Dendrotempestology and the Isotopic Record of Tropical Cyclones in Tree Rings of the Southeastern United States

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1 Introduction

Tropical cyclones (TCs) (hurricanes, typhoons, and cyclones) are considered the natural hazard with the greatest potential for loss of life and destruction of property, for several reasons. First, TCs occur with greater frequency than many other destructive natural hazards, such as earthquakes and volcanic eruptions. This frequency, we are learning, depends on trends in ocean sea-surface temperatures (SSTs) (which can be monitored using the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO)) combined with other climatic factors, such as the presence/absence of El Niño and the extensiveness of easterly wave activity. Second, TCs disburse large amounts of energy, acting as a siphon and absorbing energy from the oceans and subsequently releasing it back to the atmosphere. Higher SSTs equate to greater amounts of latent heat and greater amounts of energy released during condensation during a tropical cyclone. Third, tropical cyclones are spatially extensive, from the eye wall of cumulonimbus clouds characterized by sustained and very damaging winds that can move in excess of 250 km/h (180 mph) to the spiral bands that can extend out hundreds of kilometers

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and capable of producing flooding rainfall. Fourth, tropical cyclones affect sub-tropical and extra-tropical locations, such as Southeastern Asia, where infrastructure is poor and there is very limited ability to provide early warnings or to evacuate human populations that often number in the millions.

Impending changes to global climate could exacerbate any of these properties. For example, an increasing trend in TC intensity and longevity has been observed for the Atlantic Ocean (Klotzbach 2006), perhaps due to increasing SSTs. Energy dissipation and therefore storm intensity of tropical cyclones may increase due to global warming, but with considerable spatial variability between hemispheres and among ocean basins (Emanuel et al. 2008). The unprecedented 2005 tropical cyclone season in the Atlantic Ocean was likely caused by abnormally high SSTs (0.9°C above the 1901–1970 normal), a major percentage attributable to global warming and not to natural variability (Trenberth and Shea 2006). TC tracks in the Atlantic Ocean are likely to shift poleward with increasing global temperatures (Jiang and Perrie 2007), thus likely affecting geographic locations not accustomed to repeated occurrences of hurricanes. A greater proportion of intense hurricanes in the last 30 years may be attributable to geographic changes in tropical cyclone source regions and therefore their subsequent tracks, highlighting a need for more carefully monitoring effects of increasing temperatures (Wu and Wang 2008). Global warming is likely to cause an increase in the size of hurricanes with a simultaneous decrease in the time it takes to reach tropical cyclone status (Jiang and Perrie 2007).

Now more than ever, a long-term perspective on TC activity is needed to place these expected changes in historical context. The use of natural archives for understanding the past history of TC activity is therefore becoming increasingly important (Fan and Liu 2008). Sand layers in near-shore sediments, bracketed by radiocarbon dates, along the Atlantic and Gulf of Mexico coasts have been particularly instructive for reconstructing TC activity (Liu and Fearn 1993, 2000; Donnelly et al. 2001; Liu et al. 2008). These are produced when overwash of coastal dunes from wave activity associated with particularly intense hurricanes is deposited in the adjacent lagoon or lake. These studies have also been carried over to Pacific Ocean coastal locations in Australia (Nott and Hayne 2001) and the South China Sea (Yu et al. 2009), in some case with decadal resolution over many thousands of years. Nyberg et al. (2007) reconstructed vertical wind shear and SSTs using luminescence intensity of banded corals growing in the Caribbean Sea and found that the frequency of hurricanes in the 1970s and 1980s was anomalously low compared to the last 270 years, and that current TC activity is not unusual (although this has been debated; see Neu 2008). The isotopic composition of speleothems that formed in subtropical locations have shown striking correspondence to TC events (Frappier et al. 2007), although the length of the current record is quite short (23 years).

Although promising, such high-resolution studies are rare, attributable to the challenges (labor, time, and finances) one faces when analyzing sediments, corals, and speleothems at high temporal resolutions. Ideally, a proxy record is needed that is spatially abundant in coastal locations, has annual or finer resolution, and can be processed relatively quickly with the proper equipment.

2 Hurricanes and Tree Rings

Tree-ring data have long been known to contain a signal of TC activity. Pillow (1931) noticed hurricanes produced reaction wood once trees were forced to lean from high winds, and Manabe and Kawakatsu (1968) were able to reconstruct past typhoons back to AD 473 using reaction wood in Japanese cedar (*Cryptomeria japonica*). Most tree-ring studies, however, have been applied to understand the effects of TCs on tree growth and forest development. For example, Henry and Swan (1974) quantified in detail the effects of the 1938 New England hurricane on forest development in the Harvard Tract of southwestern New Hampshire (USA), noting how 18 downed stems dated using tree rings all pointed in a southwesterly direction. Subsequent studies focused on hurricane effects on New England forests (Foster 1988; Dunwiddie 1991) and, more recently, on forests of the southeastern U.S. Gorham (1992) and Doyle and Gorham (1996) analyzed effects of Hurricane Camille (1969) on coastal pine forests in Alabama, Mississippi, and Louisiana, and found a hurricane signal using a combination of growth suppressions, growth releases, and establishment dates. Parker et al. (2001) found growth releases in sand pine (*Pinus clausa*) growing in the panhandle region of Florida that were coincident with past TCs dating back to the 1890s. Rodgers et al. (2006) found a hurricane signal in individual tree series of pines growing in coastal Alabama via growth suppressions and releases, which were muted when multiple series were averaged together.

Lines of evidence of past TC activity based on tree growth patterns are only indirect, however, and an improved, direct geo- or bio-marker of TC activity was needed that maintained annual precision. The goal of our study was to analyze the oxygen isotope composition of longleaf (*Pinus palustris*) and slash (*Pinus elliottii*) pine tree rings to isolate the years of landfalling hurricanes from a site in southern Georgia prone to TCs that originate in both the Gulf of Mexico and Atlantic Ocean. Previous studies have shown that TC activity produces rainfall that is depleted in ^{18}O (by as much as 10‰) when compared to typical thunderstorms (Nicolini et al. 1989; Lawrence and Gedzelman 1996; Lawrence 1998). Two basic physical factors govern $\delta^{18}O$ values in TC precipitation: (1) continued fractionation during condensation, with preferential incorporation of ^{18}O in the condensate, leads to low isotope ratios in both vapor and precipitation in systems with tall, thick clouds, and (2) diffusive isotopic exchange between falling rain and ambient vapor, which results in a ^{18}O enrichment of the falling rain and a decrease in vapor compositions. Large, organized, and long-lived storms, such as TCs, particularly amplify these isotope effects (Miyake et al. 1968; Lawrence and Gedzelman 1996; Gedzelman et al. 2003). Furthermore, this ^{18}O-depleted water can remain in the soil for weeks following a TC event (Lawrence et al. 2002), ensuring uptake by trees and incorporation of the ^{18}O-poor oxygen in the wood cellulose. Lastly, the eye of a TC event need not pass directly over the study area to be recorded because TC-related isotope depletions can be significant several hundred kilometers from the eye (Lawrence and Gedzelman 1996).

3 Study Site

Pines used in this study came from two locations in southern Georgia that were collected for a separate but related study to reconstruct past climate from the tree-ring record. Core samples from living slash and longleaf pines were collected from the campus of Valdosta State University in Valdosta Georgia from trees that were felled for building construction in the late 1990s. These trees all established in a short window of time between 1825 and 1830, indicating a disturbance-mediated (fire or wind) cohort. To extend the tree-ring chronology back in time, samples from remnant longleaf pine trees were collected from Lake Louise, about 15 km (9 mi) south of Valdosta. These samples came mostly from stumps left over from late nineteenth and early twentieth century logging related to the turpentining industry which pervaded the southeastern Atlantic coastal region between ca. 1800 and 1920. The samples represent rare old-growth longleaf pines with very slow growth rates that contained tree-ring series that were sensitive to seasonal and annual changes in rainfall amounts (Fig. 1). Standard dendrochronological techniques (Stokes and Smiley 1996; Grissino-Mayer 2001) were used to develop a continuous master chronology from 61 trees total from both locations back to AD 1421. Tree rings back to AD 1770 were analyzed in this study.

Fig. 1 Longleaf pine sample LLC 004 from the Lake Louise site in southern Georgia, with tree rings that date from AD 1542 to 1813

4 Methods

TCs are more common in late summer and fall months, when pine trees at this latitude are already forming latewood. Therefore, an isotope signal of TC activity most likely will be seen in the $\delta^{18}O$ of the latewood. We began by sectioning individual crossdated tree rings from two pine trees into earlywood (EW) and latewood (LW) components. Alpha-cellulose was isolated using modified techniques described by Loader et al. (1997) to ensure complete removal of mobile resins (Miller 2005). Approximately 100 μg of each sample were weighed and loaded into silver capsules. Oxygen isotopes were analyzed using a quantitative high temperature carbon reduction elemental analyzer (TC/EA) interfaced with a continuous flow isotope ratio mass spectrometer (Finnigan MAT Delta Plus XL IRMS). Samples were pyrolyzed at 1,450°C and CO was separated from H_2 and nitrogen-bearing gases by gas chromatography. The CO was carried in a He-stream to the mass spectrometer for measurement of $^{18/16}O$ ratios.

5 Results

The oxygen isotope time series for both EW and LW show clear decadal to multi-decadal-scale variations (Fig. 2), especially in the EW values. EW tends to be enriched in ^{18}O by 1–2‰ in comparison to LW values prior ca. 1930. After 1930, the two series become more similar in composition. Divergent compositions pre-1930 are most likely related to differences in source moisture between winter/spring rainfall (which contributes to EW formation) and summer/fall rainfall (which contributes to LW formation). The decadal-scale variations most likely reflect systematic variations in seasonal temperature or sources of normal precipitation

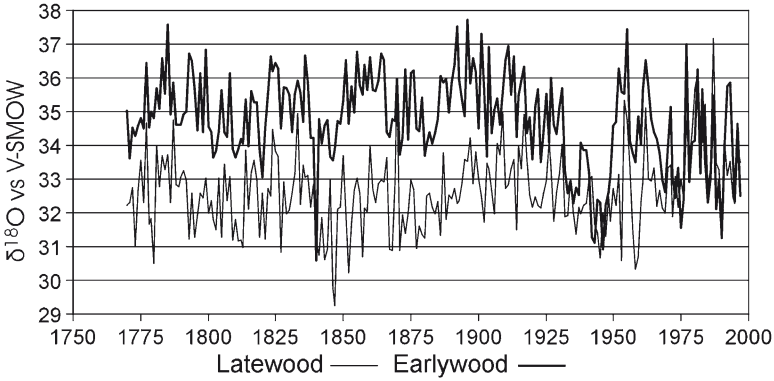

Fig. 2 $\delta^{18}O$ values for earlywood (*top*) and latewood (*bottom*) from two pines collected in southern Georgia

controlled by larger-scale climate modes, such as the AMO and North Atlantic Oscillation (NAO). For example, inspection of the EW and LW series during the twentieth century shows some similarities (and differences) with trends in the AMO. From the 1870s to early 1950s, a strong inverse relationship exists between EW and LW isotopic compositions and the AMO. From 1965 to 1990, the correlations are weaker, and positive for EW compositions, and there is no significant correlation with LW. Wavelet analysis (Torrence and Compo 1998) verified a statistically significant period at approximately 80 years (for nearly the entire record) and a near-significant period at approximately 32 years (Fig. 3), both of which could be associated with AMO activity.

The abrupt change in the relationship between the AMO and isotopic compositions coincides with a change in the predominant type of tropical cyclones, i.e., tropical or baroclinically-enhanced tropical cyclones of extratropical origin. These types of tropical cyclones form by fundamentally different mechanisms (Elsner and Kara 1999). The 1965–1990 period, in which baroclinically enhanced tropical cyclones were dominant, was one of relative quiescence for major tropical cyclones impacting the US coast. Since the mid-1990s, tropical cyclones have returned to dominance (Elsner and Kara 1999), with a greater number and greater intensity than in the previous 30 years.

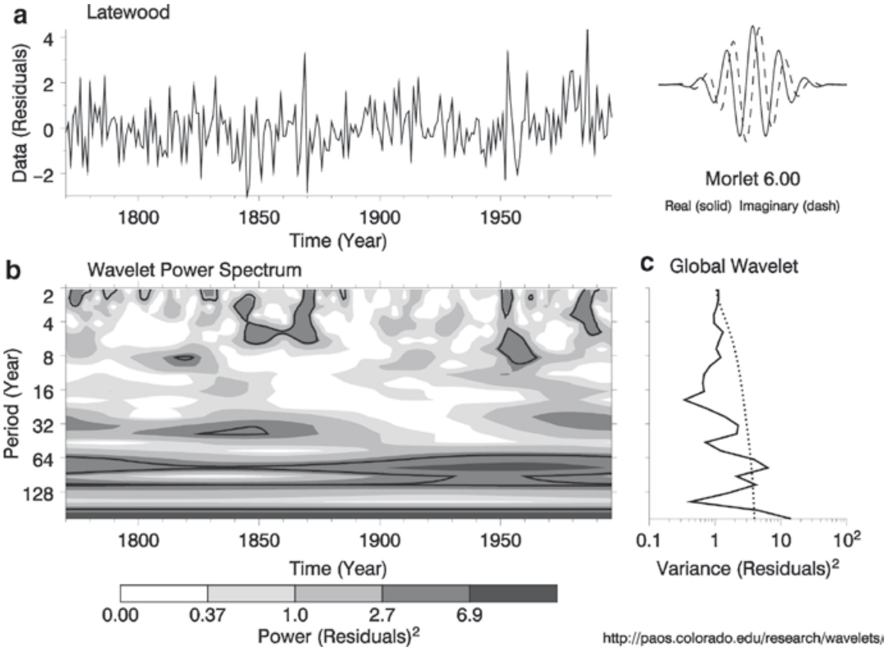

Fig. 3 (**a**) LW isotope time series along with (**b**) Morlet wavelet analysis, and (**c**) the global wavelet power spectrum (*black line*). Blackcontour in (**b**) is the 5% significance level, using a red-noise background spectrum (Torrence and Compo 1998; http:// www.ResearchSystems.com)

The low-frequency trend in the LW time series does not make apparent any relationship with TC activity, so we removed the low-frequency signal by modeling the LW series with an AR(1) process that effectively models the series as a function of itself lagged by 1 year to account for serial persistence. We used the residuals of the autoregressive model where negative values indicate low oxygen isotope compositions. We then compared the residual time series with a record of TC events recorded by instrument or historical documents that occurred within 400 km of the study area in south Georgia over the period 1851 to 1990 using the HURDAT database (Jarvinen et al. 1984; Landsea et al. 2004).

We observed that TC events coincided in years in which the residuals of the LW isotope compositions were anomalously negative (<–1.0) (Fig. 4). Using this –1 threshold, only one "false positive" (i.e., a storm detected by proxy for which there is no instrumental evidence) was noted and only three storms known to have tracked near the study area were missed ("true negatives") over the period 1855 to 1990. For example, a residual approaching –3 was found for the year 1871. In that year, no fewer than three hurricanes (Storm 4, 25–28 August; Storm 6, 6–7 September; and Storm 7, 4–6 October) affected the study area, with Storm 7 making a direct hit. In 1953, Hurricane Florence struck the panhandle of Florida as a Category 3 storm, then veered just to the north of our study site, causing large amounts of rainfall. This TC event is recorded with one of the lowest residuals in the entire record (–2.2). In 1958, Hurricane Helene stayed off the Georgia and South Carolina coasts but was still recorded with a residual of –2.0, even though local rainfall amounts from this hurricane would be considered modest (2.5 cm).

Further back in time, an unusual triad of TC events is shown in 1811, 1812, and 1813 with residuals of –1.2, –1.0, and –1.2 respectively. The years 1811 and 1813 particularly stand out because coastal areas of South Carolina were devastated in

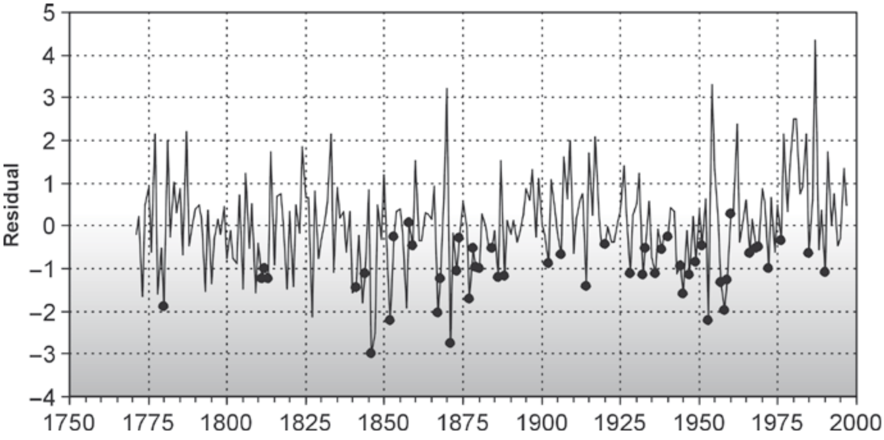

Fig. 4 Residuals (actual–predicted) created after fitting an AR(1) model to the original LW isotope time series. Documented TCs are shown as *black dots*

these years by catastrophic hurricanes (Ludlum 1989). The “Great Louisiana Hurricane of 1812” (Ludlum 1989), however, would have been a considerable distance from our study area in southern Georgia. Even further back in time, the LW residuals indicate a TC event in 1780 (–1.9) which could be showing one of the three “Great Hurricanes” that struck the Caribbean region in 1780 (Sandrik and Landsea 2003). Historical records are inconclusive whether any TC made landfall in the U.S. but a powerful hurricane (known as “Solano’s Hurricane”) struck the eastern Gulf of Mexico region north of Cuba between 17–22 October in 1780 (Ludlum 1989).

Although residual values ≤–1.0 strongly correlate to occurrence of a TC, TC activity is also noted for many years with residual values ≤–0.5 (Fig. 4), although using this threshold can lead to a few more “false positives.” For example, residuals of –0.6, –0.7, –0.6, and –0.5 occurred in 1910, 1935, 1974, and 1988, respectively, but no known TC events occurred within 400 km of the study area during these years. For residual values >–0.5, there is no apparent relationship with TC occurrence. A TC event may or may not have occurred in those years. In some cases, residual values do not capture evidence of a storm reported to have affected the study area. For example, residuals appear to miss known storms in 1893, 1896 and 1898.

6 Discussion

The magnitude of TC-related isotopic depletions in cellulose will depend on many factors, including the size and proximity of the storm, soil type, and preexisting soil moisture conditions, and is therefore most useful as positive, rather than negative, evidence of an event, and cannot be used as a measure of TC intensity. A complicating factor concerns evaporative enrichment of oxygen isotope ratios in soil and leaf water caused by drought conditions preceding or during the growing season in which the TC event occurs, as this may affect the oxygen isotope compositions (Tang and Feng 2001). Evaporative enrichment would dampen TC isotope anomalies in the soil, causing TC events to be missed by this proxy record. For example, several well-documented TCs occurred in the 1890s, a decade that was “the busiest decade on record for the Atlantic seaboard of the United States” (Landsea et al. 2004). TCs occurred near our study area in 1893 (the “Sea Islands Hurricane” off the Georgia coast), 1896, and 1898 but were not detected in the isotope proxy record because this decade experienced mild to severe drought in the study area. A reconstruction of January–April rainfall based on longleaf pines from the Lake Louise study area showed that 14.2 in. of rainfall occurred during this interval each year during the 1890s compared to the long-term (AD 1421–1999) average of 16.2 in.

Nonetheless, examination of the temporal patterns of all residuals ≤–0.5 reveals striking patterns of increased and decreased TC activity in our study area, which may indicate broader-scale patterns of TC activity throughout the region. Five periods of increased activity are indicated: 1773–1780, 1800–1815, 1838–1852, 1867–1888,

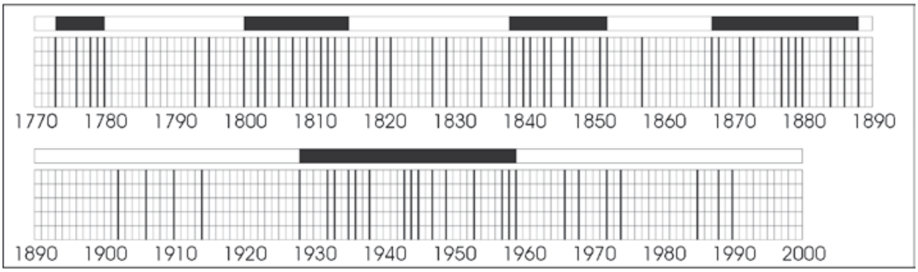

Fig. 5 Timeline of TC activity from 1770 to 1997 inferred from the residual time series (values <–0.5). *Black/white* areas above denote increased/decreased TC activity

Table 1 Periods of above- and below-average TC activity (residuals ≤–0.5)

Period of above-average TC activity	Period of below-average TC activity	Number of events (%)
1773–1780		5 (63%)
	1781–1799	3 (16%)
1800–1815		10 (63%)
	1816–1837	5 (23%)
1838–1852		9 (60%)
	1853–1866	1 (7%)
1867–1888		11 (50%)
	1889–1927	4 (10%)
1928–1959		15 (47%)
	1960–1997	7 (18%)

and 1928–1959 (Fig. 5; Table 1). Periods of decreased TC activity occurred between 1781–1799, 1816–1837, 1853–1866, 1889–1927, and 1960–1997. HURDAT records show that "the period of the 1850s to the mid-1860s was quiet, the late 1860s through the 1890s were busy and the first decade of the 1900s were quiet" (Landsea et al. 2004), which is clearly substantiated in our record. Particularly noteworthy were the decades of the 1800s (six events), 1840s (six events), 1870s (five events), 1930s (five events), and 1940s (five events).

Our isotope record may help researchers isolate unknown TC events. For example, two events are indicated in 1847 and 1857 by very low residuals (–2.5 and –1.9). No event has yet been historically documented for 1847, either on the Gulf Coast or Atlantic seaboard (Ludlum 1989), so this event could represent an unknown TC or represent a "false positive." The 1857 residual, however, may indicate a previously unknown TC event based on ongoing searches through historical documentation (Mock 2004). Efforts are currently underway by TC scientists to extend the TC record back to the 1800–1850 period and beyond, and we hope these efforts reveal TC events in such years as 1773 (–1.6), 1778 (–1.6), 1793 and 1795 (–1.5), 1805 (–1.5), 1809 (–1.6), 1819 (–1.5), 1821 (–1.4), 1827 (–2.1), 1834 (–1.1), and 1843 (–1.8). For example, in 1819 and again in 1821, TCs struck near Mobile, Alabama, 480 km from the study area, but the 1819 TC of 27–28 July was considered the worst the residents of that part of the Gulf Coast had seen up until the 1850s (Ludlum 1989). The year 1827 saw two major hurricanes, one pushing westward across the Gulf of Mexico until eventually striking Mexico and another called the "Great North Carolina Hurricane of 1827" (Ludlum 1989). The latter may be too far removed to have affected the study area, but the former may have passed in close enough proximity to the study area. In 1834, a "small hurricane" stayed off the South Carolina coast (Ludlum 1989), but rainfall may not have made it all the way inland to the study area. In 1843, a major hurricane struck the panhandle of Florida, just 120 km southwest of our study area, near today's Newport, Florida (Ludlum 1989), which in all likelihood would have caused rainfall to occur in our study area.

A more comprehensive network of sites throughout the Gulf of Mexico and Atlantic Ocean coastal areas where the isotopic composition of pines are analyzed could provide insights on tracks and/or area affected for those TCs for which we have very little information, especially prior to 1850. For example, if several sites up the Atlantic coast from northern Florida to Cape Hatteras, North Carolina reveal ^{18}O-depleted alpha-cellulose during a particular year, this could indicate the track of a TC up the coast of the Southeastern U.S. This denser network of sites would also provide finer temporal and spatial resolution for landfalling TCs and provide critical information on TC frequency and patterns of TC activity over time, and suggest specific coastal regions that have been particularly vulnerable to repeated events. Lastly, the record of TC events can be pushed back in time, limited only by the length of the tree-ring records. We currently have well-replicated longleaf pine tree-ring chronologies for Hope Mills, North Carolina (back to AD 1503), Eglin Air Force Base, near Pensacola, Florida (back to AD 1507), eastern Texas (back to AD 1632), Sandy Island, South Carolina (back to AD 1458), St. Augustine, Florida (back to AD 1680), and Lake Louise in southern Georgia (back to AD 1421).

Another useful strategy concerns sub-sampling of the LW to improve accuracy with which TCs are detected in the isotope record. Although the phenology of longleaf pine has not been studied in detail, the phenology of other yellow pines has, including the close associate species slash pine, which is faster growing and therefore has greater economic value. Slash pine diameter growth begins approximately 2 months after budbreak (i.e. growth beginning around April or May) and ending approximately 6 months later (around October and November) (Dougherty et al. 1994). Latewood in southern yellow pines can begin forming in early summer likely caused by soil moisture reserves being largely used up (Moehring and Ralston 1967; Cregg et al. 1988) coinciding with energy expended for reproduction (emergence of male and female cones) (National Phenology Network 2009). For example, mean LW transition in loblolly pine was found to occur around day 175 (Late June) (Cregg et al. 1988). This timing encompasses the majority of hurricane season and suggests that the isotopic signal of a TC event can be masked by analysis of material representing the entire LW growth period. To overcome this limitation, the latewood, which is often abundant in longleaf pines (Fig. 1), can be sub-sampled into smaller portions. For example, Hurricane Florence struck the study area on 26 September 1953 and was recorded with a residual value of –2.2. We divided the LW evenly into early LW and late LW portions and found a 4.9‰ difference in these two samples with the early LW residual being much lower at –3.0. Therefore, we believe that higher-resolution sampling of the LW will improve detection of the isotopic anomaly and clarify the interpretation of samples with modest (–0.5 to –1.0) LW residuals.

We also must consider additional chemical analyses of pine wood from coastal regions beyond just isotopic analyses. Advances have been made in the last 10 years for rapid and cost-effective analyses of the elemental composition of organic and inorganic materials using Laser-Induced Breakdown Spectroscopy (LIBS) (Lee et al. 2004; Cremers and Radziemski 2006; Singh and Thakur 2007). This technique uses a pulsed laser to ablate a small amount of the target material to cause constituent elements to emit light under high temperatures within the generated plasma plume. Atomic emission lines of elements within the plume can then be observed using an interfaced spectrometer with a wide spectral range, usually 170 nm (ultraviolet) to 1,100 nm (near infrared), where all elements have emission lines. LIBS has shown great utility in the environmental sciences for analyzing soil composition (Bublitz et al. 2001), contaminated sites (Theriault et al. 1998; Bousquet et al. 2008), and wood products (Moskal and Hahn 2002), for example. Coastal trees should be affected by considerable salt spray during a TC event, causing additional salt water to be added to the freshwater taken up by coastal pines. Although sodium is a macronutrient and expected in plant materials, chlorine is not and LIBS can be used to detect concentrations of dissociated chloride anions within the plant cellulose. Previous studies have shown that chlorine can be detected using LIBS (Kaski et al. 2004; Wilsch et al. 2005; Weritz et al. 2008). LIBS conducted on separated annual rings could potentially detect TC events by observing anomalous levels of chlorine in the wood cellulose and provide yet another proxy for reconstructing TC history.

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