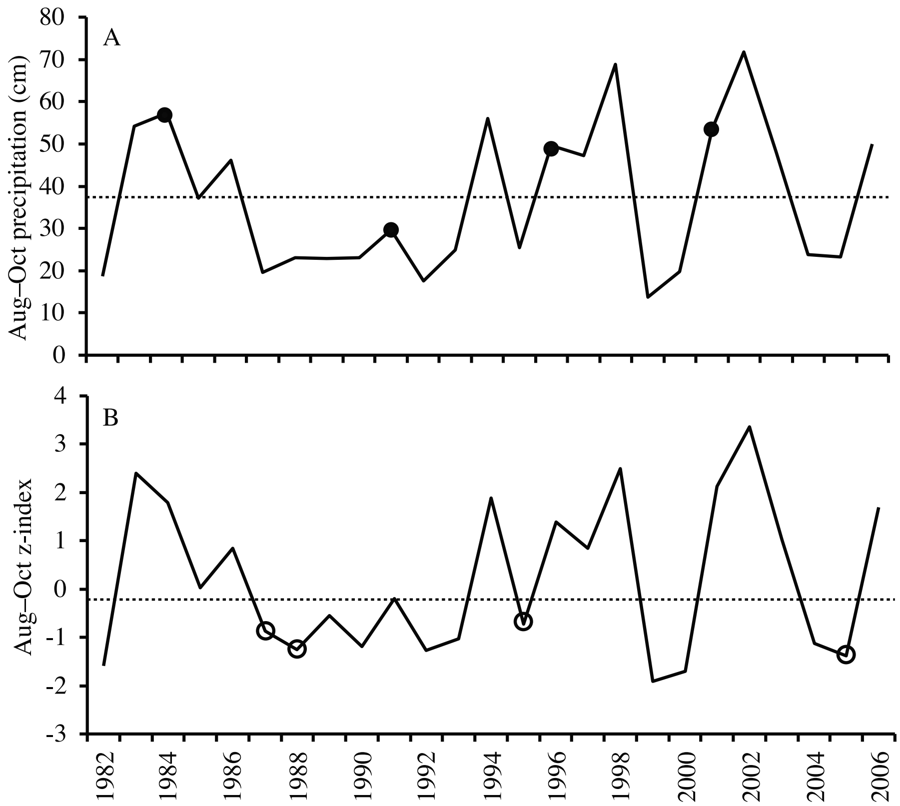

Figure 2. (a) False positives (solid circles) compared to fall (August–October) precipitation and (b) missed storms (open circles) compared to fall drought (z index) records. False positives in 1996 and 2001 resulted from above average precipitation following years of below average precipitation. Average fall precipitation for the 25 year period is represented by the dashed line (approximately 36 cm). Missed storms were coincident with dry (negative z index) conditions during the fall (August–October) portion of the growing season. The dashed line represents average z index for the 25 year period.

No tree ring hurricane records exist that incorporate more than one tree. Additional studies are necessary to evaluate the results presented here.

6.2. Mechanisms for Generating False Positives in the Record

[22] Using tree ring δ^{18}O to identify tropical cyclone events makes the assumption that only tropical cyclone precipitation generates isotopically depleted precipitation. Other climate mechanisms are capable of mimicking tropical cyclone precipitation. The TC composite chronology identified 5 false positive years. Of these 5 years, only 1 (1996) was identified by multiple trees in the stand. The BSC composite chronology also recorded 5 false positives, while 3 (1991, 1996, and 2001) were recorded by at least two trees.

[23] False positives in 1994, 1996, and 2001 coincide with significantly wet fall conditions following extremely dry conditions in the previous fall (e.g., 1993, 1995, and 2000, respectively). Fall (August–October) precipitation in 1993, 1995, and 2000 was approximately 11 cm or more below the 25 year (1982–2006) average (Figure 2a). Drought during the LW portion of the growing season results in enriched α-cellulose δ^{18}O. Wet conditions following droughts will yield identical negative isotopic anomalies to those associated with tropical cyclone events. This mechanism explains all false positives except 1984, 1991, and 1993.

[24] False positives in 1984 and 1993 have no clear climatic explanation and are only recorded in 2 and 1 tree, respectively. Year 1991 was identified as a false positive by five of the eight trees. A strong El Niño event was coincident with this false positive year. *Miller et al.* [2006] and *Nelson* [2008] also noted false positive years coinciding with El Niño events in Georgia, South Carolina, and Florida records. If the dominant moisture source switches from the Gulf to more Pacific influence during El Niño years [e.g., *Ropelewski and Halpert*, 1986], then the resulting precipitation should be depleted in ^{18}O compared to normal meteoric precipitation [*Dutton et al.*, 2005].

6.3. A Mechanism for Missed Storm Events

[25] Hurricane Rita (2005) dropped over 16 cm of rainfall near the site, but was not detected in α-cellulose δ^{18}O, even when the 2005 LW ring was sampled at finer resolution (i.e., subseasonal). Droughts result in enriched soil water δ^{18}O and α-cellulose δ^{18}O. If droughts occur simultaneous to tropical cyclone events, then the ^{18}O-depleted signal typical of tropical cyclones will be dampened or masked in the soil. The composite chronology including all eight trees missed storms in 1987, 1988, 1995, and 2005. Year 2004 was identified by three of the four BSC trees, but none of the TC

trees. Palmer z index records (short-term drought) revealed that all of these years were characterized by dry (negative z index) conditions during the LW portion of the growing season (Figure 2b). Regional PDSI records (long-term drought) exhibited dry conditions (negative PDSI) in all years except 2004. Magnitude of the drought had no effect on the recording of storms, only that conditions concurrent with the tropical cyclone were dry. Also, storm magnitude was not significant.

7. Conclusions

[26] The δ^{18}O of tree ring cellulose can be a useful tool for characterizing tropical cyclone frequency and variability. This paper demonstrates that although trees do record tropical cyclone events, climatic variability may complicate the ability of trees to record extreme weather events such as hurricanes. At this site, climatic extremes (wet and dry periods) exerted a significant influence on the tree ring hurricane record. Wet years following drought years mimicked tropical cyclone events. Droughts dampened the isotopic signal characteristic of tropical cyclone such that trees did not identify all known storm events. These results may not be typical of every tree ring hurricane chronology. Individual sites need to be evaluated to determine the degree to which climatic variability affects the record.

[27] The composite hurricane chronology identified more cyclone events than the average chronologies, but included more false positive than the average chronologies. False positives are more problematic for periods where instrumental records are not available to verify events identified by tree ring records. Using average δ^{18}O chronologies for tropical cyclone characterization affords a more conservative approach for periods prior to sufficient instrumental records. At this site, an AR-1 model applied to the average δ^{18}O chronology developed from all eight trees was as effective as the composite chronology with respect to identifying known storms. The BTNP model was superior to the BTNP composite chronology in terms of false positive events. The lack of data sets suitable for comparison makes it difficult to ascertain if the patterns characteristic of this hold true at other sites. The goal of characterizing tropical cyclones using tree rings is to obtain information about long-term changes in frequency and variability of tropical cyclones. Developing a 200 year (or more) isotope chronology using the number of trees presented here is not feasible because of the time-intensive nature of collecting tree ring isotope data. Future studies should evaluate the characteristics of the individual trees at the site to characterize the suitable number of trees to include for comprehensive analysis.

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D. B. Finkelstein, Department of Geosciences, University of Massachusetts Amherst, Amherst, MA 01003, USA.

H. D. Grissino-Mayer, Department of Geography, University of Tennessee, Knoxville, TN 37996, USA.

D. B. Lewis, 2110 Blossom Creek Dr., Kingwood, TX 77339, USA. (dlewis3066@gmail.com)

C. I. Mora, Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA.

E. Perfect, Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37996, USA.