Tree-ring isotope records of tropical cyclone activity

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The destruction wrought by North Atlantic hurricanes in 2004 and 2005 dramatically emphasizes the need for better understanding of tropical cyclone activity apart from the records provided by meteorological data and historical documentation. We present a 220-year record of oxygen isotope values of α-cellulose in longleaf pine tree rings that preserves anomalously low isotope values in the latewood portion of the ring in years corresponding with known 19th and 20th century landfalling/near-coastal tropical storms and hurricanes. Our results suggest the potential for a tree-ring oxygen isotope proxy record of tropical cyclone occurrence extending back many centuries based on remnant pine wood from protected areas in the southeastern U.S.

hurricanes | isotope proxy | stable isotopes | tree ring

Hurricanes pose a potentially devastating threat to life and property along the U.S. Atlantic seaboard and Gulf of Mexico, as demonstrated by the devastating impact of the 2004 and 2005 hurricane seasons. Recent studies suggest a sharp increase in hurricane activity and intensity since the mid-1990s (1). Hurricane frequency is related to multidecadal-scale variations in sea surface temperatures, vertical wind shear, and the coupled ocean–atmosphere climate modes that influence these factors (1–4). The relatively short instrumental record of meteorological observations makes it difficult to discern long-term (i.e., multidecadal) trends and fluctuations in tropical cyclone activity or to differentiate natural versus anthropogenic components of these trends (1–4). Before ≈1900, systematic records of hurricane occurrence are fragmentary in many localities and rely predominantly on documentary records such as ship logs and news media. The development of natural proxies for tropical cyclone activity may provide a basis for evaluation of decade- to century-scale variations in their activity and the relationship of tropical cyclone occurrence to long-term climate variations (5). Tree rings potentially provide a high-resolution, precisely dated biological archive of climate that can be extended back for centuries, and even millennia. This study reports a tree-ring isotope proxy record of tropical cyclone activity, based on a seasonally resolved, 220-year record of oxygen isotope values of α-cellulose in tree rings from longleaf pines in the southeastern United States (Fig. 1).

Oxygen isotope values of tree-ring α-cellulose mainly reflect the isotopic composition of source water and physiological isotope effects that include carbonyl-water interactions during biosynthesis, xylem water–sucrose exchange, and leaf water evaporative enrichment (6–8). Physiological effects tend to be very similar for a given species grown in the same environment (7). Thus, large inter- and intraannual differences in the oxygen isotope composition of cellulose from one or more trees of the same species in a limited study area most likely reflect changes in source water compositions.

For conifers that use shallow root systems, such as longleaf pine (*Pinus palustris* Mill.), the source water is most likely directly related to soil water, which itself is derived from precipitation (7). Well organized tropical cyclones, such as major hurricanes, produce large amounts of precipitation with distinctly lower (by as much as 10‰) oxygen isotope compositions than typical low-latitude thunderstorms (9). Evidence of isotopically depleted precipitation may persist in soil waters for several weeks after a large event (10, 11) and will be incorporated into the cellulose as the tree utilizes the soil water, capturing an isotopic record of tropical cyclone activity.

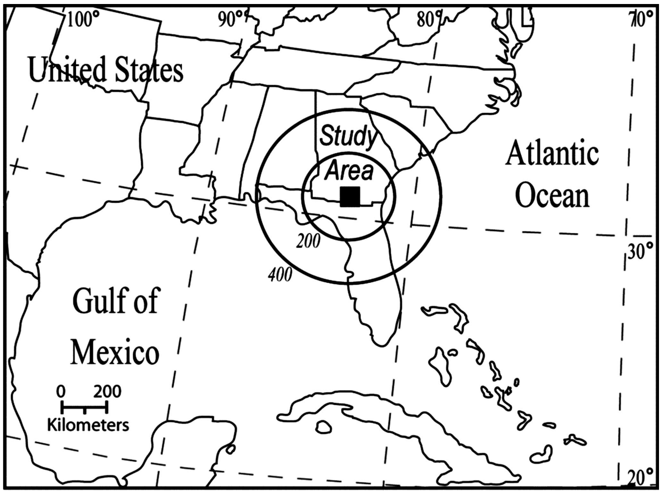

Fig. 1. Location of the study area near Valdosta, GA (shaded box). Most tropical cyclones producing precipitation captured in tree rings tracked within 200 km of the study area (inner circle), but several passing within 400 km (outer circle), or even more, were also detected.

Evaporative enrichment of soil water will eventually ameliorate the low ^{18}O signal (10). The ephemeral nature (i.e., several weeks) of tropical cyclone-related ^{18}O-depleted soil water suggests that it is captured only in cellulose produced in the weeks after a storm event. Thus, storm-related depletion may not be readily detected in an averaged annual ring sample. Longleaf pine tree rings preserve distinct earlywood (growth in the early portion of the growing season; approximately April to mid-June) and latewood (growth in the later portion of the growing season; approximately mid-June to November) components that can be separately analyzed to obtain seasonally resolved isotope compositions. Tropical cyclones most typically impact the southeastern United States from August through October (12), corresponding to latewood growth. Accordingly, we hypothesize that hurricane and tropical storm activity result in ^{18}O-depleted latewood cellulose. The magnitude of storm-related isotopic depletions incorporated into cellulose will depend on many factors, including the size and proximity of the storm rain bands to the tree, the amount of storm precipitation available to the tree, and preexisting- and postevent soil moisture conditions. Consequently, the isotope proxy may record evidence of a tropical cyclone event, but will not be a reliable measure of its intensity.

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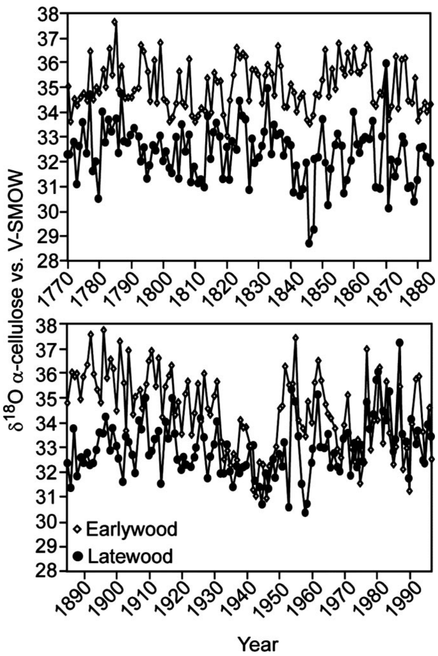

Fig. 2. Earlywood (EW) and latewood (LW) trends of $\delta^{18}O$ spanning 220 years (1770–1990). The isotopic values indicate long-term, oscillatory trends corresponding to decadal to multidecadal climate modes.

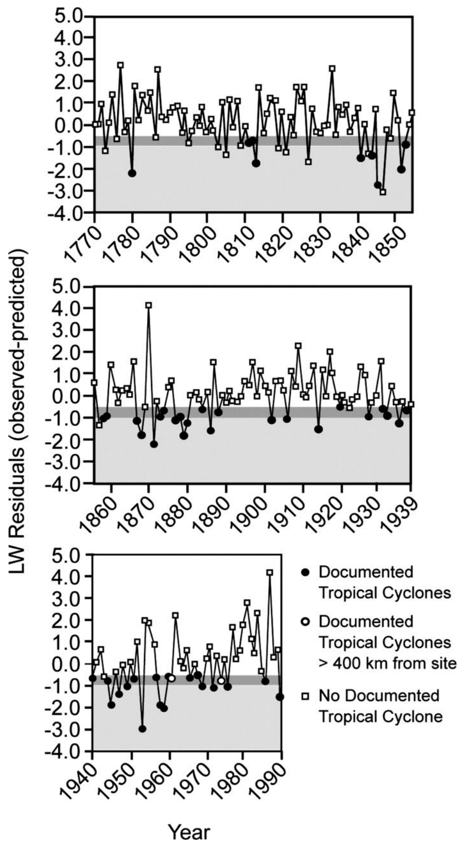

Fig. 3. AR (1) modeling of the LW (summer–fall) time series data. The great majority of tropical cyclones (TC) occur during late summer–fall, and TC stand out as the negative LW residuals (residual = observed − predicted value). The 1940–1990 record is compared with instrumental records of TC occurrence (see text).

Results and Discussion

A 220-year earlywood and latewood cellulose oxygen isotope time series for the study area shows systematic, decadal- to multidecadal-scale variations (Fig. 2). Decadal-scale variations in $\delta^{18}O$ values and differences between earlywood and latewood compositions most likely reflect systematic variations in seasonal temperature and sources of normal precipitation that are controlled by larger scale climate modes, such as the Atlantic Multidecadal Oscillation or the North Atlantic Oscillation (13–16). To detect isotopic anomalies in the time series, we used a 1-year autoregression model (AR-1; Box–Jenkins model) to remove the potential effects of short-term autocorrelation in the time series that may mask meaningful trends (http://www.agu.org/eos_elec/96097e.html), and evaluated the calculated residuals (residual = observed − model predicted values) (Fig. 3). Negative latewood residuals (i.e., residuals values less than −1; lightly shaded area of Fig. 3) result from anomalously low $\delta^{18}O$ values in latewood cellulose. Latewood residual values in the range −0.5 to −1.0 (dark shading in Fig. 3) are still considered anomalous, as they are about three times larger than our analytical uncertainty.

Instrumental records for the last half-century provide the most accurate and complete knowledge of tropical cyclone intensity, precipitation, and storm track (www.nhc.noaa.gov/pastall.shtml; refs. 17–19) and are useful to test the efficacy with which tree-ring $\delta^{18}O$ values capture a record of tropical cyclone activity. For the period 1940–1990, we compared the record of ^{18}O-depleted tree-ring cellulose to these instrumental data, noting whether an isotopic anomaly was present in latewood cellulose for any year in which a tropical cyclone storm track (http://www.nhc.noaa.gov/pastall.shtml; refs. 17–19) passed within ≈400 km of the study area (most passed within ≈250 km), and the local meteorological station recorded a concurrent precipitation event (http://lwf.ncdc.noaa.gov). A comparison of known storms, concurrent precipitation near the study site, and latewood residuals is given in Table 1, which is published as supporting information on the PNAS web site. With the exception of three years (1943, 1958, and 1961), each negative isotope anomaly (residual less than −1.0) is associated with a known tropical cyclone event, as defined by the parameters above. Many years with residuals in the range −0.5 to −1.0 were also affected. Low residuals in 1958 and 1961 may be explained by rainfall associated with major hurricanes that tracked outside of the defined target range. Previous studies indicate hurricane rain may be ^{18}O-depleted hundreds of kilometers from the storm eye (9). Hurricane Carla (1961) was a major hurricane (category 4–5) that made landfall in Texas, but rainbands from the storms reached as far as southern Georgia and 2.47 cm of precipitation fell at the Valdosta station on the appropriate dates (www.nhc.noaa.gov/pastall.shtml; www.hpc.ncep.noaa.gov/tropical/rain/carla1961.html). Rainfall from Hurricanes Helene and Daisy is likely responsible for the 1958 anomaly (http://lwf.ncdc.noaa.gov/; www.nhc.noaa.gov/pastall.shtml). Thus, for the 50 years for which the isotope proxy can be most confidently tested, only one false positive is identified (1943; Fig. 3), and the isotope proxy identified all events fitting the test criteria.

Before 1940, daily precipitation data are unavailable in the study area and tropical cyclones inferred from the isotope proxy cannot be as confidently confirmed. Over the period 1855–1940, the isotope proxy indicates 22 years with tropical cyclones, 21 of which are reported in the historical record to have affected the general study area (18–20). For the period 1770–1855, the proxy suggests many more years (25 years) affected by one (or more) tropical cyclones, 10 of which can be matched to historically documented storms, including events in 1811, 1812, and 1813 (21). The lower degree of matching is not unexpected, given the more limited historical records that are available for the earlier time period.

Previously undocumented tropical cyclones which may have impacted the study area include the "Great Hurricanes" of 1780 (Fig. 3) (21), and events in 1847 and 1857 (Fig. 3). Although no tropical storm has yet been historically documented for 1847, the results for 1857 complement limited historical data that strongly suggest a tropical cyclone (22). In addition to Hurricane 7 (1879), which was a tropical storm at the time of impact near lower Georgia, historical documents also suggest a major storm event of unspecified origin (21), which may also contribute to the low residual for this year (Fig. 3).

Tropical cyclones are dynamic systems and factors affecting their precipitation and isotopic compositions, such as the location and intensity of rainfall, change throughout the life of the storm (23, 24). The tree ring isotope proxy captures only a point in the time and space of the storm event. As a consequence, storm events may not be recorded. Hurricane David (1979) passed within ≈200 km of Valdosta, GA, as a Category 1 hurricane (www.nhc.noaa.gov/pastall.shtml), but there was no significant precipitation at the site while the storm was within ≈400 km of the site (Valdosta 3E station; http://lwf.ncdc.noaa.gov), and there is no isotope anomaly to mark the storm. Consequently, for the portion of the record without direct instrumental records of precipitation, this proxy best provides positive, rather than negative, evidence of an event.

Evaporative enrichment of oxygen isotope ratios in soil and leaf water due to drought conditions may also affect the oxygen isotope compositions (11). Isotopic enrichment will tend to dampen a tropical cyclone-related isotope anomaly and complicates interpretation of the isotope proxy hurricane record. For example, several notable hurricanes in the 1890s, such as the Sea Islands Hurricane of 1893 and hurricanes in 1896 and 1898 (19, 21) are not detected in the tree ring proxy record. This decade coincides with a period of mild to severe drought in the study area, based on instrumental data (www.ncdc.noaa.gov/paleo/usclient2.html).

Sampling for this study included material averaged from the entire latewood portion of the ring. Because of the ephemeral nature of the hurricane-related isotope depletion in soil water, only a portion of the latewood cellulose may actually record the ^{18}O depletion, and averaged seasonal isotope ratios may mask less intense storm activity. For example, in 1953, the study area was affected by Hurricane Florence, which made landfall over the panhandle of Florida as a Category 2 storm (www.nhc.noaa.gov/pastall.shtml) during the early-latewood portion of the growing season (September). The residual for the averaged latewood sample was −1.5, clearly indicative of a tropical cyclone event. In a second round of sampling, the 1953 latewood was split into early-latewood and late-latewood components. The entire isotopic anomaly is found in the early-latewood, with a significant isotopic difference between the two latewood segments (4.80‰), and a very negative residual of −3.0 within the early portion of the latewood. Higher-resolution sampling of tree-ring latewood should therefore improve the significance of measured isotope anomalies, will help to clarify the interpretation of samples with modest (−0.5 to −1.0) latewood residuals (Fig. 3), and suggests the potential to resolve the occurrence of multiple events in a given year.

The isotope record of tree-ring cellulose presented here supports its use as a proxy for tropical cyclone activity extending beyond historical records for the southeastern United States. Interpretation of the proxy record (Fig. 3) shows close agreement with instrumental records that the 1950 decade was the busiest for hurricane activity in the 20th century (www.nhc.noaa.gov/pastall.shtml). The proxy record further supports historical records that suggest significant tropical cyclone activity for the southeastern United States between 1865–1880 (www.nhc.noaa.gov/pastall.shtml; refs. 20 and 21). The isotope proxy detects six storms in the 1870 decade, although only one (1871; the largest 1870 decade anomaly; Fig. 3) appears to have made direct landfall on the Georgia coast. Other decades of apparent activity include the 1840 and 1850 decades, 1800–1820 decades, and 1770s decade. Periods of relative quiescence in Georgia appear to be the 1781–1805 (except 1793 and 1795) and the 1970 decade. Studies by our group have recently developed tree-ring chronologies several centuries in length from longleaf pines in the coastal plain region of the southeastern U.S. in areas where abundant wood has been protected from repeated burning and collection (i.e., Hope Mills, NC, 1597–2003; Elgin Air Force Base, FL, 1503–2003; Sandy Island, SC, 1629–2003; Lake Louise, GA, 1421–1997), extending the potential utility of the tree-ring proxy method to ≈600 years.

Methods

Several large cross sections were collected from longleaf pines felled on the Valdosta State University campus (Georgia; 30.84°N, 83.25°W) and from remnant stumps, left from early 20th century logging of longleaf pines from nearby Lake Louise (30.43°N, 83.15°W) (Fig. 1). Longleaf pines are common in the coastal plain region of the southeastern United States, growing in well to moderately well drained loamy sand soils (25) and have been shown to produce consistent annual rings (26). Longleaf pine trees from this area were chronologically dated by using standard cross-dating techniques (26, 27). The earlywood and latewood portions of each annual ring were sampled, and α-cellulose extracted from this wood was analyzed for its oxygen isotope ratios. Earlywood and latewood can be distinguished by the cell wall thickness and color. The earlywood and latewood segments were separated and cut into slivers (≈40 μm). Pine resins were removed by accelerated solvent extraction using 3:1 toluene and reagent alcohol at 125°C and 1,500 psi. An internal standard, Sigma-Cellulose (Sigma, St. Louis, MO), was treated by using the same approach, without change to its isotopic compositions, within uncertainty limits. α-Cellulose was extracted from whole wood by using soxhlet extraction methods (27, 28). Oxygen isotope compositions of α-cellulose (80–100 μg) were analyzed by using a Finnigan (Finnigan-MAT, San Jose, CA) high-temperature conversion/elemental analyzer (TC/EA) interfaced with a Finnigan MAT Delta Plus continuous flow mass spectrometer (29–31) and reported relative to V-SMOW. Both the internal standard and NBS-19 were routinely analyzed, and α-cellulose samples were run in triplicate. The 2σ standard deviation for wood samples is ±0.33‰.

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