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A long-term perspective on a modern drought in the American Southeast

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Abstract

The depth of the 2006–9 drought in the humid, southeastern US left several metropolitan areas with only a 60–120 day water supply. To put the region's recent drought variability in a long-term perspective, a dense and diverse tree-ring network—including the first records throughout the Apalachicola–Chattahoochee–Flint river basin—is used to reconstruct drought from 1665 to 2010 CE. The network accounts for up to 58.1% of the annual variance in warm-season drought during the 20th century and captures wet eras during the middle to late 20th century. The reconstruction shows that the recent droughts are not unprecedented over the last 346 years. Indeed, droughts of extended duration occurred more frequently between 1696 and 1820. Our results indicate that the era in which local and state water supply decisions were developed and the period of instrumental data upon which it is based are amongst the wettest since at least 1665. Given continued growth and subsequent industrial, agricultural and metropolitan demand throughout the southeast, insights from paleohydroclimate records suggest that the threat of water-related conflict in the region has potential to grow more intense in the decades to come.

Keywords: Southeastern US, water supply, water conflict, paleohydroclimate, tree-ring analysis

S Online supplementary data available from stacks.iop.org/ERL/7/014034/mmedia

1. Introduction

Drought is a pervasive phenomenon throughout much of North America with profound ecological and societal implications (Allen *et al* 2010, Breshears *et al* 2005, Hursh and Haasis 1931, Manuel 2008). Although much attention has been devoted to forecasting the frequency and magnitude of drought in semi-arid western North America, recent moisture deficits in the southeastern US have renewed water management challenges that underscore the need to better understand drought processes in humid, subtropical regions (Knight 2004, Seager *et al* 2009). Notably, the droughts of

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1986–8, 1998–2002 and 2006–9 caused severe crop damage, disruptions in electricity generation and water shortages, which prompted water restrictions and multi-state legal conflicts (Cook *et al* 1988, Manuel 2008). This is particularly evident in the state of Georgia, where droughts during the 1980s and 1990s occurred concomitant with a 50% increase in population and a 35% increase in groundwater withdrawal (Fanning 2003). During the 2006–9 drought, many municipal water supplies throughout the region, including Atlanta, were reduced to 60–120 day capacities (Goodman 2007, Campana *et al* 2011).

Given recent water shortages and emerging challenges, Georgia and adjacent states have revised water management plans to include greater focus on conservation and efficiency (MNGWPD 2009). Unfortunately, many water allocation plans are based on limited 20th century records and capture a narrow range of potential moisture variability (e.g., Stockton and Jacoby 1976). To plan for an expanded range of natural and anthropogenically forced variability, water managers have begun to incorporate tree-ring based hydroclimate reconstructions to place recent droughts in a long-term context (e.g., Cook and Jacoby 1983, Cook *et al* 2010, Gray *et al* 2004, Maxwell *et al* 2011, Stahle *et al* 1988, Stockton and Jacoby 1976, Woodhouse and Lukas 2006). Tree-ring based perspectives suggest that the 20th century has been relatively moist with respect to the last millennia in the eastern US and that although recent droughts have had significant societal implications, they are in most cases less severe relative to prior centuries (Cook *et al* 2010, Maxwell *et al* 2011, McEwan *et al* 2011, Seager *et al* 2009).

Here, we reconstruct drought, as expressed by the palmer drought severity index (PDSI), for the headwaters of the Apalachicola–Chattahoochee–Flint (ACF) river basin. PDSI is a good estimate of moisture availability because it estimates available soil moisture based upon rainfall, evapotranspiration, runoff and previous soil moisture estimates (Palmer 1965). Tree-ring work in the southeastern US includes the reconstruction of rainfall from bald cypress (Stahle and Cleaveland 1992, Stahle *et al* 1988) and a multi-species reconstruction of PDSI in the southern Appalachian Mountains (Cook *et al* 1988). We address the implications of drought history for water management for the ACF system by incorporating the first tree-ring records throughout the river basin (figure 1). Our multi-species network of tree-ring chronologies is denser and more diverse than previous studies, allowing us to better capture ACF drought variability, improve model calibration and validation statistics (Cook and Pederson *et al* 2010, Maxwell *et al* 2011), and provide an opportunity for placing the region's recent drought woes in the context of the last 350 years of climate variability.

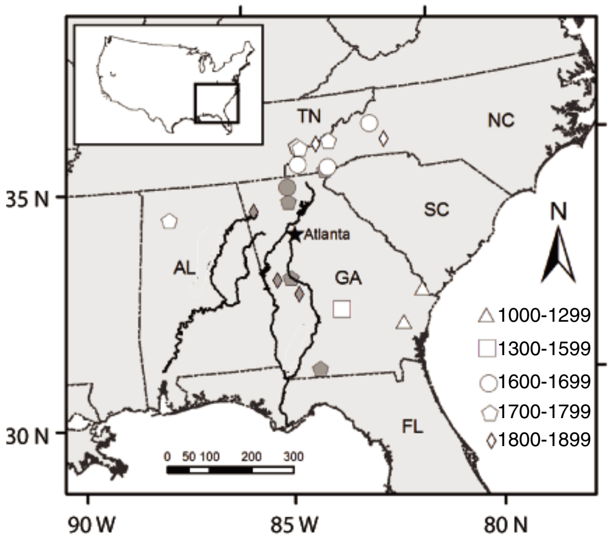

Figure 1. Map of tree-ring locations in the ACF river basin used for PDSI reconstruction. Different symbols represent the period for the beginning year of each chronology. Shaded symbols represent collections since 2008 or the first within ACF river basin. The Chattahoochee and Flint Rivers drain the climatic division in north-central Georgia that is reconstructed. The Apalachicola River begins at the confluence of the Chattahoochee and Flint Rivers at the Florida–Georgia state line.

2. Materials and methods

All series were processed using standard dendrochronological techniques (Fritts 1976, Holmes 1983, Stokes and Smiley 1968) and augmented with existing collections from the International Tree-Ring Databank (ITRDB) (NCDC 2011a) (table S1 available at stacks.iop.org/ERL/7/014034/mmedia), including collections from D Stahle (no. = 7), E Cook (4), D Duvick (1) and J Young (1). Raw-ring widths from all collections were standardized using the same methodology via the program ARSTAN, which stands for autoregressive standardization (Cook 1985, Cook and Kairiukstis 1990, Cook and Krusic 2011). The purpose of standardization is to remove or reduce non-climatic influences in ring-width series, such as the allometric growth trend or growth patterns resulting from changes in local competition. First, all series were transformed using the adaptive power transformation, which stabilizes the variance of tree-ring series through time (Cook and Peters 1997). Because many series exhibited radial increment patterns typical of disturbance in closed-canopy forests (Lorimer 1985), individual series were standardized using a flexible curve (Pederson *et al* 2004). The 'Friedman Super Smoother' was the primary option used to reduce the influence of disturbance in each series (Buckley *et al* 2010, Friedman 1984). The Friedman Super Smoother sometimes caused distortion at either end of a series where ring-width measurements would trend up (down) while the standardization curve would trend down (up), resulting in an artificial upward (downward) trend in the resulting tree-ring index. In those cases, a cubic smoothing spline two-thirds the length of the series was used to reduce end-fitting issues (Cook and Peters 1981). The chronologies were stabilized in order to account for varying sample depth through time. The rbar (average correlation between raw ring-width series) weighted stabilization method was used to stabilize variance in series where three or more trees are present for nearly all of the chronology length. In chronologies with less than three trees at the beginning of the chronology, variance was stabilized using a combination of rbar weighted and one-third spline methodology (Cook and Krusic 2011, Osborn *et al* 1997). Finally, series ring-width index values were calculated using a robust biweight mean function (Cook 1985).

Chronology quality was interpreted using the expressed population signal (EPS) statistic, which indicates the extent of common variance in a chronology (the population signal) over time. Usable chronology length was determined according to the EPS threshold of 0.85 (Wigley *et al* 1984). Standard or ARSTAN chronologies were used as potential climate predictors. In tree-ring records with little evidence of stand dynamics, standard chronologies are used (table S1 available at stacks.iop.org/ERL/7/014034/mmedia). Conversely, ARSTAN chronologies were selected for records with evidence of radial increment patterns typical of disturbance. Through autoregressive modeling, ARSTAN chronologies are useful for examining long-term variability as they retain much of the common growth variability (assumed to be exogenous) and reduce much of the stochastic or endogenous disturbances experienced by surviving trees in closed-canopy forests, making them useful for the examination of long-term variability (Cook 1985).

Newly developed and existing ITRB chronologies within 400 km of Atlanta were selected for chronology length (figure 1). Chronologies north of Alabama and west of the Tennessee–North Carolina border were excluded as potential predictors as spatial analysis indicates diverging trends in moisture availability since 1958 (Kallis *et al* 2009). An examination of retained records was conducted through principal components regression (Cook and Kairiukstis 1990). We only included chronologies that improved the per cent variance of the north-central Georgia climate division PDSI (NCDC 2011b) explained by the model during the common period (1895–76) of the final reconstruction. The remaining set of tree-ring predictors ($n = 23$) was reduced to orthogonal principle components (PCs) using principle components analysis. Median segment length of all retained chronologies is 232 yr (table S1 available at stacks.iop.org/ERL/7/014034/mmedia).

Average April–August PDSI was reconstructed based upon the common response of the retained tree-ring network. Because prior year's climate and growth can influence current year ring formation (Kagawa *et al* 2006, Trumbore *et al* 2002), current year's ring index (t) and prior year's ring index (a lag of $t + 1$) was used for each chronology. This results in a pool of 46 candidate predictors. Model selection was based upon a two-tailed correlation at the 90% confidence level and for a maximum adjusted r-square. Following these criteria, 29 potential predictors were retained, seven of which were lagged. Only six of these predictors entered slightly below the 95% confidence level at $p = 0.055$–0.082.

A nesting procedure was used to extend the length of the reconstructions where shorter chronologies exit as potential predictors moving back in time (Cook *et al* 2004, Meko 1997). Nest length is determined by the usable length of the shortest tree-ring record within each nest. For example, while the Lynn Hollow *Quercus velutina* record extends to 1743, an EPS of 0.85 is not achieved until 1854 (table S1 available at stacks.iop.org/ERL/7/014034/mmedia). Thus, the common period nest for our tree-ring network is 1854–1977; 1977 is the last year of the Linville Gorge record. The final reconstruction is developed from the model calibrated on the full 1895–76 common period between our tree-ring network and the instrumental PDSI data. Split calibration–verification was used to test the stability of each nest over the 1895–76 common period with the instrumental data; one year of the common period is lost because of the lagged effect between climate and ring width. First, a tree-ring based estimate of PDSI was calibrated on the 1895–1922 period and then verified on the 1923–76 period. To complete verification to the stability of our reconstruction, we then performed a calibration on the 1923–1976 period and verified on the 1895–1922 period. All nest models were independently verified on a subset of the common period using the reduction of error (RE) and coefficient of efficiency (CE) statistics where positive values indicate predictive skill (Cook *et al* 1994, Fritts 1976, Wigley *et al* 1984). Nests that accounted for 30% or less of the instrumental record or had negative RE and CE statistics were considered insufficient for reconstruction and were omitted. All usable nests were first normalized and then stitched together to create a continuous, normalized time series. This series was then re-scaled according to the mean and standard deviation of the instrumental PDSI data from 1895 to 2009; the reconstruction was completed before the 2010 season of reconstruction was complete. The north-central region of Georgia is the focus of this reconstruction as it includes the headwaters and upper reaches of the ACF basin. The other climatic divisions of western Georgia were tested versus the full nest to investigate their representativeness of the ACF basin.

3. Results

Seventeen nests spanning 1634–2001 passed the verification criteria for the final reconstruction (table S2, figure S1 available at stacks.iop.org/ERL/7/014034/mmedia). Therefore, to place the most recent drought in context, instrumental data is added from 2002 to 2010. For the 1854–1976 common period nest, tree-ring records account for 58.1% annual variance of the 1895–1976 instrumental data (figure 2(a)). The weakest and earliest nest, 1634–64, accounted for only 35.3% of annual variance and only contains one record from north Georgia. Therefore, climatic variability analyses are only conducted on the 1665–2010 period save for the regime shift analysis, which was limited to the tree-ring based reconstruction (figures 2(b), 3, table 1). Violin plots, which combine box plots and density estimates in displaying data structure, indicate that these tree-ring records capture most of the variability in the instrumental PDSI values, with the expected over-representation of extreme wet years as moderately wet years (figure 3(a)). This source of error is typical for most tree-ring based reconstructions because additional moisture availability beyond a certain threshold does not always lead to increased radial growth (Fritts 1976). Overall, we do not observe significant bias in the reconstruction—the reconstruction captures as much variance

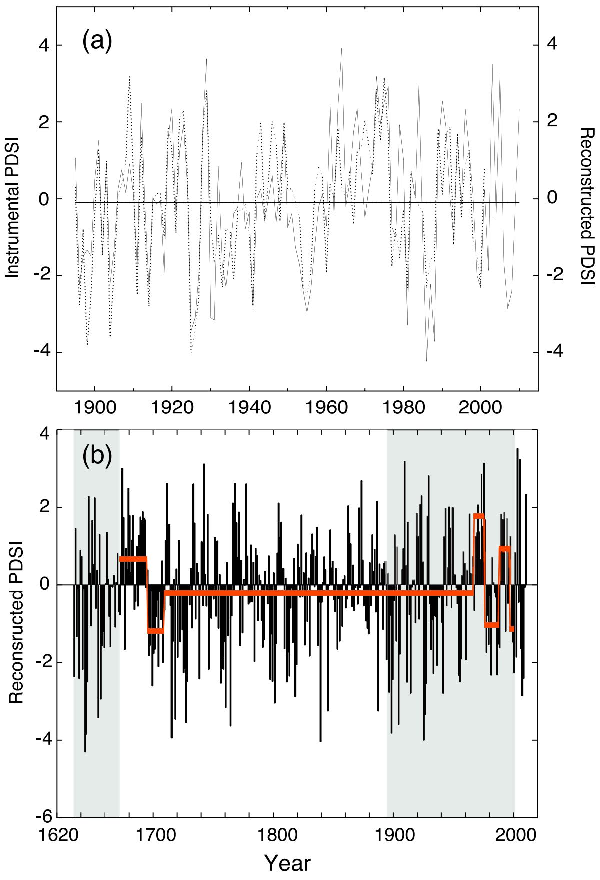

Figure 2. (a) Instrumental PDSI (solid line) versus reconstructed PDSI (dashed line) from 1895 to 2001. Instrumental from 2001 to 2010 is shown to reflect the 2006–9 drought. (b) Bar plot of ACF drought from 1634 to 2010. Shading in the 17th century highlights the era with only one ACF chronology. The shaded area on the right reflects the 1895–2001 calibration period. Bars in the white area after 2001 are instrumental data from 2002 to 2010. The orange line shows the regime shifts in ACF drought history between 1665 and 2001 as calculated by the methodology of Rodionov (2004). We limit the regime shift detection to this period so the analysis is performed only on replicated tree-ring records from within the ACF basin.

on average for dry events as for wet events (figure S2 available at stacks.iop.org/ERL/7/014034/mmedia). Finally, the reconstruction here represents much of the drought variation throughout the ACF basin, including seasonal transition from peak to low flow, or hydrological recession, in north Georgia basins (supplemental material, figure S3 available at stacks.iop.org/ERL/7/014034/mmedia). While it accounts for the lowest amount of annual, April–August drought variation in the lower reaches of the basin (r^2 for the southwest climatic division of GA = 46.1%), the full nest accounts for 53.2% and 62.2% of the annual variance for the northwest and west-central climatic divisions, respectively.

Analysis of dry and wet events from 1665 to 2010 shows a broad range of variability at annual to multi-decadal scales. The 20th century is among the wettest 100 yr periods observed in our reconstruction and had a higher ratio of wet to dry years than either the 18th or 19th centuries (figures 2(b), 3(a), (b); table 1). The 1968–1976 wet event is unmatched except for a brief wet event during the early 18th century and the longer event in the late-17th century. Regime shift detection (following Rodionov 2004 using a 10 yr cutoff with an $\alpha = 0.05$) indicates only three significant, positive regimes between 1665 and 2001 (the tree-ring only period with good replication in the ACF Basin): 1665–95, 1968–76 and 1989–97 (figure 2). Average reconstructed PDSI for 1968–76 is the highest of the positive regimes at 1.76 and is greater than 1 standard deviation from the long-term mean. In contrast, the benchmark 2006–8 drought, while severe, is surpassed at least once during each previous century and three times during the 1696–1760 and 1904–21 periods and does not appear to be remarkable in the broader context of 4 yr reconstructed PDSI averages in the record (figures 2 and 3(c)); in fact, it falls short of the previous 'benchmark' drought from 1986 to 1988.

Table 1. Ratio of 75th quantile wet years to 25th quantile dry years per century. Values greater than 1.0 represent a higher portion of wet years occurred in that century than dry years. Also listed is the number of moderate and extreme single-year events per century equal to or greater than ±1 and 2 standard deviations from the mean. This analysis is performed on the 1665–2010 portion of the reconstruction. Analyses for partial 17th and 21st centuries are shaded and based on 36 yr and 11 yr, respectively.

Century	17th	18th	19th	20th	21st
Quantile ratio	3.50	0.68	0.86	1.39	0.67
+2 Std dev	0	1	0	2	2
+1 Std dev	10	11	7	17	1
−1 Std dev	4	18	13	18	5
−2 Std dev	0	5	5	3	0

Reconstructed annual values and violin plots indicate increased climatic variability during the 20th century, the entire 18th century, and between 1665 and 1714 (figures 2(b), 3(a)). Both plots also reveal relatively dry conditions with low variability during the latter half of the 19th century. Analysis of the climate distributions formed from moving 50 yr windows over the length of the chronologies demonstrates that these distinct differences in climate variability are not artifacts of the 50 yr periods chosen for the violin plots (figure S4 available at stacks.iop.org/ERL/7/014034/mmedia).

4. Discussion

4.1. Drought variability in the ACF river basin

Our reconstruction shows that the recent drought that threatened the ACF region water supply system was shorter in duration than droughts of the past. Most notably, the 1696–1820 era is punctuated by frequent, extended droughts. Our results confirm the findings of the first reconstruction of drought in the southern Appalachian Mountain region, which indicates that the mid-18th and early 20th centuries were the driest eras since 1700 CE (Cook *et al* 1988, Seager *et al* 2009, Stahle *et al* 1988). This result is also apparent in the reconstruction of spring rainfall in south-central and southeast Georgia (Stahle and Cleaveland 1992). Results here extend the

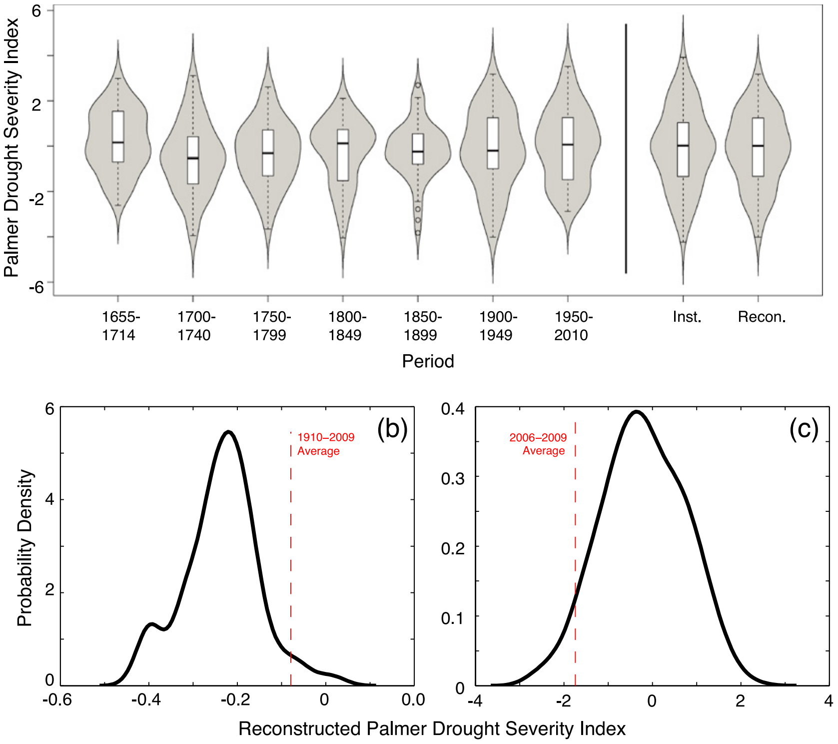

Figure 3. (a) Violin plots for 50-yr segments and for the 1895–2001 common period of the reconstructed and instrumental values, showing data quartiles and outliers (box-and-whisker plots) and probability densities (shaded gray areas). Because more reliable values during the 17th century begin in 1665, the 50-yr period from 1665–1714 is analyzed. (b) Probability density of 100-yr periods from 1665–2009 in black with 1910–2009 in red and (c) 4-yr periods from 1665–2009 in black with the 2006–2009 benchmark drought in red.

southern Appalachian Mountain reconstruction by revealing a substantial drought from 1696 to 1709 and an era of extended moisture variability in the 17th century. Like the Cook *et al* (1988) reconstruction, the instrumental PDSI value for the 1986 drought is unsurpassed in the new reconstruction.

Analyses of a range of instrumental atmospheric and oceanic parameters indicate that dry intervals are forced by local climate anomalies and to a lesser extent by synoptic-scale variability in the Pacific and Atlantic Oceans (Anchukaitis *et al* 2006, Kurtzman and Scanlon 2007, Seager *et al* 2009). Notably, Anchukaitis *et al* (2006) found that the influence of the Pacific Ocean was non-stationary in this region. While it is difficult to anticipate how anthropogenic warming will alter ocean–atmosphere climate dynamics, strengthening of ENSO or other climate dynamics could lead to extended drought or pluvial conditions.

4.2. Societal implications

Water shortages have recently returned as issues of prominence for Georgia, Florida, Alabama and rural and metropolitan communities in the tri-state ACF system. For example, Shepherd (1998) assessed drought planning in the Atlanta region in the 1990s and found weak plans with poorly defined goals and objectives, and a general lack of awareness or interest in drought. The 2006–9 drought brought the issue of water scarcity into sharp focus. The reality of water conflict emerged among Georgia, Alabama and Florida, with legal conflicts arising over water resources in US Army Corps of Engineers' Lake Lanier reservoir (Florida 2009). The battle over these resources continues at the time of writing; recently, a 2009 ruling which decided that supplying water to metropolitan Atlanta was not the priority for the Lake Lanier reservoir (and gave a 3 yr window to obtain congressional approval for water withdrawals to continue) was overturned to allow withdrawals to Atlanta on a demand-driven basis, forcing the Corps to develop a new water allocation plan within a year (US Court of Appeals 2011). For Georgia, the 2007 drought was particularly acute, and 'one of the driest recorded' (Georgia Water Council 2008); the drought and subsequent ruling have left the state struggling to find options, legal or otherwise, to meet water demand (Jackson 2011).

Our analysis demonstrates that the southeastern US can experience droughts equally or more severe than those over the instrumental record and has the potential to experience these kinds of water shortages in the future. Further, the frequency of extreme drought events in the first half of the 20th century (and relatively rare until the 1980s) was not anomalous, as similar droughts occurred in the first halves of the 18th and 19th centuries (figures 2(b), 3(b), (c), table 1). Perhaps more important is the notably high frequency of moderately dry years and low occurrence of moderately wet years during the 18th and 19th centuries. Beyond the immediate impacts of a rainfall deficit, the impacts of drought are diffuse and accumulate slowly (Kallis 2008), and are not necessarily felt within a climate year. Continued rainfall deficits that lead to agricultural droughts (only impacting crop production), can lead over time to pervasive hydrological drought, where surface and groundwater shortages manifest in a variety of socio-economic impacts (Wilhite and Glantz 1985). Though the recent drought in Georgia was not historically anomalous, these socio-economic impacts were intensified by high population numbers and significant water usage (Campana *et al* 2011). The Metropolitan North Georgia Water Planning District predicts nearly 60% growth in water demand in the region by 2035, even assuming an aggressive conservation gain of ca. 20% in per-capita water use (MNGWPD 2009). This growth will result in a demand of 3.8 million cubic meters per day, well above the current permitted supply of 3.3 million cubic meters per day and requiring the development of several new water sources (MNGWPD 2009). Increasing water use paired with extended periods of drought would make it difficult to reconcile societal needs with those of watershed ecosystems, and could lead to more persistent conflicts like those which arose in Florida between the US Army Corps of Engineers and the Endangered Species Act (Florida 2009). For example, Florida's Apalachicola Bay is a freshwater-driven estuary at the mouth of the Apalachicola River whose freshwater balance integrates the basin-wide effects of municipal and agricultural consumption. Saline intrusion brought by the disruption of the Apalachicola River flow has disastrous effects on the estuary's freshwater ecology, as well as on the important regional oyster fishery (Huang 2010, Monaco and Livingston 2003).

Drought is not the only signal our reconstruction provides insight into in the context of long-term dynamics of reconstructed PDSI. While tree-ring data is typically less reliable for reconstructing wet periods, our record decently captures the 1919–24, 1960–76 and 1989–92 wet events (figure 2(a)). The frequency of years with abundant moisture during the latter part of the 20th century is only matched in duration and intensity by a handful of events in the late-17th and early 18th centuries, and the 1768–71 event (figure 3; table 1). The difference in the frequency of wet events between the pre- and post-instrumental period is clear. Even acknowledging the representation of some strong wet anomalies as less severe (drier) in the reconstruction than in actuality, it is clear from the density of wet events that the recent instrumental history portrays the wettest period since the late-1600s, especially considering the wet regime shift from 1968 to 1976 (figures 2(b), 3(a), (b), table 1). This further demonstrates the insight into climate history afforded by tree-ring reconstructions, and the climate variability for which the Atlanta region may need to be prepared.

The latter 20th century instrumental data, upon which regional water supply management decisions are based, is characterized by frequent wet events that are not representative of much of the prior 300 yr. Investigations of long-term drought in other regions of the southeastern US have similar findings: the 20th century appears wetter in the context of the last 400–1000 years (Cook *et al* 2010, McEwan *et al* 2011, Seager *et al* 2009, Stahle *et al* 1988), although it should be noted that Cook *et al* (2010) and Seager *et al* (2009) are not independent from our reconstruction as they utilize some of the same proxy data. An analysis of two independent tree-ring records in our study area generally supports the indication that the 20th century was wetter in the context of the last 250 years (figure S5 available at stacks.iop.org/ERL/7/014034/mmedia). This is particularly true for the 1956–84 era (Stahle *et al* 1988), the era recently suggested to be the target for reservoir storage for the Atlanta watershed region (Florida 2009). A diverse body of literature suggests that better availability of water resources might perversely lead to greater vulnerability to drought, by not providing the impetus for developing efficient resource use or adaptation to severe or prolonged water shortage (Dahlin 2002, Hornbeck and Keskin 2011, Lucero 2002). Moreover, long-term evidence from paleoclimatology and archeology indicates that political, social and economic institutions dedicated in the management of complex water infrastructure may be vulnerable to droughts or flooding that exceed their social or technical capacity for resilience in the face of unexpected or extreme events (e.g. (Lucero 2002, Buckley *et al* 2010)). In sum, it may be prudent for water resources planning in the American Southeast to consider the drier centuries of climate variability that precede current experience and instrumental record.

The climatic patterns revealed here—the pervasively drier 18th century, the weak wet periods of the 19th century, and the high frequency of extreme drought in the early 18th and 19th centuries—provide valuable baseline scenarios for simulation of inter-annual climate variability and water resources planning that do not appear in the more recent, relatively wetter instrumental records. Although non-stationarity of the climate system could cause climate variability to differ from what has occurred historically Milly *et al* (2008), this reconstruction provides a broader representation of the potential range of climate variability than is available from the instrumental record alone, and thus is a valuable tool for understanding the context of extreme events to which our infrastructure must be able to adapt (Harou *et al* 2010). With these reconstructions as a resource, we are planning applied social research into the role that paleo-climate data can play in water resources planning, as has been done in other states (e.g., in Arizona—Block *et al* 2008).

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