A 1,461-Year Growing Season Precipitation Reconstruction for the Carolina Coastal Plain

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A 1,461-YEAR GROWING SEASON PRECIPITATION RECONSTRUCTION FOR THE CAROLINA COASTAL PLAIN
A 1,461-YEAR GROWING SEASON PRECIPITATION RECONSTRUCTION FOR THE CAROLINA COASTAL PLAIN

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Arts in Geography

by

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Abstract

A recollection and dating of ancient cypress trees and subfossil logs was performed at Black River, North Carolina, and the separate Black River, South Carolina. The new updated and expanded chronologies date from AD 365 to 2010 and 549 to 2010, respectively. Baldcypress ring-width chronologies are dominated by high inter-annual to decadal variability and do not tend to capture century scale fluctuations in tree-ring growth that could be associated with centennial scale change in climate. The tree-ring chronologies were standardized with a technique designed to preserve low frequency variance known as regional curve standardization. The two chronologies were averaged into a single baldcypress growth history for the coastal plain of North and South Carolina. The averaged coastal Carolina and Black River, NC chronologies were used for reconstructions of growing season precipitation and provides estimates of centennial scale dryness during the Medieval Climate Anomaly and early Colonial Era and wetter than average conditions during the 8th, 16th and 17th centuries, the latter possibly associated with the Little Ice Age. A long-term trend of improved tree growth and greater reconstructed growing season precipitation is observed from approximately 1750 to 2010, even though the instrumental precipitation data available from 1895-2005 do not exhibit significant linear trend. It is possible that the recent trend in tree growth is a function of anthropogenic disturbance to our baldcypress collection sites (including logging, land clearing of the drainage basin, atmospheric deposition of nutrients, carbon dioxide fertilization), or even the standardization procedures used for chronology development. However, the Medieval Climate Anomaly, Little Ice Age, and the trend toward greater wetness in the 20th century have been detected in hydrological proxies elsewhere in North America. These centennial scale changes in
southeastern USA precipitation need to be tested with additional climate proxies and historical documentary evidence.
This thesis is approved for recommendation

To the Graduate Council.

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“Blessed is the man that trust in the LORD, and whose hope the LORD is. For he shall be as a tree planted by the waters, and that spreads out her roots by the river, and shall not see when heat comes, but her leaf shall be green; and shall not be careful in the year of drought, neither shall cease from yielding fruit.”

Jeremiah, 17:7-8
DEDICATION

This edition of *A 1,461Year Growing Season Precipitation Reconstruction for the Carolina Coastal Plain* is dedicated to Tom, Karen and Morgan Perkins who have always believed in me, as well as my loving husband, David, and dogs, Calvin and Alladin.
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A 1,461-Year Growing Season Precipitation Reconstruction for the Carolina Coastal Plain

I. Introduction

a. Study Objective

Baldcypress (Taxodium distichum) tree-ring chronologies in the Carolinas provide a long term perspective on growing season climate variability (Stahle et al., 1988). This species is a slow growing, long lived deciduous conifer native to the floodplains of the southeastern United States, Mexico, and Guatemala (Stahle et al., 2012) and has been proven to be an accurate proxy for the reconstruction of climate (Bowers 1973; Stahle and Hehr 1984 and Stahle et al., 1985a). The two longest baldcypress chronologies currently available were developed at Black River, North Carolina, and the separate Black River, South Carolina. These sites were last collected in the mid-1980’s and early-1990’s making an update necessary in order to better assess the nature and causes of climate variation in the southeastern United States and to possibly detect anthropogenically forced hydroclimate change in this region.

Baldcypress ring-width chronologies are dominated by high inter-annual to decadal variability and do not tend to capture century scale fluctuations in tree-ring growth that might be linked with low frequency climate changes (Stahle et al., 2012). There are two main schools of thought for the absence of long timescale climate change in baldcypress, the first dealing with the statistical techniques used to optimally detrend the raw ring-width measurements by removing the biological growth trend. This removal of the biological growth trend removes much of the low frequency variability. The other hypothesis is the lack of low frequency variability may be a function of the baldcypress growth habitat (Stahle and Cleaveland, 1992). The unique frequently flooded environment (Figure 1) and physiological response of
baldcypress trees appears to create a kind of “natural high pass filter” that allows the trees to adapt to centennial-scale changes in the mean water level (Stahle et al., 2012). The fine root hairs that baldcypress trees adventitiously sprout from the stem, upper root system and the vertical root formations also known as “knees” (see Figure 2 for a photo of the baldcypress knees) might track long-term changes in mean water levels and maximize the fine feeder root mass in the zone of well oxygenated near surface water (Stahle et al., 2012).

Alternative standardization techniques have been developed that can maximize low frequency variability in the derived chronology known as regional curve standardization (RCS; Briffa and Melvin, 2011). RCS will be applied to the Black River, NC, and Black River, SC, raw ring-width measurements using pith offset estimates (number of rings to pith estimated from the first ring measured based on other cores from the same tree and the curvature and growth rate of the rings). This process allows all radii to be arranged by the approximate biological age of each ring. The regional growth curve is then fit to these age-aligned radii and used to remove the biological growth curve while still preserving low frequency variability in common to a majority of the dated series that could be associated with climate (Briffa and Melvin, 2011). Without the pith offset estimates a systematic bias can arise in RCS curves, reducing the expected ring-width maximum in early years of tree growth and consequently lowering the expected trend of declining growth with increasing age (Briffa and Melvin, 2011).

The strength of the baldcypress climate correlation varies during the 20th century. Stahle and Cleaveland (1992) speculated that the changes in the strength of the growing season moisture signal during the 20th century could be related to some climate forcing or anthropogenic disturbances such as logging or nutrient enrichment. Temporal changes in the spatial homogeneity of spring rainfall over the Southeast, between large scale frontal and local
convective precipitation dominated regimes might have occurred (Stahle and Cleaveland, 1994). Tree-ring records are, in some cases, the results of multivariate, nonlinear biological and physical processes (Fritts, 1976; Vaganov et al., 2006). Apparent nonstationarity in the biological response of trees to climate could actually be a function of changes in climate itself (e.g., Gershunov et al., 2001); however, the nonstationarity could just arise stochastically. The two tree-ring records from the Black River’s may also be reflecting the influence of endogenous site disturbances. However, drought in the Southeast has been associated with the strength and position of the Bermuda High (Stahle and Cleaveland, 1992), and negative anomalies are seen in summer sea level pressure (SLP) over the western Atlantic during the last 25 years, which is consistent with other analyses of the seasonal characteristics of the North Atlantic Oscillation (Anchukaitis et al., 2006). North Atlantic circulation has been linked to decadal scale sea surface temperature (SST) forcing, associated with shifts in the Atlantic Multidecadal Oscillation (Sutton and Hodson, 2003). A trend towards increasing SST’s in the tropical western Pacific and Indian Oceans may be responsible for driving changes in North Atlantic circulation in the last few decades (Hoerling et al., 2001), which may be related to anthropogenic greenhouse gas emissions (Hoerling and Kumar, 2003). Climate modeling has indicated the SLP centers of action in the North Atlantic may move eastward under increasing levels of CO₂ (Anchukaitis et al., 2006). These anthropogenic impacts could have significant influence on moisture advection into the southeastern United States. It appears that the nonstationary climate response of the Black River, NC, and SC, chronologies could arise from sensitivity to local-scale climate which is affected by large-scale climate variability. However, further analysis needs to be conducted.

Persistent climate anomalies and increased water demand require comprehensive planning and baldcypress tree-ring chronologies provide a better understanding of the ocean
atmospheric dynamics that cause drought and may aid future water resource management. The potential impacts of a drought regime on agriculture, energy demand and water supply show the importance of continued efforts to verify and explain the long term changes in growing season climate over the Carolinas (Stahle et al., 1988). New tree-ring collections from living trees at the two Black River sites and tree-ring dating of 26 subfossil cypress logs found at Black River, NC, were used to update and expand the millennium-long chronologies previously available from these sites. The revised chronologies were then used in an effort to reconstruct interannual, decadal and centennial scale variability in precipitation over the low country of North and South Carolina.

b. Background

Baldcypress logging began in the late eighteenth century and reached a maximum around AD 1900 but there are small relict stands of old growth that remain and are scattered throughout its native range (Mattoon 1915). Stahle et al., (1988) discovered living baldcypress trees up to 1,622 years old in the southeastern United States. These millennium old trees are rare and provide climate information that dates back to the late-Holocene. The discovery of climate information contained in tree-ring data is reliant upon the regular formation of distinctive annual growth layers, the selection of trees from climate sensitive sites, and on the accurate crossdating of annual rings to their exact year of formation (Douglass 1941; Stokes and Smiley 1968; Fritts 1976). However, excessively wet cypress swamps are not the type of forests expected to produce rainfall sensitive tree-ring chronologies. The strongest precipitation signal is normally found in trees from well drained xeric sites where drought causes reductions in available soil moisture (Stokes and Smiley, 1968). Nevertheless, it has been proven that baldcypress growth is strongly correlated with rainfall (Stahle and Cleaveland, 1992). Analyses
of surface waters in Southeastern swamps indicate the importance dissolved oxygen (DO), pH and nutrient concentrations have on baldcypress growth (Stolzy et al., 1981). Whitford (1956) was able to show that baldcypress root systems grow better in well aerated water and Stahle and Cleaveland (1992) indicate that part of the baldcypress root system, particularly the fine root hairs are responsible for most moisture and nutrient uptake and often become stratified below the mean water level in the upper 10-30 cm soil layer. This is where dissolved oxygen concentrations tend to be highest (Lugo et al., 1984). High (low) rainfall amounts during the growing season are generally associated with high (low) dissolved oxygen levels and good (poor) cypress growth (Stahle and Cleaveland, 1992). This root stratification effect causes cypress trees to be susceptible to a partial dry down of the root system, internal moisture stress and reduced growth with relatively small fluctuations below the mean water level.

The combination of longevity, climate sensitivity and preservation of ancient cypress wood in submerged or buried deposits is unique among native tree species in eastern North America (Stahle et al., 1985a). Three species or subspecies have been recognized and fall under the family Cupressaceae; southern swamp baldcypress (Taxodium distichum), pond baldcypress (Taxodium ascendens) and Montezuma baldcypress (Taxodium mucronatum). Several centuries-long ring-width chronologies have been developed from the genus in the southeastern United States, Mexico and Guatemala (Stahle et al., 1988; Stahle and Cleavleand, 1992: Villanueva-Diaz et al., 2007; Stahle et al., 2012). Drought index and precipitation reconstructions derived from these long cypress chronologies have been used to investigate the dynamics of climate variability of the tropical and subtropical North America (Stahle et al., 2012). Baldcypress tree-ring reconstructions have been used to study large scale climate forcing, such as the El Nino/Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Bermuda High
(BH) and the Pacific North American Oscillation (PNA) in order for a better understanding of the growing season moisture regime which strongly influences crops, forests, industries and municipalities (Stahle et al., 1985b). These climate proxies have also been used to document extreme droughts that may have impacted human activities and societies during the prehistoric and early colonial eras (Stahle and Cleaveland, 1992; Stahle et al., 1998; Cook et al., 2007).

The two longest baldcypress chronologies yet made were developed at Black River, NC, and SC (Figure 3). These millennial length tree-ring chronologies can provide accurate estimates of the natural variability of important climate regimes such as pluvials and droughts during the centuries prior to the modern instrumental record. However, up until this point they have only been useful for interannual to decadal climate variability. The paleoclimatic record extracted from Black River baldcypress tree-rings indicates that the growing season climate of the Carolinas has undergone many significant changes between regimes of drought and wetness that persists for approximately 30 years (Stahle et al., 1988; Stahle and Cleaveland, 1992). However, longer term, lower frequency climate changes have not been detected in previous studies of baldcypress in the Carolinas, and the southeastern United States may not be as prone to persistent multi-year droughts that plague the interior West and Great Plains (Seager et al., 2009).

II. Natural Habitat

Baldcypress is found in four distinct wetland habitats in the southeastern United States, including overflow alluvial swamps along large sediment-rich brown water streams such as the Mississippi River; non-alluvial clear black water streams that carry very little sediment and are blemished by the decomposition of organic matter; large near-coastal swamps with slightly
brackish tidal water which are subject to wind stress and saltwater overflow during heavy gales; and the isolated acidic nutrient-poor ponds found scattered through the coastal plain uplands from Virginia to Florida over to Louisiana where the pond cypress (*T. ascendens*) dominates (Stahle et al., 2012).

These trees tend to grow in even aged cohorts within all aged stands in virgin cypress forests (Mattoon, 1915), reflecting the infrequent periodic surges of reproduction that occur only when climatic conditions (drought) and the water level (very low) of the swamp are ideal for germination (Stahle et al., 2012). The conditions have to stay ideal for several years for rapid vertical growth to allow the young cypress seedlings to survive consequent inundations.

**a. Black River, North Carolina**

**Latitude:** 35° 11’ 13” N

**Longitude:** 78° 40’ 46” W

**Elevation:** 2.13 meters (7 feet) above mean sea level (amsl)

**County:** Pender County

Black River, North Carolina, originates in Sampson County with the confluence of the Great Coharin and Six Forks Creek. It runs southeasterly for approximately 96.5 kilometers (60 miles) before joining the Cape Fear River about 24 kilometers (15 miles) northwest of Wilmington, NC. The Nature Conservancy currently owns 3,000 acres on the Black River with an additional 8,000 protected acres owned by the state of North Carolina (Angie Carl, personal communication, June 18, 2011). Areas that are not owned by the state or The Nature Conservancy are privately owned with most of the land belonging to the Comb estate. Black
River is only about 2 meters (7 feet) above sea level, but has no tidal effects, most likely because it is a tributary of the Cape Fear River and far upstream from the estuary.

Tree-ring samples have been collected at Black River, NC, by the University of Arkansas Tree-Ring Laboratory on five separate occasions over the last 20 years; in 1985, twice in 1986, in 1993 and the most recent collection was made in June of 2011: where most of the tree ring samples were collected off of Highway 11 under the bridge upstream to the three sisters area near Haw Bluff Church. During the first trip 26 baldcypress cores were collected and it became apparent that this site was the best stand of old growth climate sensitive cypress in the Southeast and laid the foundations for millennial length climate reconstructions and multiple publications. During the second and third trip approximately 120 cores were collected and led to the subsequent Black River, NC, chronology which dates from AD 365 to 1984. During these field trips the oldest known baldcypress was cored (BLK69) with an inner ring date of AD 365. The fourth trip was conducted for the purpose of collecting subfossil logs. Drought conditions were so extreme during this visit that is was possible to collect numerous subfossil logs. The last collection made in June 2011 was for the purpose of updating the existing chronologies in order for a more detailed analysis of the climate response of baldcypress.

The baldcypress located at Black River, NC, are swamp grown and are among the oldest trees in eastern North America. Stahle et al., (1988) first documented the advanced age of the baldcypress in the black water ecosystem. As vegetation decays in the water, tannins are leached out, resulting in transparent, acidic water that is darkly stained, resembling tea or coffee. Black River braids into several channels of whiskey-colored water flowing over white sands among these gigantic baldcypress. The nutrient poor, acidic waterway allows for a very slow growth rate in the ancient cypress which results in the trees reaching incredible age. In
many areas along the Black River it is possible to turn in a circle and see 10 to 20 baldcypress trees in the 1,000-year age class. This cypress stand does not include huge trees with valuable timber. Instead the baldcypress are over-mature and decrepit due to recurrent drought and gales over the centuries. This non-commercial aspect of the stand appears to have protected it from logging. In several days of hiking and boating through hundreds of acres of ancient baldcypress wetland at Black River, NC, only a few cut stumps were seen. Many species use this naturally diverse swampland as refuge. A colony of over 100 wood storks was seen in the high rising tree tops of the ancient cypress in June 2011.

b. **Black River, South Carolina**

**Latitude:** 33°28’45” N  
**Longitude:** 79°28’15” W  
**Elevation:** 0.61 meters (2 feet) above mean sea level (amsl)  
**County:** Georgetown County  

Black River, SC, flows through the coastal plain of South Carolina. The headwaters originate in Lee County south of the town of Bishopville and the river flows southeasterly through the counties of Sumter, Clarendon, and Williamsburg for 241.4 kilometers (150 miles) as it makes its way to join the Great Pee Dee River in Georgetown County. Black River, SC, is a black water river shouldered by dense swamp forest. The majority of the land along the lower Black River is owned by the Nature Conservancy, International Paper Company and the Fulton Estate. This cypress swamp forest is situated along the Black River and has been heavily cut over. The ivy, trees, moss and mud covering most of the logging slash indicates the majority of
these logs were cut quite some time ago. It is possible some logs were cut in the 18th and early 19th century after the colonization of Georgetown (AD 1729). However, the swamp forest along the north side of the lower Black River contains many tall ancient cypress and smaller mature cypress which are centuries old given the extraordinarily slow growth rate of these cypress. The site was previously collected in September of 1993 where the majority of the living cypress collected north of the river and east of Big Dam Swamp between highways 41 and 51.

The Black River is tidal water with perhaps a four foot tidal range. There is quite a bit of saw grass and other floating aquatic vegetation in the area. Hurricane Hugo (September 1989) ravaged the swamp causing many broken trees and fallen canopies which makes travel by foot or boat very difficult away from the main channel. The cypress fared much better than the majority of hardwoods in the area due to their entrenched root system. The area is considered a black water ecosystem with channels meandering throughout the bottomland hardwood forest (Stahle et al., 2012). Black water rivers are much lower in nutrients than white water rivers and have ionic concentrations only slightly higher than rainwater (Stahle and Cleaveland, 1992). These types of systems tend to support ancient cypress and the low nutrient load in the rivers allows for a slow growth rate in the trees.

III. Methods

A recollection was made at Black River, NC, and Black River, SC. Increment cores were extracted nondestructively from living baldcypress (Figure 4) trees using a Swedish increment borer (Figure 5). Cores were extracted from 45 trees at Black River, NC, and 24 trees at Black River, SC. Previous collections of 26 subfossil logs were obtained in the early-1990’s, and were used for the purpose of extending the existing chronology. For all the datable living trees and
subfossil wood standard dendrochronological techniques were used to prepare and date the specimens. The specimens were dated against master chronologies created by Dr. Stahle at Black River, NC, and Dan Griffin at Black River, SC. A new and shorter master chronology was created for both sites in order to update the existing master chronology to 2010. After the exact annual dates were determined for all growth rings, each annual ring-width was measured with 0.001 millimeter (mm) precision and merged into a single file with the previous ring-width measurements (Figure 6A and B for NC and SC, respectively). The updated measurements were then run through the quality control program COFECHA (Holmes, 1986) to check the crossdating and overall quality of the dating of the raw ring-width measurements in order to assure accuracy.

In an attempt to preserve long-timescale variance in the updated baldcypress chronologies a pith offset file was created and each dated radius at each collection site was detrended and standardized using regional curve standardization (RCS) procedures (Briffa and Melvin, 2011). The raw ring-width file and the pith offset file for each site were submitted to the ARSTAN program to compute the chronologies (Cook and Holmes, 1986). The reordering of the data from calendar age to biological age is intended to remove the effect of climate variability on the expected growth over time as the trees become older (See Figure 7A for NC and Figure 8A for SC). The regional curve (Figure 7B for NC and Figure 8B for SC) was then fit to each series and the indices were computed by dividing each measured value by the value of the regional growth curve in the same year even though the fit of the curve is poor in some places. The chronologies were detrended using the regional curve estimated separately for each site. The derived ring-width indices were averaged among all specimens for each year using a robust mean value function designed to discount the effect of outliers (Cook and Pederson, 2011).
The ARSTAN program computes four types of tree-ring chronologies, the simple mean ring-width without any detrending and the detrended and standardized “standard” chronology. Autoregressive modeling is used to identify and remove low-order growth resistance in the “residual” chronology. The ARSTAN chronology is computed by adding the autoregressive modeled persistence structure back into the residual chronology (Cook, 1985). The derived RCS chronologies from the two Black River collections were compared and exhibited similar low frequency variability after about AD 1150. The two RCS chronologies from each site were then averaged together creating a regional coastal Carolina chronology to be used for the reconstruction of growing season precipitation.

A point wise correlation was computed between the derived coastal Carolina RCS ARSTAN chronology and gridded climate data (the 0.5° monthly data of Heim, 2012) on a monthly basis to identify a climate variable, the season and the region of strongest climate influence on the tree-ring data (Cook and Pederson, 2011). Once the climate variable, season, and region of strongest climate influence were identified, the gridded climate data were separated into three sub-periods, 1895-1931, 1932-1968 and 1969-2005, in order to explore the stability of the climate response. The climate data for grid points that were well correlated with the regional chronology over all three sub periods were then extracted from the Heim database and were averaged together into a single instrumental time series that was used for the reconstruction (i.e., the predictand). To reconstruct growing season precipitation over the Carolina coastal plain, the seasonalized March-June precipitation totals were first extracted from the Heim 0.5° grid and averaged into a “growing season” instrumental regional average for calibration with the total ring-width chronologies. Evaluation of the strength of the
reconstructions was done using calibration and verification statistics in DendroTools (Dorian Burnette, personal communication, March 1, 2012).

For comparative purposes, a RCS precipitation reconstruction was made for Black River, NC and an ‘optimal’ or ‘normal’ detrended version of the reconstruction was made using the averaged coastal Carolina chronology which uses both Black River’s. The purpose for constructing the RCS precipitation reconstruction using only Black River, NC was to address the lower sample size at Black River, SC compared to Black River, NC (Figure 9). The ‘optimally’ detrended reconstruction was computed to assess if there were any fundamental differences between it and the RCS reconstruction.

IV. Results and Discussion

Cores were extracted at Black River, NC, from 45 different trees in June 2011. A total of 84 cores were extracted and 50 were dated. At Black River, SC, 50 cores were extracted from 24 different trees. Out of these 50 samples 24 were dated. A total of 26 subfossil logs were previously collected in 1993 and out of these 24 were dated with the goal of extending the existing chronology past the inner ring date of AD 365. The subfossil logs did not extend the chronology but did attain an inner ring date of AD 429 and allowed for better replication of the Black River, NC chronology as indicated in Figure 10. Some living trees and subfossil logs could not be dated mainly due to suppressed growth rings and reaction wood causing a distortion in the rings. In some instances the ring-widths of the cores or logs were so tight that it was nearly impossible to see the distinction from ring to ring. A small number of subfossil logs contained heart rot and beetle galleries which inhibited the dating in some areas of the cross sections. The summary tables computed with COFECHA are included in Appendix 1 and 2 for
Black River, NC, and Black River, SC, respectively, to provide a complete listing of the radii included in each chronology (155 series for Black River, NC, and 105 series for Black River, SC).

The new and updated chronologies date from AD 365 to 2010 at Black River, NC, and from 549 to 2010 at Black River, SC. The RCS version of each chronology exhibits interesting low frequency variability. Figure 11A and B plots the Black River, NC, and SC, chronologies with 10-year and 100-year smoothing splines. The two chronologies exhibit similar interannual to multi-decadal variability with generally lower than average growth in the medieval and colonial times as well as similar increasing trends occurring for the last 250 years. The 100-year splines (Figure 11B) indicate similar low frequency variability from AD 1150 to 1990. Before AD 1150 the chronologies are out of phase with one another perhaps due to the low sample size at Black River, SC consisting of only 9 cores from four trees; Figure 9B. The fact that the two sites have analogous interannual to decadal variability and similar low frequency variability after AD 1150, but are separated by 193 kilometers (120 miles) suggests that the coherency between these two sites could be a function of growing season climate. Given the similarities between the two sites we computed a regional average of Black River, NC, and Black River, SC, to be used for climate reconstruction.

Correlation analyses were computed with gridded precipitation, palmer drought severity indices (PDSI), and Palmer z-indices and indicates that the response of baldcypress is mainly linked with March, April, May and June (growing season) precipitation over the Carolina coastal plain during the instrumental era (Figure 12). When broken down by sub period (Figure 13) the size and strength of the precipitation signal varies (strongest in 1895-1931; Figure 13A). Nevertheless, a positive response to spring precipitation was seen in all three sub periods over
the Carolina coastal plain. Gridded growing season (MAMJ) precipitation totals were then extracted approximately from the North Carolina-Virginia border to the South Carolina-Georgia border, from the Carolina coastal plain and back to the foot hills of the Appalachians (see Appendix 3 for a full list of the exact grid points used). An average of all 106 grid points were then made into a single time series of growing season (MAMJ) precipitation for the Carolina coastal plain (the predictand).

DendroTools (Dorian Burnette, personal communication, March 1, 2012) was used to (a) calibrate the tree-ring chronologies with growing season precipitation, (b) to compute a reconstruction for 1,461 years and to (c) to verify the reconstruction during part of the instrumental era. Split period calibration and verification experiments were conducted to test the stability of the relationship of tree growth and precipitation during the instrumental era (1895-2005). The averaged tree-ring chronology was calibrated with growing season precipitation during 1895-1949 period and then verified from 1950-2005. The tree-ring chronology was also calibrated with growing season precipitation from 1950-2005, and verified from 1895-1949. These results are presented in Table 1. The best calibration sub period in the instrumental era was from 1895-1949, however it was still possible to successfully calibrate and verify the reconstruction based on the weaker sub period, 1950-2005 (Table 1). The decision was made to calibrate the reconstruction based on full instrumental era (1895-2005) which explains 46% of variance (Figure 14; Table1). The transfer function used for the reconstruction was:

$$\hat{Y}_t = 2.636 + 1.375 X_t$$

where $\hat{Y}_t$ is the estimate of MAMJ precipitation totals in year $t$ for the Carolina coastal plain, $X_t$ is the regional RCS ARSTAN chronology average of Black River, NC, and SC.
The RCS precipitation reconstruction is plotted in Figure 15A with a smoothed version emphasizing decadal variability. The new reconstruction indicates several interesting episodes of drought and wetness since AD 549. Persistent drought is seen during the 800’s, 1000’s, mid-1200’s, late-1600’s and early-1700’s (Figure 15A). Above average reconstructed spring precipitation is evident during the 700’s, 900’s, 1100’s, and 1300’s (Figure 15A), with a persistent trend of increasing growing season precipitation occurring from approximately 1750-2010 (Figure 15A). The new reconstruction provides some evidence for the Medieval Climate Anomaly (MCA), the Little Ice Age (LIA), an early Colonial dry episode and the increasing trend in precipitation for the last 250 years. Some of these reconstructed low frequency precipitation excursions are evident in moisture reconstructions from the Corn Belt and the western United States, including the droughts seen in the 1000’s and mid-1200’s (Cook et al., 2007, Stambaugh et al., 2011). The increasing trend in precipitation from approximately 1750-2010 is also somewhat evident in all these moisture reconstructions, (Cook et al., 2007; Stambaugh et al., 2011). The presence of the multi-centennial excursions could provide evidence for an impact of the Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) on spring precipitation over the southeastern United States. The severe early Colonial droughts have not yet been attributed to any particular forcing but may have had important impacts on Colonial agriculture in the Carolinas. It is important to note that some climate proxies from the eastern United States indicate differing climate anomalies during the MCA and LIA. Pollen assemblages were used to reconstruct late Holocene paleohydrologic patterns in the lower Roanoke River basin in North Carolina and indicate wetter than average conditions during the Medieval Climate Anomaly and dryer than average conditions during the Little Ice Age (Willard et al., 2010). An eastern Red Cedar precipitation reconstruction for West Virginia
illustrated similar wetter than average conditions during the MCA and drier than average conditions during the LIA as the pollen assemblages in the Roanoke River of North Carolina (Stockton et al., 2012).

Information derived from proxy records suggests that the MCA and the shift to the subsequent colder period, the LIA, involves somewhat coordinated climate shifts across different regions of the globe (e.g. Seager et al., 2007; Mann et al., 2009; Graham et al., 2010). A suite of in-situ proxy records indicate that the tropical eastern and central Pacific sea surface temperatures (SST) were relatively cool during the MCA (Cobb et al., 2003; Rein et al., 2004; Conroy et al., 2008) which is supported by a change in hydroclimate that is indicated by proxy records from western North and South America (Swetnam et al., 1993; Stine et al., 1994; Cook et al., 2004). This change in hydroclimate coincides with a series of long term droughts that affected large portions of North America which have been well documented from tree-ring records. (Herweijer et al., 2007; Cook et al., 2007, 2010). Cobb et al., 2003 used coral oxygen isotope data from Palmyra in the central equatorial Pacific Ocean and showed that SST’s were quite likely lower throughout the majority of the MCA. This coral record has been used to create tropical SST fields that were imposed as forcing for an ensemble of 16 atmosphere global circulation model (AGCM) simulations (Seager et al., 2008). The results indicated the tropical Pacific SST’s were sufficiently cool and persistent enough to create multidecadal megadroughts over North America that illustrated similar spatial patterns and amplitude as the tree-ring reconstructed droughts (Seager and Burgman, 2011). Recent evidence suggests that North Atlantic SST, through the Atlantic Multidecadal Oscillation (AMO) may have also had a strong effect on the persistent nature on the droughts of the MCA during this time period (Oglesby et al., 2011). During the AMO warm (cold) phases, most of North America is dry (wet).
Investigations of proxy SST records in both the tropical Pacific and North Atlantic (Feng et al., 2008) found a basin wide warming in the North Atlantic Ocean during the MCA. It is likely that the persistent nature of droughts during this time period occurred through a combination of La Nina like conditions in the eastern Pacific as well as the warm phase of the AMO in the North Atlantic (Oglesby et al., 2011). A connection between the influence of AMO on the subtropical high pressure zone in the North Atlantic provides further evidence of the climatic variables that led to increased aridity during the MCA (Feng et al., 2008). In summer the poleward flow on the western side of this high pressure system advects moisture in the central and western US which provides a source for convective precipitation in the area. During the warm phase of the AMO, the subtropical high is displaced north and east of its mean location, reducing moisture transport into the US with the exception of the mid Atlantic coastal states. During the cool phase, the subtropical high strengthens and pushes westward, allowing moisture to transport into the central and western US with dryer conditions along the Atlantic coast. Similar factors appear to have occurred during the MCA (Oglesby et al., 2011).

The positive trend in reconstructed precipitation from approximately AD 1750 to 2010 is evident at both sites and may represent a real shift in growing season climate over the southeastern United States during the last 250 years. However, both chronologies were developed from low lying swamp forests which may have been disturbed by human activity. Logging could be a contributing factor to the recent growth excursions. Logging did occur at Black River, SC, but not occur at Black River, NC. Both drainage basins have been extensively deforested which may have contributed sediments and nutrients to the rivers which could have caused fertilization of baldcypress growth over the past two centuries. Another potential cause could be atmospheric deposition of nutrients and conceivably rising carbon dioxide (CO₂) levels
which may have contributed to improved tree growth. However, Pederson et al., (2012) used nested reconstruction techniques for 32 tree-ring chronologies to analyze the hydroclimate of the Northeast and indicated that reduced aridity has been seen in the area since about AD 1800 following repeated droughts during the 16\(^{th}\) and 17\(^{th}\) centuries. The trend of reduced aridity appears to be an expression of a broader hydroclimate change across the eastern US. Much of the eastern US has been unusually and persistently wet since the 19\(^{th}\) century (Pederson et al., 2012). Precipitation variations in the region have been linked to variability of the storm tracks over North America and the North Atlantic Ocean (Pederson et al., 2012) and also to variations in the position and strength of the North Atlantic subtropical high (Stahle and Cleaveland, 1992). Further analysis was conducted on baldcypress tree ring sites extending from North Carolina to Florida. RCS methodologies have been applied to these chronologies and although the chronologies are out of phase with one another prior to about AD 1600 they all come into agreement thereafter reaching a low growth period during the Colonial era followed by an increasing growth trend for the better part of the last 250 years (Figure 16). This evidence indicates that the eastern United States is most likely witnessing a shift in climate that may have begun some 200 years ago.

Because Black River, SC, had a lower sample size before AD 1150 than Black River, NC a RCS precipitation reconstruction was made with the North Carolina RCS chronology only (Figure 15B). DendroTools (Dorian Burnette, personal communication, March 1, 2012) was again used to perform split calibration and verification experiments to assess the stability of the relationship between Black River, NC tree growth and precipitation during the instrumental era (AD 1895-2005). The reconstruction was created using a calibration model during 1895-1949 and verifying 1950-2005. The statistical results are presented in Table 2, and the calibration
model explained 40% of the growing season precipitation variance. Evidence for the MCA, LIA, early Colonial droughts and the increased trend in precipitation levels over the last 250 years are still present in the reconstruction based on the single chronology from Black River, NC (Figure 15B). However, the low frequency precipitation changes prior to AD 1150 are quite different from the two site regional average reconstruction. Given the good replication and strong climate signal in the Black River, NC, chronology, the centennial scale moisture regimes reconstructed from the NC chronology prior to AD 1000 are probably more reliable (i.e., Figure 15B).

For comparative purposes, a reconstruction of spring precipitation based on a regional average of the two Black River chronologies using ‘normal’ or ‘optimal’ dentrending procedures was also developed (Figure 15C). All radii at each site were detrended with a cubic smoothing spline with 50% variance reduction set at 67% of the length of each radius, using the ARSTAN program. This reconstruction was calibrated using the 1895-2005 period and explains a little less variance than the RCS version ($R^2_{adj} = 0.453$ vs. $R^2_{adj} = 0.455$, respectively). These statistics are illustrated in Table 3. The reconstruction based on optimal detrending is presented in Figure 15C and it exhibits the same interannual to decadal variability as the RCS-based reconstruction, but the evidence for the long term centennial scale climate excursions is much more muted.

Simple changes in sample size do not appear solely responsible for the presence of low frequency variability in the coastal Carolina RCS precipitation reconstructions. An RCS chronology was computed from a selection of very old trees from Black River, NC, which all dated from AD 1000 to 1985. In fact the fixed sample size chronology segments were (1) developed based on 17 radii from AD 1000 to 1985 and (2) on seven radii from AD 549 to 999
(Figure 15D). The fixed sample size from Black River, NC, exhibits the low frequency changes seen in both RCS precipitation reconstructions, including evidence for a MCA, LIA, early Colonial drought, and persistent increase in precipitation for the last 250 years (compare Figure 15A with Figure 15D). The fixed sample size series suggests that these low frequency changes may have been a function of climate or some anthropogenically forced disturbance. However, sample size changes do not play a factor in long term excursions (Figure 15D).

V. Conclusions

With increasing concern of global climate change, the need for millennial length climate proxies capable of preserving low frequency variability continues to grow. High frequency proxies are useful for decade to decade comparisons, however standard curve fitting and detrending methods used for tree ring chronology development may not be well suited for exploring the long term context of recent tree growth changes in response to factors such as recent temperature rises, increasing atmospheric CO₂, or other hypothesized anthropogenic influences on terrestrial ecosystems (Briffa and Melvin, 2011). The coastal Carolina RCS reconstructions of spring precipitation provide evidence of centennial scale climate fluctuations throughout the last 1,461- years which likely had important environmental impacts on the Southeast.

The reconstructions of spring rainfall using baldcypress tree-ring chronologies indicate that periods of drought prevailed during the Medieval Climate Anomaly and early Colonial Era and normal to above average growing season rainfall was common during the Little Ice Age over the Carolina coastal plain. The reconstructions also suggest that increasingly wetter conditions have been prevalent throughout the 18th, 19th and 20th centuries, even though the
instrumental precipitation data available from 1895-2005 do not exhibit a significant positive trend. It is possible that the recent tree growth and inferred precipitation trend is a function of anthropogenic disturbance to our baldcypress collection sites or the standardization procedures used for chronology development. The new reconstructions suggest that large scale atmospheric circulation over eastern North America may have been amplified during the century-scale excursions in average growing season rainfall (e.g., Seager et al., 2009). Medieval drought conditions were also witnessed in western North America and have been linked to persistent La Nina like conditions in the tropical Pacific Ocean (Cobb et al., 2003; Seager et al., 2009). The late 17th and early 18th century droughts have not yet been attributed to any possible cause. The tree-ring records clearly indicate that longer and more severe droughts have occurred in the Southeast than appear in the instrumental record of the 20th century (see also, Seager et al., 2009).

Preserving multi-centennial climate variability in long tree-ring records is critically important for reconstructing the full range of precipitation variability within the last millennium over the southeastern United States. The new coastal Carolina reconstructions suggest that the Medieval Climate Anomaly did have some impact on the spring moisture balance over the Southeast. However, further research needs to be conducted to verify the presence of low frequency variability with additional climate proxies and historical documentation.
VI. References


Cambridge, United Kingdom and New York, NY, USA.


VII. Tables

Table 1: This table lists the split calibration and verification computed for the reconstruction of March, April, May and June (MAMJ) precipitation using the coastal Carolina chronology computed with the computer program DendroTools (Dorian Burnette, personal communication, March 1, 2012). The fixed reconstruction was based on the full 111-year calibration period (1895-2005). The variance explained adjusted downward for loss of degrees of freedom ($R^2_{adj}$), the standard error of the regression estimates (SE, in inches of precipitation), the Durbin-Watson statistic (DW) and its significance are listed for the tree calibration periods. The Pearson correlation coefficient ($r$), the reductions of error (RE), and coefficient of efficiency (CE) are listed for comparisons between the reconstructed and observed instrumental precipitation data during the verification sub periods (see Fritts, 1976).

<table>
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<th>DW</th>
<th>Verification Period</th>
<th>r</th>
<th>RE</th>
<th>CE</th>
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<td>1950-2005</td>
<td>0.72</td>
<td>0.5</td>
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Table 2: This table lists the calibration and verification statistics computed for the reconstruction of March, April, May and June (MAMJ) precipitation using the Black River, NC chronology computed with the computer program DendroTools (Dorian Burnette, personal communication, March 1, 2012). The fixed reconstruction was based on the split calibration period AD 1895 to 1949 and the verification period 1950 to 2005. The variance explained adjusted downward for loss of degrees of freedom (R_{adj}^2), the standard error of the regression estimates (SE, in inches of precipitation), the Durbin-Watson statistic (DW) and its significance are listed for the tree calibration periods. The Pearson correlation coefficient (r), the reductions of error (RE), and coefficient of efficiency (CE) are listed for comparisons between the reconstructed and observed instrumental precipitation data during the verification sub periods (see Fritts, 1976).

<table>
<thead>
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<th>Calibration Period</th>
<th>Calibration Statistics</th>
<th>Verification Period</th>
<th>Verification Statistics</th>
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<td>r  RE  CE</td>
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<tr>
<td>1895-2005</td>
<td>0.33  0.62  2.12, p = 0.53</td>
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Table 3: This table lists the calibration and verification statistics computed for the ‘optimally’ or ‘normally’ detrended reconstruction of March, April, May and June (MAMJ) precipitation using the coastal Carolina chronology computed with the computer program DendroTools (Dorian Burnette, personal communication, March 1, 2012). The fixed reconstruction was based on the full 111 year calibration period (1895-2005). The variance explained adjusted downward for loss of degrees of freedom ($R^2_{adj}$), the standard error of the regression estimates (SE, in inches of precipitation), the Durbin-Watson statistic (DW) and its significance are listed for the tree calibration periods. The Pearson correlation coefficient ($r$), the reductions of error (RE), and coefficient of efficiency (CE) are listed for comparisons between the reconstructed and observed instrumental precipitation data during the verification sub periods (see Fritts, 1976).

<table>
<thead>
<tr>
<th>Calibration Period</th>
<th>Calibration Statistics</th>
<th>Verification Period</th>
<th>Verification Statistics</th>
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<td>$R^2_{adj}$</td>
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<td>DW</td>
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<td>0.45</td>
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<td>2.05, $p = 0.80$</td>
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Figure 1: This image shows the ancient cypress and white sanded banks of Black River, NC. As vegetation decays into the river, tannins are leached out resulting in dark, nutrient poor, acidic water which allows for the slow growth rate of the baldcypress.
Figure 2: This image illustrates the beauty of the low lying swamp forest of Black River, NC. Note the person for scale standing next to the gigantic ancient cypress. Baldcypress that reside on the banks of Black River, NC tend to be stunted due to their slow growth rate whereas the trees on slightly higher terrain off the main channel of the waterway are able to reach substantial height. The vertical root formations (Knees) of the cypress extend up through the tall grasses.

Photo courtesy of: Dan Griffin
Figure 3: The locations of the two tree-ring chronologies used to develop the growing season rainfall reconstruction are situated near the border of North and South Carolina. Satellite images illustrate the portion of the two Black River’s sampled during this research.
Figure 4: This image illustrates the technique used to extract cores nondestructively from the ancient cypress using a Swedish increment borer. It is important to extract the core above the swollen buttress so as not to have ring distortion in the core.
**Figure 5**: This image illustrates the Swedish increment borer with a 5 millimeter diameter core being extracted from a living cypress tree.
Figure 6: Raw ring-width measurements for all dated radii at Black River, NC, (A) and Black River, SC (B) show pulses in tree growth indicating possible recruitment events. The red curve is the robust mean ring width for all time series at each site.
Figure 7: (A) This figure illustrates the raw ring width measurements alligned by biological age rather than calendar age (compare with Figure 6A). This is the method used to derive the regional growth curve for regional curve standardization (RCS). The robust mean of the aged aligned ring widths is in red. (B) This figure illustrates the robust mean of the aged aligned ring widths in black with the regional growth curve estimated from Black River, NC (red).
Figure 8: (A) This figure illustrates the raw ring width measurements alligned by biological age rather than calendar age (compare with Figure 6B). This is the method used to derive the regional growth curve for regional curve standardization (RCS). The robust mean of the aged aligned ring widths is in red. (B) This figure illustrates the robust mean of the aged aligned ring widths in black with the regional growth curves estimated from Black River, SC in red.
Figure 9: The image illustrates the sample size of dated radii through time at Black River, NC (A) and Black River, SC (B).
Figure 10: This graph illustrates the start and end dates of the subfossil cross sections that were dated from Black River, NC. The actual dated segments are the solid lines in between the brackets, whereas the dashed lines indicate portions that were only ring counted. The dating range of the updated and improved full chronology for Black River, NC, is indicated at the bottom. Dating these subfossil logs allowed for better replication at the chronology before AD 1500 and came close to extending the pre-existing chronology.
Figure 11: (A) The Black River NC, and SC, chronologies were both smoothed to emphasize 10-year variability (using a smoothing spline with a 50% frequency response of 10 years, Cook and Peters, 1981). The two smoothed chronologies are correlated ($r = 0.44$) and exhibit similar inter-annual to multi-decadal variability, especially after AD 1150 when the sample size improves at Black River, SC. (B) This figure shows both Black River chronologies smoothed to emphasize 100-year variability. The two chronologies exhibit similar low frequency variability especially after AD 1150 when the sample size improves at Black River, SC.
Figure 12: The spatial distribution of the precipitation correlation with the average of the two baldcypress chronologies from Black River, NC, and SC, is mapped. The coastal Carolina chronology was correlated with growing season rainfall (MAMJ) on the Heim 0.5° grid across North America. The strongest positive correlations were computed for the Southeastern grid points. The spring precipitation data were extracted for the Southeastern grid points, roughly extending from the Virginia-North Carolina to the South Carolina-Georgia border, and from the coast to the upper piedmont of the Carolinas. These 106 extracted grid points were averaged into a single spring total rainfall time series for the reconstruction. For a list of the exact points extracted see Appendix 3.
Figure 13: The regional average baldcypress chronology was correlated with gridded growing season precipitation data were separated into three sub-periods; 1895-1931 (A), 1932-1968 (B) and 1969-2005 (C) in order to identify the period of strongest correlation. The strongest period of correlation was 1895-1931 (A) while the weakest correlation occurred during 1932-1968 (B). The extracted grid points were reasonably well correlated with the cypress chronology during all three intervals (A, B, and C).
Figure 14: The observed (blue) and reconstructed growing season precipitation series (red) for the Carolina coastal plain are plotted for the instrumental era (1895-2005). The reconstruction (Figure 15A) was calibrated on this full 111-year period, because calibration and verification experiments on sub-periods indicated that verifiable reconstructions can be computed for the sub periods (Table 1).
Figure 15: (A) The growing season reconstruction based on the regional average RCS ARSTAN baldcypress chronology is plotted here with a smoothed version emphasizing decadal variability. Persistent drought occurs in the 800’s, 1000’s, 1200’s, late 1600’s and early 1700’s. Above average reconstructed precipitation is evident in the 700’s, 900’s, 1100’s, 1300’s, and 1500’s. This reconstructed low frequency precipitation series may provide evidence for the impact of the Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) on spring precipitation over the southeastern United States. However, the early Colonial droughts have not yet been attributed to any forcing. The reconstruction also indicates a positive trend in spring precipitation from approximately 1750-2010. This trend is evident at both sites and could indicate a real shift in spring climate over the southeastern United States during the last 250 years. However, we cannot rule out human activity as a contributing factor. (B) Due to the low sample size at Black River, SC before AD 1150 a reconstruction of growing season precipitation was created based on just Black River, NC. As indicated in Figure 15B low frequency variability is still present in this single site reconstruction. The MCA, LIA, early Colonial droughts and the persistent increasing precipitation trend in the last 250 years are still evident in the reconstruction. (C) For comparative purposes a reconstruction of growing season precipitation based on the regional average of the two Black River chronologies developed using ‘normal’ or ‘optimal’ detrending techniques was computed. All radii were identically detrended using a cubic smoothing spline with 50% variance reduction set at 67% of the length of each radius, using the ARSTAN program. This reconstruction indicates similar interannual to decadal variability as the regional average RCS reconstruction (Figure 15A), however, the evidence for long term climate excursions during the MCA, LIA, early Colonial droughts and the precipitation excursion during the last 250 years are much more muted. (D) Simple changes
in sample size are probably not responsible for the low frequency changes seen in the two RCS reconstructions. An RCS chronology was computed from a selection of 17 old trees from Black River, NC, all dating from at least AD 1000 to 1985. A second fixed sample size chronology was computed with RCS techniques for seven radii all dating from AD 549 to 999 (Figure 15D). These millennial long series from Black River, NC, exhibit the low frequency changes seen in the two reconstructions including the MCA, LIA, early Colonial droughts and persistent increase in precipitation for the last 250 years (compare Figure 15A and B with Figure 15D) and may represent evidence for centennial scale change in growing season climate on the Carolina coastal plain.
Figure 16: Regional Curve Standardization chronologies were created for most of the east coast baldcypress sites from North Carolina to Florida. Each site was smoothed with a 100 year spline. The RCS chronologies from each site indicate similar low frequency variability after AD 1600 showing a smaller growth rate during the early Colonial era with an increased growth rate lasting for the last 250 years. Before AD 1600 the sites are out of phase with one another mainly due to sample size issues.
IX. Appendices

Appendix 1: This table shows all the dated individual series from Black River, NC. Included in the table are the series I.D., dated interval for each series, number of years dated, correlation for each series with the master and other descriptive statistics (see Holmes, 1986 and Grissino-Mayer, 2001). The chronology was made with 155 individual series.

<table>
<thead>
<tr>
<th>Seq</th>
<th>Series</th>
<th>Interval</th>
<th>r with Master</th>
<th>Std dev</th>
<th>Auto corr</th>
<th>Mean sens</th>
<th>Max value</th>
<th>Std dev</th>
<th>Auto corr</th>
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| Tot | mean: | 0.689 | 0.33 | 0.417 | 0.634 | 3.64 | 0.402 | 0.002 |   |   |

53
Appendix 2: This table shows all the dated individual series from Black River, SC. Included in the table are the series I.D., dated interval for each series, number of years dated, correlation for each series with the master and other descriptive statistics (see Holmes, 1986 and Grissino-Mayer, 2001). The chronology was made with 155 individual series.

<p>| Seq | Series | Interval | ( r ) with Master | Std dev | Auto corr | Mean sens | Max value | Std dev | Auto corr | AR (|  |
|-----|--------|----------|----------------------|---------|-----------|-----------|-----------|---------|-----------|-----|
| 1   | BLA02A | 1437     | 0.618                | 0.295   | 0.641     | 0.68      | 2.75      | 0.345   | 0.025     | 1   |
| 2   | BLA02C | 1695     | 0.696                | 0.336   | 0.531     | 0.477     | 2.54      | 0.296   | 0.057     | 1   |
| 3   | BLA03A | 1540     | 0.452                | 0.487   | 0.776     | 0.33      | 2.78      | 0.356   | 0.011     | 2   |
| 4   | BLA05A | 1529     | 0.598                | 0.649   | 0.746     | 0.415     | 2.52      | 0.284   | 0.019     | 1   |
| 5   | BLA05B | 1595     | 0.64                 | 0.535   | 0.793     | 0.442     | 2.67      | 0.361   | 0.007     | 1   |
| 6   | BLA05C | 1407     | 0.57                 | 0.678   | 0.658     | 0.383     | 2.55      | 0.368   | 0.007     | 1   |
| 7   | BLA09A | 1993     | 0.434                | 0.414   | 0.685     | 0.624     | 2.8       | 0.373   | 0.046     | 1   |
| 8   | BLA09B | 1993     | 0.585                | 0.204   | 0.667     | 0.515     | 2.62      | 0.335   | 0.017     | 3   |
| 9   | BLA10A | 1640     | 0.667                | 0.591   | 0.603     | 0.454     | 2.78      | 0.34    | 0.006     | 1   |
| 10  | BLA10B | 1640     | 0.648                | 0.528   | 0.604     | 0.487     | 2.8       | 0.397   | 0.012     | 1   |
| 11  | BLA11A | 1368     | 0.684                | 0.563   | 0.67      | 0.404     | 2.67      | 0.419   | 0.068     | 1   |
| 12  | BLA11B | 1334     | 0.602                | 0.491   | 0.491     | 0.376     | 2.71      | 0.474   | 0.078     | 1   |
| 13  | BLA12A | 1993     | 0.573                | 0.353   | 0.316     | 0.752     | 2.77      | 0.358   | 0.013     | 1   |
| 14  | BLA12B | 1580     | 0.626                | 0.447   | 0.293     | 0.722     | 3.02      | 0.481   | 0.074     | 1   |
| 15  | BLA12C | 1860     | 0.545                | 0.342   | 0.411     | 0.777     | 2.86      | 0.426   | 0.021     | 1   |
| 16  | BLA15A | 1993     | 0.638                | 0.665   | 0.482     | 0.66      | 2.86      | 0.548   | 0.078     | 1   |
| 17  | BLA15B | 1993     | 0.649                | 0.819   | 0.48      | 0.619     | 2.96      | 0.547   | 0.006     | 3   |
| 18  | BLA16A | 1993     | 0.617                | 0.333   | -0.04     | 0.681     | 2.79      | 0.547   | 0.103     | 1   |
| BLA16B | 1821 | 1993 | 1428 | 0.588 | 0.501 | 0.337 | 0.758 | 3 | 0.552 | 0.055 | 1 |
| BLA18A | 1610 | 1800 | 2020 | 0.626 | 0.232 | 0.428 | 0.51  | 2.73 | 0.494 | 0.018 | 1 |
| BLA18B | 1993 | 1428 | 2020 | 0.657 | 0.227 | 0.431 | 0.619 | 2.56 | 0.427 | 0.004 | 1 |
| BLA18C | 1993 | 1830 | 2020 | 0.637 | 0.273 | 0.527 | 0.594 | 2.73 | 0.357 | 0.008 | 3 |
| BLA18D | 1993 | 1760 | 2020 | 0.613 | 0.223 | 0.556 | 0.541 | 2.7  | 0.384 | 0.013 | 1 |
| BLA19A | 1993 | 1688 | 760  | 0.686 | 0.474 | 0.297 | 0.5  | 3.02 | 0.51  | 0.014 | 1 |
| BLA19B | 1993 | 760  | 1688 | 0.629 | 0.523 | 0.511 | 0.595 | 2.73 | 0.334 | 0.001 | 1 |
| BLA20A | 912  | 760  | 1688 | 0.569 | 0.499 | 0.565 | 0.454 | 2.88 | 0.481 | 0.082 | 1 |
| BLA20B | 1180 | 760  | 1688 | 0.649 | 0.399 | 0.682 | 0.693 | 2.95 | 0.398 | 0.001 | 1 |
| BLA20C | 1176 | 1167 | 1688 | 0.652 | 0.395 | 0.625 | 0.691 | 2.88 | 0.423 | 0.015 | 1 |
| BLA22A | 1500 | 1167 | 1688 | 0.552 | 0.524 | 0.753 | 0.477 | 2.82 | 0.406 | 0.048 | 2 |
| BLA22B | 1463 | 1167 | 1688 | 0.581 | 0.568 | 0.825 | 0.465 | 2.76 | 0.411 | 0.071 | 1 |
| BLA22C | 1292 | 1676 | 1688 | 0.504 | 0.648 | 0.728 | 0.373 | 2.97 | 0.547 | 0.014 | 1 |
| BLA23A | 1993 | 1673 | 1688 | 0.581 | 0.523 | 0.793 | 0.484 | 2.78 | 0.423 | 0.018 | 9 |
| BLA23B | 1993 | 1910 | 1688 | 0.624 | 0.507 | 0.644 | 0.482 | 3.06 | 0.456 | 0.014 | 1 |
| BLA27A | 1993 | 1880 | 1688 | 0.573 | 0.486 | 0.251 | 0.395 | 2.69 | 0.403 | 0.006 | 1 |
| BLA27B | 1993 | 1202 | 1688 | 0.529 | 0.392 | 0.517 | 0.548 | 2.56 | 0.432 | 0.014 | 1 |
| BLA29A | 1410 | 1476 | 1688 | 0.619 | 0.639 | 0.817 | 0.36  | 2.66 | 0.327 | -0.07 | 2 |
| BLA29B | 1547 | 1135 | 1168 | 0.397 | 0.158 | 0.614 | 0.41  | 2.42 | 0.43  | 0.085 | 1 |
| BLA30A | 1440 | 1153 | 1168 | 0.565 | 0.354 | 0.797 | 0.374 | 2.71 | 0.38  | 0.032 | 2 |
| BLA30B | 1540 | 1380 | 1168 | 0.566 | 0.342 | 0.736 | 0.393 | 2.74 | 0.333 | 0.048 | 1 |
| BLA32A | 1599 | 881  | 1168 | 0.485 | 0.349 | 0.511 | 0.352 | 2.96 | 0.512 | 0.016 | 1 |
| BLA33A | 1168 | 881  | 1168 | 0.656 | 0.509 | 0.816 | 0.41  | 2.71 | 0.367 | 0.039 | 1 |
| BLA33B | 1472 | 881  | 1168 | 0.609 | 0.453 | 0.815 | 0.453 | 2.6  | 0.345 | 0.018 | 2 |</p>
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al or mean:

Total or mean: 0.615 0.464 0.552 0.544 3.19 0.404 0.019
Appendix 3: This table lists the numbers of all grid points extracted from the Heim data set (106 total grid points). The grid point number, latitude, longitude, elevations, percent of land cover within the grid box, and the correlation with the coastal Carolina RCS ARSTAN baldcypress chronology are presented in this table. The highest single grid point correlation with the averaged baldcypress chronology is 0.65.

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