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Tropical cyclone rainfall variability in coastal North Carolina derived from longleaf pine (*Pinus palustris* Mill.): AD 1771–2014

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Abstract Records of tropical cyclone precipitation (TCP) in the USA typically begin in the mid-20th century and are insufficiently long to fully understand the natural range of TCP variability. In southeastern North Carolina, USA, we use longleaf pine (*Pinus palustris* Mill.) latewood chronologies from two study sites and a combined chronology as a proxy for TCP during AD 1771–2014 as the latewood growth period of June 1st–October 15th coincides with 93 % of annual TCP. We correlate latewood radial growth with TCP based on days when tropical cyclones tracked within a 223 km rain field, with the results ($r = 0.71$, $p < 0.01$) supporting the viability of this species to chronicle interannual variations in TCP for multiple centuries. Using annual latewood data during 1953–2014, we reconstruct TCP back to 1836 for the combined chronology. We creat three radial-growth groups (low, near-average, high) and find that corresponding TCP values are significantly different ($p < 0.05$) between groups. Low radial-growth values are a strong marker (91 % occurrence) of below-average TCP years and high radial-growth years are (73 % occurrence) also good indicators of above-average TCP years. Examination of the temporal occurrence of below- and above-average TCP years into the late 18th century indicate that a predominance of below-average TCP years occur from 1815 to 1876 that are unmatched in the historic record. The high fidelity between longleaf pine latewood growth and TCP coupled with the geographic distribution of the species throughout the southeastern USA where tropical cyclones are common suggest the utility of this species to help better understand the temporal variability of precipitation delivered via tropical cyclones.

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1 Introduction

Tropical cyclone (TC; tropical depressions, tropical storms, and hurricanes) precipitation (TCP) is an important facet of the southeastern U.S. hydroclimate as it helps recharge groundwater supplies, can abruptly end severe drought conditions (Maxwell et al. 2012; Maxwell et al. 2013), and serves an important ecological role (Prat and Nelson 2013; Walls et al. 2013). Conversely, landfalling tropical cyclones often impose substantial societal costs. In the US, landfalling TCs and the remnants of decaying TCs over land caused in excess of $370 billion in economic losses and more than 3750 human deaths during the early 1950s–2006 (Prat and Nelson 2013), with much of the losses associated with inland flooding (e.g., Bales 2003). The costs of Hurricane Sandy in the U. S. in 2012 were over $50 billion (Abramson 2012) and 117 fatalities were reported by the Red Cross, most from drowning (CDC 2013). Currently unknown is where TCP observed over the instrumental record falls within a multi-century probability distribution. Potentially, droughts associated with a lack of TCP or flooding events outside of known recurrence intervals may have occurred, and a paleoclimatic reconstruction of TCP would contribute to better understanding the range of interannual variability in TCP within the southeastern U.S.

Tropical cyclone activity and landfall frequency in the southeastern U.S. exhibit spatio-temporal variability at intra-annual, interannual and interdecadal time scales (Cry 1967; Keim et al. 2007; Knight and Davis 2007; Nogueira and Keim 2010, 2011; Zhu and Quiring 2013). TC landfall climatologies constructed for select locations from proxy records indicate multidecadal variability in landfall frequency in the southeastern U.S. during previous centuries (Liu and Fearn 2000; Elsner et al. 2000; Miller et al. 2006; Frappier et al. 2007; Elsner et al. 2008; Hall and Hereid 2015). However, these records provide evidence of the *occurrence* of a TC, but not TCP amounts. Prior to the 1950s, less information is available to determine the natural range of variability and magnitude for TCP because of the paucity of serially complete and high-quality meteorological data. Although Cry (1967) produced a TC climatology for the southeastern U.S. during the period 1930–1960, examinations of TCP variability typically begin in the mid-20th century (e.g., Zhu and Quiring 2013) and the understanding of longer-term variations in TCP is incomplete. Here we assess TCP variability over multiple centuries based on the strong relationship between TCP and latewood ring widths of longleaf pine (*Pinus palustris* Mill.) and present evidence that a multidecadal period of reduced TCP and TC occurrence occurred in the mid-19th century that is unique to the last two centuries.

Tropical cyclone reconstructions in the U.S. have focused on obtaining information from historical documents (Glenn and Mayes 2009) and proxy data from: 1) sand layers accumulating in coastal lakes and lagoons (Liu and Fearn 1993, 2000; Donnelly et al. 2001); 2) luminescence intensity of corals (Nyberg et al. 2007); 3) isotopic composition of speleothems (Frappier et al. 2007); and 4) tree-ring data (Johnson and Young 1992; Latimer et al. 1996; Rodgers et al. 2006; Grissino-Mayer et al. 2010). Detecting TC activity using tree-rings has been traditionally based on identifying abrupt growth changes in ring widths coincident with TCs using reaction wood (Pillow 1931; Manabe and Kawakatsu 1968), growth releases or suppressions (Doyle and Gorham 1996; Parker et al. 2001; Rodgers et al. 2006) and establishment dates of co-occurring species (Doyle and Gorham 1996; Gentry et al. 2010). More recently, analysis of $\delta^{18}O$ isotope values from cellulose of longleaf pine latewood has been used to directly identify TC activity (Miller 2005; Miller et al. 2006). All of these studies have focused on various aspects of detecting occurrence, frequency and strength of the TCs.

Both historical and proxy approaches to documented TC occurrence have limitations. Use of historical documents including newspaper accounts, ship logs, personal correspondence and limited instrumental data have allowed for the successful identification of TCs to early colonial times (Barnes 2001), but older records become increasingly incomplete with time (Hudgins 2000), are regionally biased towards where population centers exist(ed), and are subject to both inaccuracies and hyperbole (Barnes 2001; Glenn and Mayes 2009). Additionally, the entries contain few meaningful meteorological specifics and there is a high likelihood of "unrecorded significant storms" prior to 1870 (Hudgins 2000, p. 1). The most direct approach thus far for identifying TCs—oxygen isotope analysis—is limited by extensive labor requirements to extract the isotopic data. Further, this method does not provide a means to assess the amount of TCP.

Latewood radial growth of longleaf pine has been strongly linked to late summer rainfall that would include TCP (Devall et al. 1991; Meldahl et al. 1999; Foster and Brooks 2001; Henderson 2006; Gentry 2008; Henderson and Grissino-Mayer 2009) and post-TC growth surges have been identified (Devall et al. 1991). The only published study (Lodewick 1930) that has specifically examined the timing of longleaf pine radial growth found that latewood formation occurs from approximately mid-June through mid-October and is consistent with our field observations in North Carolina. Further, because latewood growth coincides with the majority of the TC season, a physiologically critical relationship between TCP and longleaf pine latewood growth has been hypothesized (e.g., Gentry et al. 2010). Yet, to our knowledge no study has examined the direct influence of TCP on latewood growth where non-TCP has been removed from the TC-season record. Here, based on the high fidelity between TCP and longleaf latewood radial growth we: 1) reconstruct the TCP record to the early 1800s to document temporal variability prior to historic records; 2) test for differences in TCP during the instrumental period (1953–2014) based on three categories of latewood growth; 3) examine variability of TC activity and TCP back to the late 1700s based on the three categories of latewood growth; and, 4) discuss the uniqueness of a multidecadal period with minimal TCP in the 1800s.

2 Data and methods

2.1 Study areas

We collected longleaf pine tree-ring data from two sites (CFL, 34.972 N, 77.119 W, 12.2 m; and MRL, 34.743 N, 76.985 W, 11.6 m) in southeast North Carolina on the Croatan National Forest during winters 2013 and 2015 (Fig. S1). The sites contained open stands of longleaf pine with a wiregrass-dominated (*Aristida stricta* Michx.) understory (Fig. S2) and represent rare locations with old-growth longleaf pine savanna on the coastal plains. Longleaf pine grows in a variety of topoedaphic habitats along the coastal plains, but more park-like woodlands typically occur on sandy upland soils. We found the oldest stands situated on Carolina bay (shallow, elliptical or ovate depressions; Lide et al. 1995) ridges, which are visually subtle but topoedaphically and vegetatively distinct features of the Atlantic coastal plain. The bay ridges rise 0.5–1 m above the surrounding area with slopes of 1–2 % (similar to the crown profile of an athletic field) that facilitate drainage (Fig. S2). Soils at CFL and MRL are classified as Leon Sand (NRCS 2015), which is comprised of sand from 0 to 56 cm depth and fine sand from 56 to 203 cm depth. The water-table depth is 0 to 30 cm and the soils transmit water rapidly (up to 15 cm/h; NRCS 2015).

Natural wildfires have been allowed to occur at the sites (Croatan NF, pers. comm., 2013) and evidence (e.g., blackened bark) of low-intensity fires is present at both sites. At each location we collected two increment cores from the stem of 30 trees at 1.3 m height. We sampled on opposite sides of the tree selecting only visibly healthy trees (i.e., no sign of disease, scaring, damaged upper bole, etc.…) in open-canopy locations to minimize potential growth surges/declines associated with canopy loss/infilling, disease, or structural damage. Additionally, we recorded height, diameter at 1.4 m height, physical condition, and near-exact location of each tree via GPS.

2.2 Chronology development and growth/climate model development

All samples had distinct earlywood and latewood segments with abrupt transitions and were sanded to 600 *u*m grit and then crossdated using standard laboratory procedures for dendroecological samples (Stokes and Smiley 1968; Swetnam et al. 1985; Yamaguchi 1991; Speer 2010). We used the software program Measure J2X to measure earlywood, latewood and total ring-width (Voor Tech Consulting 2008). Following measurement, we used COFECHA (Holmes 1983; Grissino-Mayer 2001) to check the crossdating accuracy and corrected problems prior to chronology standardization using ARSTAN (Cook and Holmes 1997). We examined climate/growth relationships using both negative exponential curves and a two-thirds smoothing spline (Cook and Peters 1981) and found using the "Standard" chronology from the negative exponential output provided the strongest correlation between growth and climate for both chronologies. Additionally, we merged the CFL and MRL chronologies to create a combined chronology (hereafter, CMB) by averaging the annual values of the two standardized site chronologies.

For each site chronology we initially developed a bivariate regression model using the annual sum of TCP as the dependent variable and the mean standardized latewood widths as the independent variable. While TC season is June 1st-November 30th, we found the strongest relationships between latewood growth and TCP occurred between June 1st and October 15th, thus our definition of TCP is based on this period. We paired each site with a climatic station that provided the closest match with the site's physical characteristics and had a long, nearly complete, and accurate record of daily precipitation. We calculated TCP for a site by determining when a TC tracked over the region using the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010) with a TC-moisture plume radius of 223 km (i.e., the average rain-field size at landfall; Matyas 2010) (Fig. S1). We also examined relationships on days with precipitation and TCs tracking within 500 km from the storm center (Nogueira and Keim 2010), but our results were similar, and we selected the more conservative rain-field radius to reduce the possibility of including non-TCP events in the TCP totals.

We analyzed TCP data during 1953–2014 ($n = 62$ years). We correlated latewood growth at CFL with same-day daily precipitation data (June 1st-October 15th) from New Bern (GHCND:USW00093719; 13 km NE of CFL) and MRL latewood data with same-day daily precipitation data from Havelock (GHCND:USW00013754; 16 km NE) (Fig. S1). Because data were absent during 1994–97 at New Bern, we replaced them with data from Jacksonville (GHCND:USW00093727; 33 km SW) during this four-year period as the Jacksonville data are an additional long-term record that closely correlate with CFL. For the CMB chronology, we averaged TCP from New Bern (average = 780 mm/yr) and Havelock (699 mm/yr). We attributed all precipitation that occurred on days when a TC tracked through the 223 km rain field to the TC. Based on the selected weather stations, we used TC positions at 6z, 12z and 18z and following day 0z for the current-day precipitation measurements. Our method of rainfall attribution to TCs coincident with these tracking times may potentially include non-TC events (e.g., frontal passage, air-mass thunderstorm). Further, the climatological influences conducive to TC development (e.g., interaction between the Atlantic multidecadal oscillation [AMO] and El Niño Southern Oscillation [ENSO] and the position of the North Atlantic Subtropical High [NASH]) can direct additional moisture into the region.

To reconstruct TCP, we developed a regression model with the CMB standardized latewood tree-ring chronology as the independent variable and the CMB TCP as the dependent. We divided the CMB TCP record (1953–2014) in half to perform calibration and verification of the regression model to ensure stability in the relationship through time. We used the early portion (1953–1983) to calibrate a model and predict the late period (1984–2014). We correlated the resulting predicted values for the late period with the observed data for the same period and reversed the procedure to calibrate a model and predict the early period. To validate the model we used the reduction-of-error statistic (RE; Fritts 1976) and the coefficient-of-efficiency statistic (CE; Nash and Sutcliffe 1971), with positive values of these statistics (Table S1) indicating that the model represented a sufficient amount of the observed variance for validation.

To examine if TCP totals were significantly different based on latewood widths, we separated the 62-year record into three groups using data from the standardized chronologies and categorized as: low growth (index value ≤0.75), near-average growth (0.76–1.09), and high growth (≥ 1.1). We used a Kruskal-Wallis test with pairwise comparisons to test for significant ($p < 0.05$, 1-tailed) TCP differences between the three radial-growth groups for each (i.e., CFL, MRL, CMB) chronology. We used the same radial growth groupings to highlight the temporal pattern of dry and wet years back to 1771 (CFL) and 1836 (MRL, CMB).

2.3 Accounting for confounding influences

The relationship between latewood growth and TCP has a few potential limitations. TCs can affect the southeastern U.S. after latewood growth has ceased, although this is uncommon. The median date for peak TC activity in the Atlantic basin is approximately September 10th (Nogueira and Keim 2011) and most TCs occur between mid-August and mid-October (Elsner and Kara 1999). Similarly, hurricanes can occur before latewood growth has begun, although less than 5 % of all hurricanes occur in June (Elsner and Kara 1999). While longleaf pine has evolved in a region of high winds and frequent low-intensity fires, “mature longleaf pine is quite resistant to most damaging agents and thus has a low mortality rate” (Outcalt 2008; p. 3355). Low-intensity fires are considered the primary disturbance factor affecting longleaf pine (Chapman 1932; Landers 1991; Outcalt 2008), and may actually be promoted by the species via growth traits including high shed rates of long needles serving as fuel loads and resinous boles and stumps that can burn for weeks and reignite fires (Platt et al. 1988). Conversely, spacing between adult trees minimizes the possibility of damaging crown fires (Platt et al. 1988, Fig. S2). Strong hurricanes also may cause structural damage to the tree because of high winds, thereby decreasing latewood growth for that year, “but longleaf pine is quite resistant to hurricane-force winds” and suffers minimal damage (< 2 % of trees) even during major storms (Provencher et al. 2001, p.96). Finally, the IBTrACS dataset is derived from multiple sources to create a consensus track (Knapp et al. 2010; Schreck et al. 2014). While it suffers from incomplete TC counts and loses reliability early in the record (i.e., undetected ocean-based storms than never make landfall), it is considered the best source of annual TC data in the southeastern U.S. and the record has been adjusted to account for missing TCs preceding basin-wide satellite monitoring beginning in 1966 (Chang and Guo 2007; Landsea 2007; Mann et al. 2007; Vecchi and Knutson 2007).

3 Results

3.1 Chronology statistics

Interseries correlations, which measure the signal strength shared between sampled trees at a site, were 0.57 for both CFL (n = 27 samples) and MRL (n = 38). Both chronologies had high mean sensitivities (CFL =0.53, MRL =0.54), indicating considerable interannual variability in ring widths. The beginning year for the chronologies based on signal strength of 0.85 (Wigley et al. 1984) was 1771 for CFL and 1836 for MRL.

3.2 Correlations

Latewood widths were strongly related with TCP at both sites and CMB (Table S2) during the 62-year study period. Conversely, the relationship between latewood growth and non TC-precipitation during June 1st–October 15th was weak at CFL and not significant for MRL and CMB (Table S2). We examined the standardized residuals at both sites to determine if outlier (>2.5) values were unduly affecting the correlation values. Outliers occurred at CFL in 1971 and 1996 and at MRL in 1955, yet exclusion of these variables changed r values <0.01 at both sites. Thus, we retained these years for analysis.

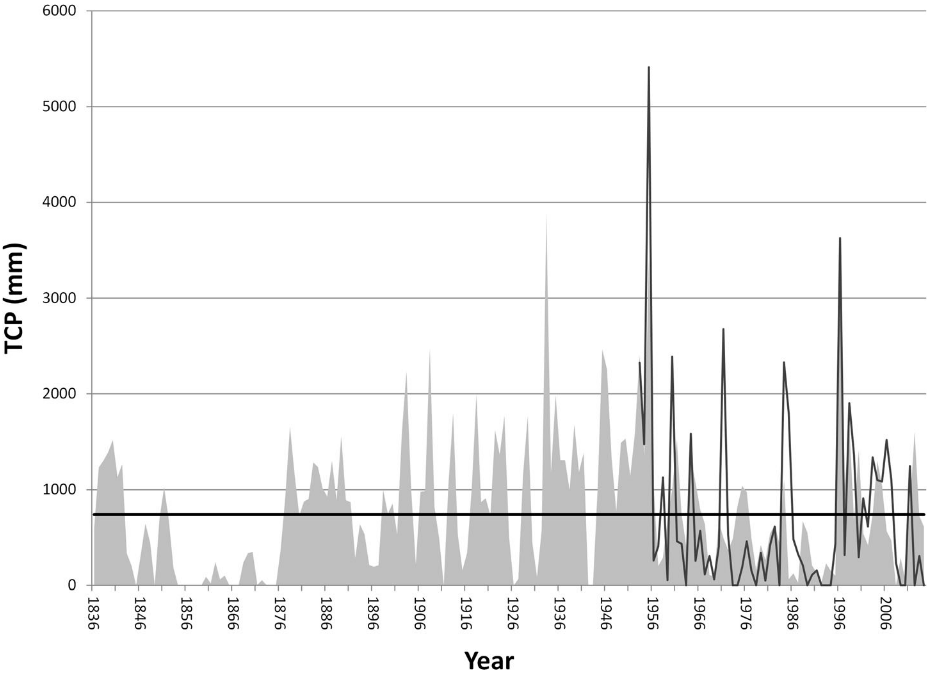

Fig. 1 Time series of reconstructed TCP from the CMB standardized tree-ring chronology (gray shaded) and the observed TCP (gray line). Mean TCP during 1953–2014 is also shown (black line)

3.3 Reconstruction of TCP

The reconstruction of TCP explained 50 % of the variance of observed TCP (Table S1). Further, the reconstruction model was significantly validated, with both split-period calibrations returning positive RE and CE values, indicating that the relationship is stable through time (Table S1). The reconstructed TCP matches well with the observed data (Fig. 1) and extended the TCP record to 1836, which is over a century beyond the instrumental record.

3.4 TCP characteristics and TC frequency based on radial growth groups

At CFL, mean TCP values between the low-growth (annual standardized radial growth ≤0.76) and high (≥ 1.1) groups and near-average (0.76–1.09) and high-growth groups were significantly ($p < 0.05$, 1-tailed) different (Table 1). At MRL, TCP average values were significantly different between both the low-growth and high-growth and near-average and high-growth groups (Table 1). TCP mean values between the three groups for CMB were significantly different from each other (Table 1).

We found that radial growth and TCP match closely throughout the period of overlap, especially for high and low growth years. For MRL, CFL and CMB, low radial-growth years were seldom concurrent with years with above-average TCP (8.7–13 % of years; Table 1). Conversely, the majority of years with high radial growth were associated with above-average TCP (50–72.7 %; Table 1). These relationships were mirrored by the frequency of years with zero TCP. The low and medium groups had similar mean annual TC occurrences, but were both significantly lower than the high radial-growth group (Table 1).

3.5 Temporal occurrence of high and low TCP years

Several patterns exist in the frequency of wet and dry years as suggested by radial growth and the TCP reconstruction. For the CFL chronology (Fig. 2a), a pronounced period of low radial-growth years, inferring below-average TCP, occurred from 1815 to 1875 where 41of 61 years (67 %) had radial growth values ≤0.76 and only four years were in the high-growth group (inferring above-

Table 1 Comparisons between radial-growth groups during 1953–2014. Different superscripted letters between groups indicate where significant ($p < 0.05$, 1-tailed) differences in values exist for mean TCP and mean annual number of TCs based on Kruskal-Wallis pairwise comparisons

Site	Radial Growth Group	# Years 1953–2014	Mean TCP (mm)	# Years with above- average TCP ($\bar{x}$ =all years)	%Years with above- average TCP (by group)	# Years with 0 TCP	Mean Annual #TCs
CFL	Low	23	351^a	3	13	10	1^a
CFL	Near average	29	780^b	10	34.4	4	1.21^a
CFL	High	10	1779^b	5	50	1	2.6^b
MRL	Low	24	345^a	3	12.5	7	1.04^a
MRL	Near average	24	646^a	9	37.5	5	1.16^a
MRL	High	14	1398^b	7	50	1	2.21^b
CMB	Low	23	304^a	2	8.7	8	1^a
CMB	Near average	28	673^b	9	32.1	4	1.18^a
CMB	High	11	1865^c	8	72.7	1	2.54^b

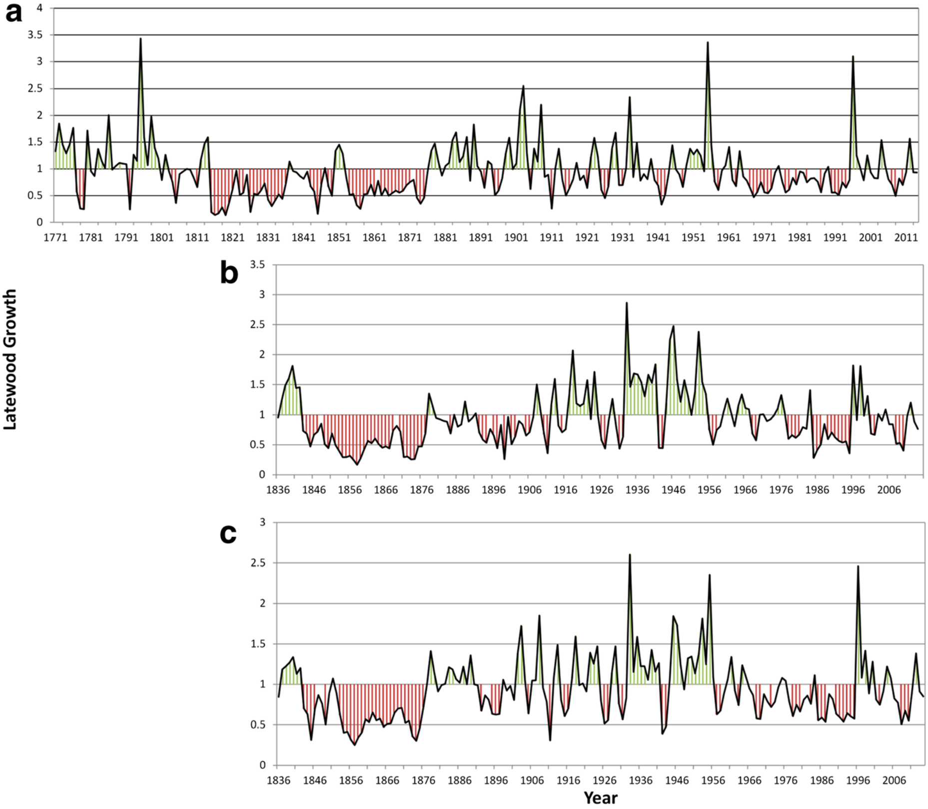

Fig. 2 **a-c** Occurrence of dry (red lines, radial growth ≤0.76) and wet (green lines, radial growth ≥1.1) TCP years at CFL (**a**), MRL (**b**) and CMB (**c**). TCP years inferred from annual standardized latewood radial growth widths (black line)

average TCP). A shorter period of pronounced low-growth occurred between 1967 and 1994 where 13 of 28 years (46 %) had radial growth values ≤0.76. Roughly the same period (1965–1995) is marked by an absence of above-average years. Similar patterns occurred at MRL (Fig. 2b). For CMB (Fig. 2c), low radial growth occurred for 29 of the 34 years (85 %) during 1843–1876. This pattern of low growth is unmatched in the tree-ring record, and the reconstruction suggests a virtual absence of TCP from ca. 1854 to 1875. Two periods of consistently above-normal TCP evident in the instrumental record occurred in the 1950s and the late 1990s to early 2000s and are effectively captured in the reconstructed record (Fig. 1).

4 Discussion

Variations in latewood widths of longleaf pine have high fidelity with TCP and are particularly good markers of years with below-average TCP as well as TC frequency as shown by the consistency of the results. For example, for CMB there were only two false-positive years (i.e., TCP was above average) for the low radial-growth group out of 23 observations and both (1958 and 1985) occurred when the first TCP occurred near the end of the growing season. The strength of the growth-climate relationships and the TCP reconstruction suggests that multi-century tree-ring records allow for the expansion of the temporal patterns of TCP well beyond the instrumental record and can provide insights into the natural range of variability. Here, the most noteworthy pattern is the extended period with minimal TCP from the early 1840s until the late 1870s. This period in the tree-ring record suggests much longer periods of minimal TCP have occurred that are unmatched in the instrumental record. Historic records of TC frequency (i.e., IBTrACS, Knapp et al. 2010) that partially coincide with this period support the likelihood of well-below average TCP, and Hudgins (2000) and Barnes (2001) also identify fewer TCs in North Carolina during this period. Beginning with the first year of historic record in 1851(Knapp et al. 2010) through 1876, 19 TCs were recorded for an average of 0.73 TCs/year, which is below the mean for the low radial-growth group (cf. Table 1). Additionally, 50 % of the years from 1851 to 1876 recorded no TCs in the 223 km rain fields (thus, no TCP), which is also a higher frequency than the low radial-growth group during 1953–2014 (cf. Table 1). These results further support the viability of variations in latewood growth-width to record TC frequency.

The data suggest that wide latewood bands—while good markers of higher TCP—are comparatively less viable predictors of above-average TCP years and subject to both false-positive and false-negative years. Examination of known above-average TCP years with narrow ring widths (false negatives) suggest that major TCP events occurring at the tail-end of the TC season may occur too late to promote a flush of latewood growth commensurate with the amount of TCP (e.g., during 1985, 1801 mm of TCP occurred on September 26–27, but reconstructed TCP was 115 mm). Years with large ring widths coincident with below-average TCP (false positives) may reflect instances where either singularly or in concert: 1) large TCs tracking outside the 223-km rain-field produce spiral bands with heavy precipitation (e.g., 1961 category 4 Esther tracked approximately 50 km outside the rain field); 2) heavy TCP occurred prior to June 1st with remnant ground water remaining during the onset of the latewood growing season (e.g., TS Beryl, May 29–30, 2012); and, 3) favorable conditions enhancing summertime moisture existed (e.g., +NAO), but TC steering patterns were away from the North Carolina coast (e.g., 2000).

Our results indicating latewood width accounts for over 50 % of TCP variability are strong, yet present an intriguing question of why a low percentage (12.5 %) of the total rainfall during TC season contributes to the majority of latewood growth. We suggest that the duration and amount of rainfall during TC events allows rainwater to penetrate the soil to greater depth than most non-TC-based rainfall events, and because of the typically large-scale nature of rainfall distribution, TCP can cause an overall rise in the regional water-table level where water cannot easily drain away laterally. More water reaching the root system, and the duration it remains, may trigger a summer–early fall growth flush and the production of latewood. The root structure of longleaf pine is well-suited to maximize this effect as Heyward (1933) analyzed their root system growing on deep sandy soils and found: 1) a taproot extending >4 m depth; 2) lateral taproots >1.5 m deep, beginning approximately 1.5 m from the central taproot; and 3) lateral roots extending >20 m from the tree base at a depth of 0.30 m until the end when they are >1 m below the surface. Thus, it may be the extensive lateral root structure that maximizes water uptake during TC-derived rainfall events, while the deeper roots ensure some degree of water during summers with limited rainfall.

The influence of TCs to ameliorate droughts has long been underappreciated and was not quantitatively documented until the late 1960s when Sugg (1968, p. 39) demonstrated the cessation of droughts following landfalling TCs and noted that “[t]here are no detailed accounts in our meteorological journals and texts”…and that “[t]here is only an occasional and very general reference to beneficial rains.” Despite this work, the influence of TCs as drought-enders escaped further examination for the next four decades until several studies (e.g., Maxwell et al. 2012, 2013; Brun and Barros 2013; Kam et al. 2013; Prat and Nelson 2013; Ortegren and Maxwell 2014) documented the rainfall contributions of North Atlantic TCs and their drought-ameliorating effects.

Maxwell et al. (2013) showed that during 1895–2011 up to 30 % of droughts occurring during hurricane season could be ended by a TC, but considerable variability occurred between 30-year periods regarding the drought-ending effects of TCs. Similarly, Prat and Nelson (2013) found that during 1998–2009 TC contributions to annual precipitation along the coastline of the Carolinas were 15–20 %, but during years with TC landfall, annual precipitation contributions could double.

Our study documents a means to examine the spatio-temporal variability in TCP well beyond the historic record. Additionally, these results suggest that pronounced periods of reduced TCP have a significant influence on radial growth rates of longleaf pine, but raise the question if suppression periods (i.e., small latewood bands recorded from ca. 1815–1875) also may be an artifact of ecological processes such as fire and wind damage. Damage from these events, however, is spatially inconsistent with minor-to-major affects to growth. In contrast, the uniform response of minimal latewood growth in our samples across sites, including the end to the below-normal growth regime in 1876, suggests the role of the mechanisms that affect TCP variability. Low latewood growth during 1815–1875 is coincident with sea surface temperature anomalies in the North Atlantic observed from reconstructed tree-ring data (Gray et al. 2004) and $\delta^{18}O$ isotope values from cellulose of longleaf pine latewood (Labotka et al. 2015) that are significantly correlated with the AMO, suggesting the influence of the AMO affecting tropical cyclone precipitation patterns because of suppressed TC occurrence. Positive (negative) phases of the AMO from 1871 to 2008 (Alexander et al. 2014) are harmonious with periods of above- (below-) average latewood growth observed at our study sites. Finally, the CFL chronology shows an abrupt shift from large to narrow latewood between 1814 (index value =1.59) to 1815 (0.19), which is coincident with the April 1815 Tambora eruption and consistent with the findings of Guevara-Murua et al. (2015) who found tropical cyclone frequency decreased for several years following major eruptions.

In summary, TCP is highly effective in drought cessation (Maxwell et al. 2013), critically important in the southeastern U.S. both ecologically and hydrometeorologically, and exhibits significant spatio-temporal variability based on the available instrumental records. Our TCP reconstruction suggests that instrumentally recorded TCP may not capture the true potential range of variability of TCP and thus serves as a viable method to complement other TC reconstruction approaches. This finding is meaningful for water management planning in the southeastern U. S. coastal plain as the period of low TCP in the 1800s cautions that one source of precipitation in the southeastern US can be minimal or absent for more extended periods than observed in the instrumental record. While the natural range of TCP is understudied and limited by length and quality of historic instrumental records, the proxy record contained in tree-rings of longleaf pine that occurs throughout the range of landfalling TCs from Texas to North Carolina offers a viable means to expand our understanding of the long-term variability of TCP in the U.S..

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