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Changes In Southeastern USA Summer Precipitation Event Types Using Instrumental (1940-2018) and Tree-Ring (1790-2018) Data

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LETTER

Changes in southeastern USA summer precipitation event types using instrumental (1940–2018) and tree-ring (1790–2018) data

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T J Mitchell¹ , P A Knapp¹ and T W Patterson² ¹ Carolina Tree-Ring Science Laboratory, Department of Geography, Environment, and Sustainability, University of North Carolina at Greensboro, Greensboro, NC, 27403, United States of America² School of Biological, Environmental, and Earth Sciences, The University of Southern Mississippi, Hattiesburg, MS, 39406, United States of AmericaE-mail: tjmitche@uncg.edu**Keywords:** summer precipitation, climatology, dendroclimatology, southeastern United States, longleaf pineSupplementary material for this article is available [online](#)**Abstract**

We examined short- and long-term changes in precipitation event types using instrumental (1940–2018) and tree-ring (1790–2018) data from North Carolina, USA. We documented the amount and frequency of summer (July–September) precipitation events using daily weather station data. Stationary front precipitation (SFP) represented 71% of total summer rainfall and SFP and convective uplift combined (i.e., quasi-stationary precipitation, QSP) represented 87%. SFP ($r = 0.52$, $p < 0.01$) and QSP ($r = 0.61$, $p < 0.01$) precipitation reconstructions from a montane longleaf pine latewood chronology both recorded significant declines during 1940–2018, matching the instrumental record. Conversely, no significant change in either SFP or QSP occurred during the full reconstruction indicating the instrumental decline was unmatched throughout 1790–1939. Our method demonstrates that variations in latewood growth can be attributed to specific precipitation event types and that the relative contribution of each event type can be quantified over a multi-century period.

1. Introduction

Longleaf pine (*Pinus palustris*) serve as useful proxy for reconstructing hydroclimate conditions including drought (Ortegren 2008), tropical cyclone precipitation (Knapp *et al* 2016), and streamflow (Harley *et al* 2017). Longleaf pine is principally represented in coastal plain environments, while few stands of longleaf pine exist at its interior range limit leading into the Appalachian Mountains foothills (Peet 2007). At these mountainous (hereafter montane) sites, longleaf pine grow on steep, rocky, south- and southwest-facing slopes (Patterson and Knapp 2016). In central North Carolina's Uwharrie Mountains, Mitchell *et al* (2019) reported a strong relationship between monthly precipitation and latewood growth that exceeds previously reported values throughout much of the species' range (Meldahl *et al* 1999, Foster and Brooks 2001, Henderson and Grissino-Mayer 2009), yet attribution to either specific event types or possibilities for reconstructing precipitation were not explored. Here, we examine the specific mechanisms for precipitation in central North Carolina using instrumental data and investigate multi-century changes of reconstructed precipitation from longleaf pine tree rings.

Summer precipitation event types for the southeastern US include frontal systems, cyclones (tropical and extratropical), and convective systems. Several studies (e.g., Li *et al* 2011, Li *et al* 2013) have shown that interannual variability in summer precipitation has increased since the late 1970 s, attributing this increase to greater variability of the North Atlantic Subtropical High. Similarly, Maxwell *et al* 2012, Powell and Keim 2015, and Skeeter *et al* 2019 suggest overall increases in intense precipitation events across the southeastern USA, yet precipitation event types were not always identified. Research quantifying precipitation amounts attributed to each precipitation event type is limited and either focused on extreme events or discusses changes to the

mechanism type. For example, Kunkel *et al* 2012 found that tropical cyclones contributed to 58% of summer extreme rainfall events for the entirety of the southeastern USA and for the eastern two-thirds of North Carolina, these tropical systems comprise the majority of the heaviest precipitation events (Konrad and Perry 2010). In the Northern Hemisphere, summer extratropical cyclones have declined (Chang *et al* 2016), and likely shifted to higher latitudes (Chang *et al* 2012, Scheff and Frierson 2012, Coumou *et al* 2015), yet information regarding precipitation changes in these systems over the southeastern USA is unknown. Studies using tree-ring data have reconstructed moisture conditions in the southeastern USA. Stahle *et al* 1988, Stahle and Cleaveland 1992, Maxwell *et al* 2012, and Pederson *et al* 2012 all reconstructed either spring or early summer precipitation. Seager *et al* 2009 analyzed interannual variability in May–October precipitation during the last millennium. Pederson *et al* 2012 and Seager *et al* 2009 noted that droughts during the late-20th and/or early-21st century were not unprecedented in the context of their study periods, while Maxwell *et al* 2012 determined that late-spring precipitation increased during the last century.

We address two questions regarding summer precipitation event types in central North Carolina. First, what are the relative amounts and frequencies of each precipitation event type during the instrumental record? Second, if significant changes in the instrumental record exist for specific precipitation event types, can these changes be placed in a longer-term, multi-century context using tree-ring data? Here, we: (1) examined daily weather maps and weather station data during summer (July–September) 1940–2018 to quantify the amount and frequency of each precipitation-producing event; (2) correlated latewood width with each precipitation event type; and, (3) reconstructed stationary front precipitation (SFP) and quasi-stationary precipitation (combined convective and stationary front activity; QSP) during 1790–2018. Our purpose is to demonstrate that by isolating precipitation event types, studies can determine either which type or types combined best represent fluctuations in latewood for use in reconstructions. Further, trends in specific precipitation event types can be identified even in instances where overall precipitation amounts remain unchanged.

2. Methods

2.1. Climate data and storm-type events

We collected monthly precipitation data during July–September from the National Climate Data Center (NCDC) for North Carolina Climate Divisions 3–8 and correlated summed July–September precipitation (hereafter, summer precipitation) with adjusted latewood (see section 2.3) identifying the strongest correlation with Climate Division 4 ($r = 0.64$, $p < 0.01$). Additionally, we collected daily summer precipitation data from Siler City, North Carolina (Station ID: USC00317924) to examine the storm type responsible for each precipitation event during 1940–2018. The Siler City data were the most complete data falling within Climate Division 4 and had high correlation with adjusted latewood ($r = 0.62$, $p < 0.01$) suggesting the station is consistent with precipitation variation recorded by the climate division. Siler City precipitation data were complete with the exception of 1981 and were replaced by data from nearby (~34 km) Asheboro, North Carolina (Station ID: USC00310286).

We collected daily weather maps from NOAA (available online at: library.noaa.gov/Collections/Digital-Collections/US-Daily-Weather-Maps) during 1940–2018 to analyze summer precipitation event types. For each precipitation day recorded at Siler City we visually classified event type from the weather map as either: (1) Convective, (2) Frontal (cold, occluded, stationary, warm), or (3) Tropical (tropical depression through hurricane tracking within 223 km (*cf* Matyas 2010, Knapp *et al* 2016) of the study area as indicated by IBTrACS (Knapp *et al* 2010)).

2.2. Tree-Ring data

We collected tree-ring data from three south- to southwest-facing open-canopy montane stands of longleaf pine in the Uwharrie Mountains (Dutchman Tract [DTL] 35.3598, –80.0284; Fraley Grove Tract [FTL] 35.4110, –80.0609; and Gold Mine Branch [GMB] 35.4159, –80.0361). The DTL data were collected in 2016, GMB in 2015, and FTL in 2015 and in 2019. Stands are located at elevations between 150–265 m on 15%–45% extreme bouldery slopes (Soil Survey Staff, Natural Resource Conservation Service 2019) with approximately 120 m of relief. Land-use history records indicate limited cutting in the early 1900 s and wildfire events occurred prior to the implementation of repeated prescribed burns beginning in 2010 (D. Walker, personal communication, US Forest Service 2019).

We collected two cores per tree at each site following standard dendrochronological sampling methods (Stokes and Smiley 1996) and recorded basal diameter, height, and location for each tree. Remnant stump slabs at FTL were collected to extend the chronology. The stump and core samples were scanned at high resolution (DPI ≥ 1200), measured at 0.001-mm precision using WinDENDRO (Guay 2012), and crossdating accuracy was assessed using COFECHA (Holmes 1983).

We developed the longleaf pine tree-ring chronology combining samples from Mitchell *et al* 2019 and cores and stumps sampled from FTL in 2019 ($n = 69$ samples, comprised of 53 live trees and 16 stumps). We examined standardization options and found that adjusted latewood (Meko and Baisan 2001) using negative exponential detrending produced the strongest climate signal. The adjusted latewood chronology (hereafter latewood chronology) has an interseries correlation of 0.571, a mean sensitivity of 0.505, ranges from AD 1740–2018 with an $EPS > 0.85$ (Wigley *et al* 1984) beginning at 1790 concurrent with our reconstruction period.

2.3. Statistical analysis

We examined the regional-scale representation of the latewood chronology with summer precipitation in the southeastern USA using KNMI Climate Explorer (Trouet and Van Oldenborgh 2013). Summer precipitation (CRU TS v. 4.03) at 0.50° gridded resolution (Harris *et al* 2014) was correlated with standardized latewood during 1940–2017 (2018 data unavailable) to closely approximate the Siler City station data.

Potential significant differences in precipitation amounts based on event type were analyzed using one-way ANOVA with Tukey post-hoc procedures (Tukey 1949). We correlated latewood with each event type precipitation amount using Pearson product-moment correlation and trends were examined in both event type precipitation amount and frequency using simple linear regression. SFP and QSP data were normally distributed, while the other event types were not. Because our focus was on reconstructing SFP and QSP, we selected parametric testing.

2.4. Reconstructed SFP and QSP

We developed a multiple linear regression model using stepwise selection ($\alpha = 0.001$) with latewood as the dependent variable and Siler City precipitation amounts by event type as the independent variables to determine the strongest combination of precipitation event types. Convective and stationary front precipitation were the only variables retained in the model as they were the two dominant precipitation event types during the summer with greatest explanatory power. Additionally, these events share characteristics including temporal duration, intensity, and upper-atmospheric support, therefore combining convective and stationary front precipitation into one precipitation type allows for the investigation of a more comprehensive precipitation metric. We developed two simple linear regression models using (1) SFP; and, (2) convective and stationary front precipitation combined (i.e., QSP) as the dependent variable and the standardized latewood widths from the chronology as the independent variable to reconstruct summer SFP and QSP during 1790–2018. The other precipitation event types were not used for reconstruction because they were either infrequent (tropical cyclone precipitation) and/or represented a low percentage of total summer precipitation (cold, occluded, and warm fronts).

We assessed the predictive reliability of the reconstructions using split-sample calibration and verification (Fritts 1991, Cook *et al* 1999) using the R package *treeclim* (Zang and Biondi 2015) to produce reduction of error (RE), coefficient of efficiency (CE), and Durbin–Watson values using 1940–1978 and 1979–2018 as the two periods. Both RE and the more rigorous CE statistics provide assessments of model reliability with RE values > 0 indicating greater skill than climatology and CE values > 0 indicating more skill than verification-period climatology (Cook *et al* 1999). Durbin–Watson values identify the extent of autocorrelation in the model with a value of 2.0 indicating no autocorrelation (Durbin and Watson 1951).

3. Results

3.1. Precipitation frequency

We identified 2259 precipitation events (i.e., days with precipitation) during 1940–2018 ($\bar{x} = 28.6$ events/summer, range 16–40, table 1, figure 1(a)). Frontal activity was the most dominant precipitation type and accounted for 1534 (67.9%) events (figure S1(a) is available online at stacks.iop.org/ERC/1/111005/mmedia) with this amount being represented by 1339 stationary fronts, 177 cold fronts, 14 warm fronts and 4 occluded fronts. Stationary fronts represented 87.3% of all frontal activity and 59.3% of all events (figure 1(b)). There were 691 convective events representing 30.6% of all observations (figure S1(b)), while tropical cyclone precipitation (34 events) represented 1.5% of the total (figure S1(c)). Frequency of stationary fronts significantly ($p < 0.01$) decreased (figure 1(b)) during the 79-year study period. Cold front and occluded front frequency experienced significant ($p < 0.05$) increases. No changes in frequency occurred when combining all events.

3.2. Precipitation amount

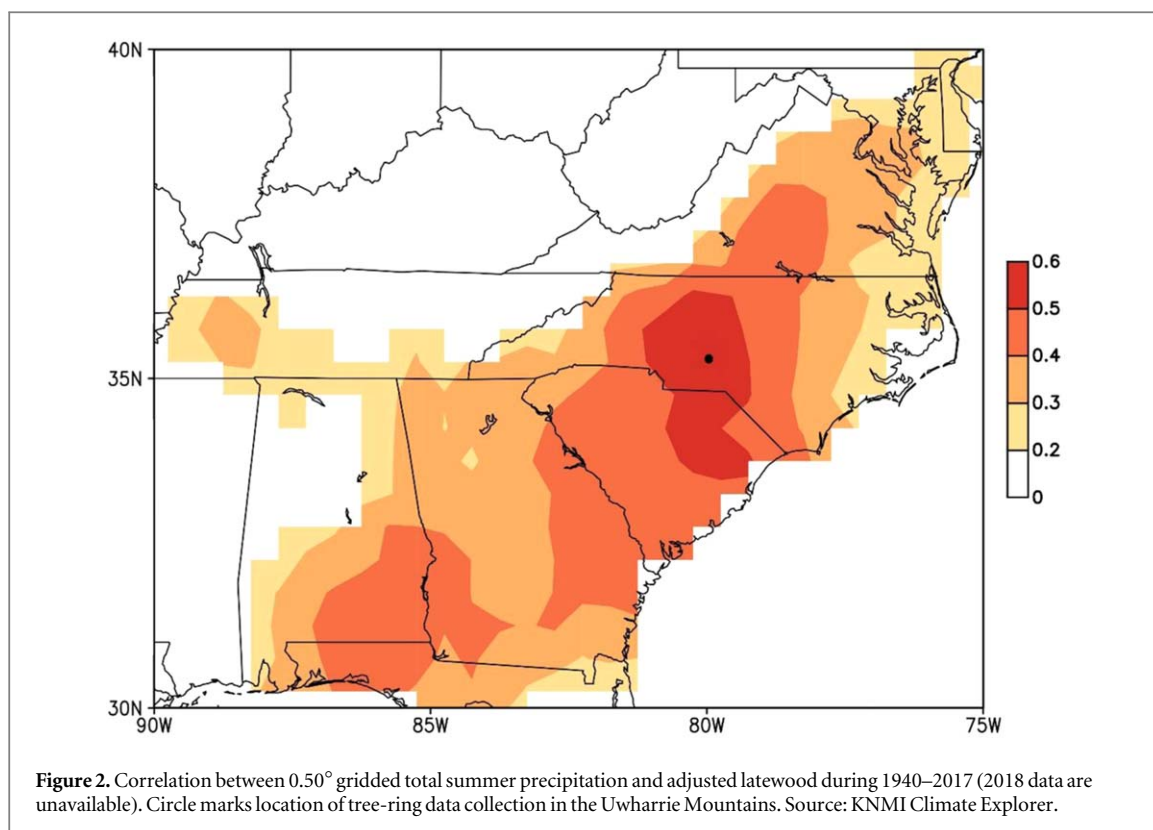
Mean summer precipitation during 1940–2018 was 345.3 mm (range 132.4–693.8 mm, table 1, figure 1(a)). Stationary fronts ($\bar{x} = 14.5$ mm/event) represented 71.4% of all summer precipitation (figure 1(b)) while cold fronts ($\bar{x} = 9.2$ mm/event) represented 6.0% of summer precipitation. Convective events ($\bar{x} = 6.0$ mm/event) comprised 15.1% of summer precipitation (supplemental figure 1(b)). Tropical cyclone events were



Table 1. Characteristics of summer precipitation events during 1940–2018. Data are from Siler City, NC, USA. ** denotes $p < 0.01$.

Event type	Frequency (precipitation days)	Mean precipitation (mm per day)	Percent of total precipitation	Correlation between precipitation amount and latewood
Convective	691	6.00	15.1%	$r = 0.41^{**}$
Frontal	1534	13.91	78.2%	$r = 0.49^{**}$
Cold	177	9.20	6.0%	$r = -0.14$
Occluded	4	20.58	0.3%	$r = -0.13$
Stationary	1339	14.45	71.4%	$r = 0.52^{**}$
Warm	14	10.73	0.5%	$r = -0.01$
Tropical	34	52.90	6.7%	$r = 0.38^{**}$

substantially wetter ($\bar{x} = 52.9$ mm/event), yet comparably infrequent (avg. one event per 2.3 years) representing 6.7% of the summer total (supplemental figure 1(c)). Stationary front precipitation amounts significantly ($p < 0.01$) decreased (figure 1(b)) during 1940–2018, and cold front and occluded front precipitation amounts significantly ($p < 0.05$) increased. Precipitation amount per stationary front event did not significantly change during 1940–2018. No change in precipitation occurred when combining all events (figure 1(a)), but there was a decline when combining QSP amounts (figure 1(c)).

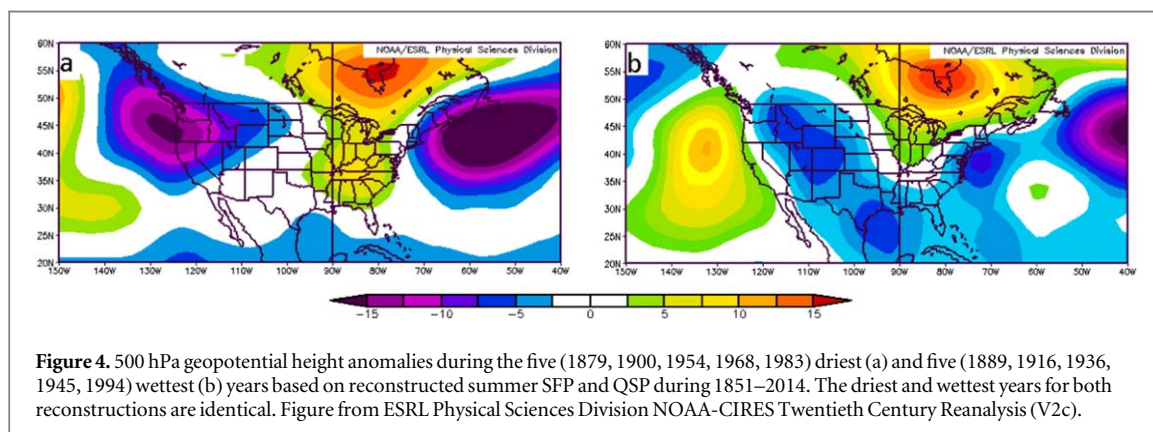
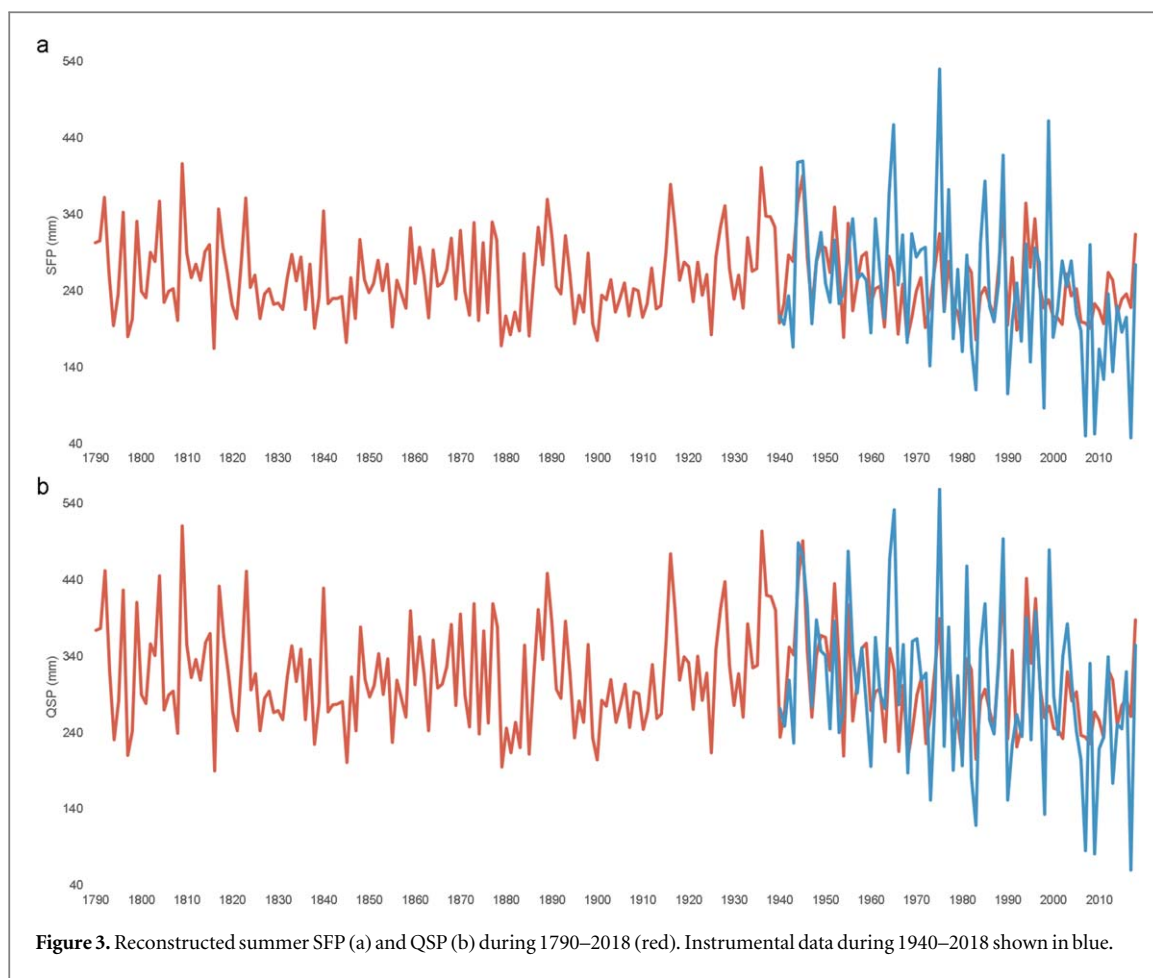


3.3. Tree-Ring data

Latewood correlated significantly (r ranges from 0.20 to > 0.50 , $p < 0.05$) with gridded total summer precipitation throughout the southeastern USA (figure 2). Significant correlations extended from Virginia to Alabama with the strongest correlations ($r = 0.5–0.6$) occurring in the lower piedmont region of North Carolina through northeast South Carolina.

There was considerable variability in the correlations between latewood and precipitation types during 1940–2018 (table 1). The strongest correlations with latewood existed with all precipitation types combined ($r = 0.62$, $p < 0.01$) and stationary front precipitation ($r = 0.52$, $p < 0.01$). Weaker significant correlations existed between latewood and convective precipitation ($r = 0.41$, $p < 0.01$) and tropical cyclone precipitation ($r = 0.38$, $p < 0.01$). No other event type had a significant correlation with latewood and thus were not further analyzed (table 1). Both SFP and QSP were successfully reconstructed during 1790–2018 (figures 3(a) and (b) and figure S2(a) and (b)). Calibration and verification results suggest stable climate-growth relationships during the 1940–2018 climate record thus suitable to develop reconstruction models. The chronology explains 20% of SFP (30% of QSP) variance over the 1979–2018 calibration period. RE and CE values for the corresponding 1940–1978 verification period are 0.38 and 0.03 (0.48 and 0.31). Reordering the periods and using 1940–1978 for calibration, the chronology explains 29% of SFP variance (40% of QSP), RE and CE values of the corresponding 1979–2018 verification are 0.29 and -0.02 (0.39 and 0.22). Durbin–Watson values for SFP were 1.90 (early period) and 2.37 (late period) and for QSP, 1.73 (early) and 2.28 (late). All Durbin–Watson p -values were > 0.05 indicating no significant autocorrelation.

We evaluated 500 hPa geopotential height anomalies to determine if synoptic conditions were consistent with either representative dry or wet years. We examined the mean conditions for the five (1879, 1900, 1954, 1968, 1983) driest and five (1889, 1916, 1936, 1945, 1994) wettest reconstructed SFP and QSP years (identical) using ESRL monthly climate composites during 1851–2014 (available online at: <https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/plot20thc.v2.pl>; Compo *et al* 2011). Dry and wet summers expressed distinctly different 500 hPa anomaly patterns (figures 4(a) and (b)). 500 hPa patterns during dry years were marked by upper-level ridging atmospheric conditions in the southeastern USA with troughs both on the northwest and northeast consistent to an Omega block pattern in the central USA (figure 4(a)). Conversely, the five wettest years were characterized by troughing in the southeastern USA with an area of upper-level divergence, moisture advection, and sustained precipitation over our study area (figure 4(b)).



4. Discussion

Stationary fronts are the dominant precipitation type during summer, accounting for 71% of total precipitation and best representing interannual variations in latewood widths. Convective precipitation was the second-most dominant event type and when combined with stationary front precipitation these two quasi-stationary mechanisms accounted for 87% of the total precipitation. Konrad and Perry 2010 and Kunkel *et al* 2012 found the majority of extreme precipitation events belong to tropical cyclones; results consistent with our findings (table 1). However, when examined with all other precipitation types tropical cyclone events represent a minor contribution to total precipitation at our site.

Montane latewood widths obtained from central North Carolina significantly ($p < 0.05$) capture variations in summer moisture throughout the southeastern USA (figure 2), providing an opportunity to create a proxy

record of precipitation variability at a regional scale. Our reconstructions relying on a single chronology developed from a single species identified a modest amount of explained variance for SFP (27%) and QSP (37%), and likely would capture more variability with increased sample size from multiple sites providing higher skill for event-type reconstructions.

The sole significant decrease in summer precipitation was associated with decreasing stationary front activity and the combined high-frequency, moderate-intensity precipitation characteristics of stationary fronts produced significantly ($p < 0.01$) more precipitation than any other event type. The quasi-stationary movement of stationary fronts and convective uplift can initiate precipitation events during a multi-day period, and our results indicate these events are effective at saturating the soil at depth and positively influence latewood growth. Longleaf pine have extensive lateral root structures (Heyward 1933) that may extract soil moisture during ground-soaking events associated with stationary fronts and stimulate latewood growth.

Both reconstructed SFP and QSP are marked by significant ($r = -0.29$ SFP, $r = -0.28$ QSP, $p < 0.05$) declines during 1940–2018 suggesting fidelity with the instrumental data, which also had significant declines ($r = -0.32$ SFP, $r = -0.30$ QSP, $p < 0.05$). No other multi-decadal period prior to 1940 had a significant decrease, suggesting the uniqueness in the decline of summer precipitation in the context of a multi-century reconstruction. Conversely, if variability in either SFP or QSP is viewed in a longer-term context (1790–2018), there has been no significant change. Our results suggest the likelihood of a continued drying trend with warming temperatures, yet the research modelling 21st century precipitation changes in the southeastern USA are inconclusive. Results for models projecting precipitation changes for the southeastern USA in the 21st century are inconsistent as Schoof (2015) found no changes, Karmalkar and Bradley (2017) found decreases with increasing temperatures, and Shields *et al* (2016) found no to slight increases.

The five driest and five wettest years of reconstructed SFP and QSP were supported by 500 hPa geopotential height conditions (figures 4(a) and (b)). Drier years were marked by the reduction of upper-level atmospheric support mechanisms for rainfall (figure 4(a)). Conversely, wetter years were marked by an upper-level low west of our study area and an upper-level high to the northeast providing conditions conducive to upper-level divergence and sustained precipitation (figure 4(b)). Despite an overall agreement between the reconstructions and instrumental data, our models did not detect all of the low extremes for SFP or QSP near the end of the historic record (i.e., some low SFP and QSP values coincided with near-average latewood widths). Specifically, two years (2008 and 2018) were marked by tropical cyclones and two years (2010 and 2014) by warm fronts. Both event types are uncommon, yet extreme events were concentrated near of the end of the study period. There was no significant decline in the climate–growth response indicated by 30-year moving averages of correlations between latewood and SFP and QSP (figure S3), suggesting the relationship is temporally stable. However, the latter-period CE value for the SFP reconstruction was marginally negative (-0.02), a result of the weaker correlation between SFP and latewood in the latter period. Warm front events were rare during 1940–2018 and produced little precipitation (table 1) with the exception of the 2010 and 2014 outlier ($SD > 2.0$) events, which produced >30 mm rainfall above the mean. The reconstructed CE value following the removal of these two events is 0.07 suggesting inclusion negatively impacted model strength.

Contextualizing instrumental hydroclimate changes with tree-ring reconstructions has been successful in the southeastern USA as studies have found that extreme events during the 20th or early 21st century are preceded when viewed from a multi-century proxy perspective. Maxwell *et al* (2012) examined the 20th century increase in springtime precipitation for eastern West Virginia finding that 50-year pluvial and drought phases of the instrumental record were exceptional but not unique during their 797-year reconstruction. Pederson *et al* (2012) reconstructed PDSI for the Apalachicola–Chattahoochee–Flint River Basin to examine early 21st century droughts, finding recent droughts were not atypical. Harley *et al* (2017) reconstructed streamflow for the Suwanee River in Florida, finding that historic variations exceeded current instrumental values, while Anderson *et al* (2019) found mixed results when comparing current flow extremes in their long-term reconstructions of rivers in the Tennessee Valley. These studies provide context to examine hydroclimate and demonstrate that current changes are not unusual when placed in a multi-century context. Conversely, our reconstructions of SFP and QSP indicate that the instrumental decline is unmatched when viewed from a multi-century perspective. Attribution to specific precipitation event types using latewood widths has been successfully shown for the North American Monsoon in southwestern USA and northwestern Mexico (Griffin *et al* 2013) and tropical cyclone precipitation in the southeastern USA (Knapp *et al* 2016). Here, our results have ecological and climatological implications as variations in latewood growth were better explained by either SFP or QSP events in comparison to all summer precipitation event types combined, suggesting an unequal influence of precipitation type during latewood formation.

5. Conclusion

Precipitation event types can be separated during the summer growing season and inclusion of all storm types may mask specific changes that occurred in event types. Our findings suggest that longleaf pine latewood widths have strong fidelity with summer stationary front and convective precipitation, allowing the reconstruction of both SFP and QSP amounts. Further, these results show precipitation amounts reflected by latewood width variability were specific to two event types and suggest that attribution to specific event types may reduce error in tree-ring based precipitation reconstructions. In our study, latewood widths significantly ($r = -0.28, p < 0.05$) decreased during 1940–2018 suggesting an overall decrease in total precipitation, yet the instrumental precipitation record did not show a significant change. Here, a reconstruction that did not separate event types would erroneously show a significant ($p < 0.05$) decline in total precipitation during 1940–2018 (figure S4). However, by isolating relationships between event types and latewood, more precise assessments can be made to determine where potential changes have occurred such as the decrease in stationary front precipitation that we identified. Further, these changes in event types can be placed in a multi-century context to determine either their rarity or uniqueness.

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