Deciphering Climate from the Characterization of Ring Width, Carbon, and Oxygen Isotopes in Latewood Tree-Ring Cellulose, Big Thicket National Preserve, Texas, USA

A Dissertation
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Dedication

This dissertation is dedicated to my older sister, Kim, who left this life far too early, with so much ahead of her.

Acknowledgements

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Abstract

Trees are excellent archives of paleoclimatic information. They can preserve records of past temperature, precipitation, drought, and extreme weather events. The focus of this dissertation is to use tree ring width, carbon isotopes, oxygen isotopes from multiple trees to characterize climate variability and the tree-ring tropical cyclone record. Living longleaf pine trees (*Pinus palustris* Mill.) were sampled from the Turkey Creek and Big Sandy Creek Units at Big Thicket National Preserve, Texas. Annual tree rings were measured and assigned yearly calendar dates. The latewood portion of each annual ring was shaved with a scalpel, and alpha-cellulose was extracted for carbon and oxygen isotopic analyses. Oxygen isotope records from both sites indicated that individual trees growing in the same stands could vary significantly from each other. The heterogeneity of tree-ring oxygen isotopes was driven by variability in the oxygen isotope composition of soil moisture used for tree growth. Average oxygen isotope chronologies from both sites yielded significant correlations with regional fall (August–October) precipitation (Turkey Creek $r = -0.71$, $p < 0.001$; Big Sandy Creek $r = -0.62$, $p < 0.001$) and z-index (Turkey Creek $r = -0.69$, $p < 0.001$; Big Sandy Creek $r = -0.63$, $p < 0.001$). An average carbon isotope chronology from Big Sandy Creek was also significantly correlated with fall precipitation ($r = -0.59$, $p < 0.001$) and z-index ($r = -0.57$, $p < 0.001$). Individual trees at both sites did not always record similar tropical cyclone events. A composite tropical cyclone chronology from Turkey Creek identified 58% (7 of 12) of the storms known to have produced rainfall at the site. The Big Sandy Creek composite chronology identified 65% (8 of 12) known storms. Wetter than average years that followed dry years were found to mimic the oxygen isotopic signal associated with tropical cyclone events. Additionally, dry years masked the tropical cyclone signal so that it could not be recorded in tree rings.

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Introduction

1.1 Introduction

Trees offer excellent opportunities for climate reconstructions as they serve as archives of annual and seasonal change. Physical tree-ring components (i.e. ring width, ring density) can contain information regarding precipitation variability, drought frequency, temperature variability, and large-scale ocean/atmospheric oscillation patterns (e.g. Grissino-Mayer 1995; Cook et al. 1999; Gray et al. 2004; Henderson and Grissino-Mayer 2009; Stahle et al. 2009). Stable isotopes of tree-ring cellulose (typically hydrogen, oxygen, and carbon) allow for the analysis of temperature, precipitation, relative humidity, drought, and large-scale ocean/atmospheric oscillations. These records are possible because trees are stationary organisms, dependent on the surrounding environment. Using quantitative analyses, detailed information on the tree growth/climate relationship can be obtained.

Although tree-ring width chronologies are plentiful along the southeastern and south central US, tree-ring stable isotope chronologies are few. Extracting meaningful climate information from tree-ring parameters (i.e. ring width) can be difficult in semi-tropical regions, because no one climate parameter (e.g. temperature, precipitation) is limiting to tree growth (Fritts 1976). Using stable isotopes in semi-tropical areas may provide critical information regarding regional climate that is not readily evident using other tree-ring indicators (Helle and Schleser 2004).

Currently, only three tree-ring isotope studies have addressed the relationship between stable isotopes and climate parameters in the southeastern US. Anderson et al. (2005) developed carbon isotope chronologies from baldcypress (*Taxodium distichum* (L.) Rich.) and pond cypress (*Taxodium ascendens* Brongn.) in Florida. Significant correlations were found between $\delta^{13}C$ and precipitation, but site-specific environmental conditions complicated the relationships. Two recent studies utilized the oxygen isotope composition of tree-ring cellulose as a record for tropical cyclone (hurricane) frequency and variability (Miller et al. 2006; Nelson 2008). Miller et al. (2006) developed a 221-year record of hurricane events from southern Georgia as a proof of concept. Nelson (2008) analyzed recent hurricane records from South Carolina and a 300-year record from Pensacola, Florida to determine the portability of the record to other locations along the Gulf and Atlantic Coasts. No tree-ring isotope records exist for the south central US (i.e. Texas).

What remains unclear with respect to the tree-ring hurricane record is whether individual trees in a stand respond similarly (in terms of $\delta^{18}O$) to regional climate and record the same tropical cyclone events. Single-tree isotope chronologies may be problematic for interpreting climate variability and tropical cyclone activity because of isotopic variability between individual trees in a stand. Furthermore, the isotopic composition of soil water being used by trees for photosynthesis may not be homogeneous across a stand. The amount of ^{18}O-depleted rainwater characteristic of tropical cyclone events may not uniformly replace the existing soil moisture across a stand. Lastly, internal and external stand disturbances may affect an individual tree, rendering it incapable of capturing enough of the common climate signal to characterize the regional climate signature.

1.2 Tree-ring Isotopes

1.2.1 Oxygen isotopes in tree rings

The oxygen isotope ratio ($\delta^{18}O$) of tree-ring cellulose is primarily controlled by the isotopic composition of source water (rain, soil water), evaporative enrichment of water in the leaves, and biochemical fractionations (Roden et al. 2000; Anderson et al. 2002; Helle and Schleser 2004; McCarroll and Loader 2004). No fractionation occurs during uptake of water through the roots. Large fractionations can occur in the leaves due to transpiration, leaving leaf water enriched in $\delta^{18}O$ with respect to source water (Roden et al. 2000; Anderson et al. 2002). The oxygen isotopic composition of sucrose synthesized in the leaves is further modified via exchange with stem water (source water) prior to formation of cellulose (Sternberg et al. 1986; Farquhar et al. 1998; Anderson et al. 2002). These fractionations are relatively constant for trees of the same species growing in close proximity to one another, so that the year-to-year variability in cellulose $\delta^{18}O$ likely reflects isotopic changes in source water (Anderson et al. 2002).

The $\delta^{18}O$ of water in the upper portion of the soil column is related to the isotopic composition of meteoric precipitation (Tang and Feng 2001; Anderson et al. 2002). The degree to which soil water $\delta^{18}O$ reflects meteoric precipitation depends on the frequency of rainfall events and the hydrological characteristics of the soil (Tang and Feng 2001; Darling 2004). Soil water $\delta^{18}O$ becomes increasingly enriched in the upper soil column through evapoconcentration as residence time increases (Tang and Feng 2001). Therefore, the interannual variability in cellulose $\delta^{18}O$ should reflect the variability in rainfall amount.

Tropical cyclones are capable of producing precipitation 10–20‰ depleted in ^{18}O with respect to normal precipitation (Gedzelman and Arnold 1994; Lawrence and Gedzelman 1996; Lawrence 1998). This rainfall signal is capable of remaining in the soil for several weeks after the event before is it dampened through evaporative enrichment or mixing with subsequent rainfall events (Tang and Feng 2001). Large depletions in the oxygen isotope composition of tree-ring α-cellulose may reflect rainfall from tropical cyclone events.

1.2.2 Carbon isotopes in tree rings

The carbon isotope composition ($\delta^{13}C$) of tree-ring α-cellulose is primarily a product of the concentration of atmospheric CO_2 (c_a), the concentration of CO_2 inside the leaf (c_i), and fractionation as a result of carboxylation. Diffusion of CO_2 through leaf stomata results in an approximately –4.4‰ discrimination, while carboxylation results in an approximately –27‰ fractionation (Farquhar et al. 1989). When c_i/c_a is high, stomatal conductance is high, which results in a strong discrimination against ^{13}C during carboxylation. Low c_i/c_a related to decreased stomatal conductance results in decreased discrimination against ^{13}C, leading to enriched $\delta^{13}C$ values in tree-ring cellulose. Therefore, variations in the $\delta^{13}C$ of tree-ring cellulose should reflect changes in climate variables directly related to stomatal aperture (i.e. temperature, precipitation, relative humidity).

1.3 Site Description

Big Thicket National Preserve (BTNP) is located along the southeastern Texas Coastal Plain. The preserve was established in 1974, and consists of numerous land units typically located along creeks or rivers. Mean annual precipitation over the last 25 years is 1350 mm, and mean annual temperature is 21 °C. Two sites were selected for sampling, the Turkey Creek Unit (TC) (30.59º N, 94.33º W) and the Big Sandy Creek Unit (BSC) (30.65ºN, 94.67ºW) (Figure 1.1). The dominant soil type in the Turkey Creek Unit was the Kirbyville-Niwana Complex, which is moderately well drained (hydrologic soil group B) and contains approximately 45% sand (National Resources Conservation Service 2009). Slope throughout the sample area was less than 1%, and depth to water table in the stand was approximately 80 cm (National Resources Conservation Service 2009). The stand consisted mainly of young (60–75 yrs) longleaf pine and young (50–70 yrs) loblolly pine (*Pinus taeda* L.). Understory vegetation was sparse at the time of sampling (March 2007) because the stand had recently been burned. Significant tree mortality resulted from Hurricane Rita (2005). Several canopy trees had been either uprooted or snapped off up the stem.

The majority (85%) of the soils in the Big Sandy Creek Unit were Pinetucky fine sandy loam (hydrologic soil group B, moderately well drained) (National Resources Conservation Service, 2009). The other 15% were Pinetucky and Conroe (hydrologic soil group C, moderately well drained). Soils were approximately 65% sand, and depth to water table was >2 m. Big Sandy Creek was characterized by mature (ca. 150 yrs) longleaf pine and loblolly pine. Understory vegetation was sparse during sampling because of prescribed burning. Significant tree mortality resulted from Hurricane Rita (2005) and Hurricane Ike (2008).

1.4 Methods

Tree-ring samples for this study were collected using a standard 12 mm increment borer, which allows for live sampling of a tree with minimal risk of damage. Living mature longleaf pine (*Pinus palustris* Mill.) trees were targeted for sampling because the species has previously been utilized for isotopic studies in the Southeast (Miller et al. 2006; Nelson 2008). Increment cores were dried and mounted in core mounts for surfacing. Each core was surfaced with progressively-finer sanding paper so that the ring structure was clearly visible under standard magnification. Annual tree rings were visually and statistically crossdated to ensure correct assignment of yearly dates to each annual ring (Holmes 1983; Stokes and Smiley 1996). Annual tree-rings and seasonal ring components (earlywood and latewood) were measured on a movable-stage micrometer to the nearest 0.001 mm, and master tree-ring width chronologies were developed from the measured series using the computer program ARSTAN (Cook 1985).

Carbon and oxygen isotope data were collected by shaving the LW portions of each annual ring under a microscope with a scalpel. Alpha-cellulose was obtained from the whole wood samples using soxhlet extraction techniques (Loader et al. 1997; Rinne 2005), which removes all other wood components (i.e. resins, lignin, hemicellulose, and holocellulose). To ensure the α-cellulose samples were not contaminated by adhesives used during core mounting, total carbon was analyzed for several samples, including whole wood, extracted α-cellulose, and IAEA C3 cellulose (international carbon cellulose standard (Table 1.1).

Approximately 100 μg of α-cellulose was weighed in silver capsules for oxygen isotope analysis, and duplicate analyses were collected for every year. Oxygen isotope data were collected on a Finnigan Thermochemolysis/Elemental Analyzer (TC/EA) connected to a Finnigan Delta XL Plus mass spectrometer. The $\delta^{18}O$ results are reported as VSMOW in per mil (‰) notation where $\delta = (R_{sample}/R_{standard}-1)*1000$. Analytical reproducibility of the international and laboratory working standards for all analyses was < 0.20‰ (n = 120).

Approximately 1 mg of α-cellulose was weighed in tin capsules for oxygen isotope analysis. Carbon isotope data were collected on a Costech Elemental Analyzer (EA) connected to a Finnigan Delta XL Plus mass spectrometer. The $\delta^{13}C$ results are reported versus PDB in per mil (‰) notation where $\delta = (R_{sample}/R_{standard}-1)*1000$. Analytical reproducibility of the international and laboratory working standards for all analyses was < 0.15‰ (n = 35).

Regional instrumental climate data were obtained from the National Climatic Data Center (NCDC 2009) to characterize the relationship between tree-ring indicators (carbon, oxygen, and ring width). Climate data were seasonalized over the LW portion of the growing season where the climate correlations were statistically significant (August–October). Pearson correlation analyses were conducted using seasonalized climate data and multiple tree-ring indicators to quantify the statistical relationship. Multiple regression and principal component analyses were also conducted where appropriate.

The tree-ring hurricane record was evaluated using autoregressive (AR-1) modeling of oxygen isotope series to highlight the negative ^{18}O anomalies associated with hurricanes (Miller et al. 2006; Nelson 2008). The predicted values (model) were subtracted from the observed values (isotope time series) to obtain a residual chronology. Using this method, Miller et al. found that most negative residuals ≤ –1.0 indicated anomalously light isotope values associated with confirmed storm events. Additionally, many years with negative residuals between –0.5 and –1.0 were also affected by storm events. For this study residuals ≤ –0.5 were considered anomalous. However, this –0.5 AR-1 residual threshold is further evaluated to determine if it is appropriate for all sites (Chapter 3).

1.5 The Dissertation

The focus of this study is to use multiple tree-ring indicators (carbon, oxygen, and ring width) to characterize the tree-ring/climate relationship at Big Thicket National Preserve, Texas. The dissertation has four primary research objectives. The first is to quantitatively address the isotopic variability that can be expected among individual trees in a stand (Chapter 2, Chapter 4). Second, the implications of isotopic variability on the tree-ring climate relationship are evaluated with respect to correlation with regional climate parameters (Chapter 2, Chapter 4) and the tree-ring tropical cyclone record (Chapter 2, Chapter 3). Thirdly, the dissertation examines the effects of sample depth (number of trees) and regional climate variability on the tree-ring tropical cyclone record (Chapter 3). Finally, multiple tree-ring indicators (ring width, carbon isotopes, oxygen isotopes) are evaluated to address the relationship of each indicator to regional climate parameters (Chapter 4).

Although the tree-ring tropical cyclone record is addressed in this dissertation, a rigorous evaluation of the tropical cyclone record is not the focus. The effects of isotopic and regional climate variability on the record are addressed. Sampling methods for this study are inherently biased to extracting seasonal climate information during the latewood (August–October) portion of the growing season. This portion of the growing season corresponds to the peak Atlantic hurricane season, but incorporating the entire latewood portion of the ring can result in missing storms as a result of the dynamic nature of tropical cyclones (Lawrence et al. 2002, Gedzelman et al. 2003) and ephemeral nature of rainfall events in soil water (Tang and Feng 2001).

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Appendix 1

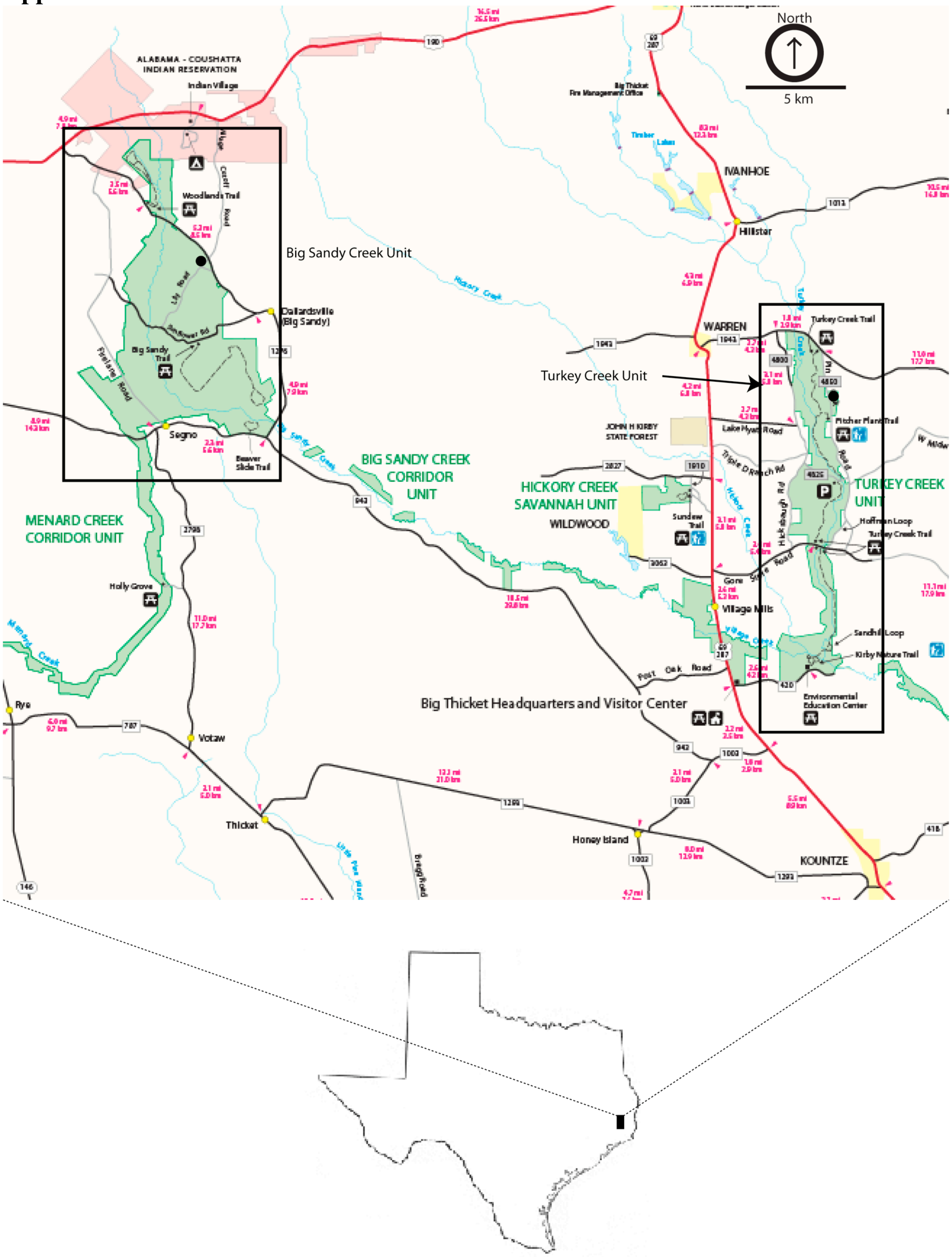

Figure 1.1. Map of the Turkey Creek and Big Sandy Creek Units. Map adapted from the National Park Service.

Table 1.1. Total carbon for whole wood, extracted α-cellulose, and IAEA C3 cellulose. Total carbon for extracted α-cellulose (*) represent the average of four samples. Extracted α-cellulose and IAEA C3 cellulose are almost identical, indicating no contamination.

Sample Type	Total Carbon (%)
Whole Wood	56.66
Extracted α-cellulose	39.69* (40.6–39.1)
IAEA C3 cellulose	40.5

Chapter 2

A Multi-Tree Perspective of Oxygen Isotope and Climate Variability from Longleaf Pine (*Pinus palustris* Mill.), Big Thicket National Preserve, Texas, USA

This manuscript was submitted to the Journal of Geophysical Research-Biogeosciences for review October 2009. Figures 2.4 and 2.5 were changed to color for this version.

Abstract

Single-tree stable isotope chronologies used to characterize regional climate and tropical cyclone events may be problematic due to variability among individual trees in a stand. External factors such as soil water isotopic variability, soil heterogeneity, and/or stand disturbance will affect the isotopic composition of individual trees in a stand. Single-tree isotope chronologies should be tested against multiple-tree chronologies to determine whether individual trees sufficiently characterize regional climate and tropical cyclone variability. Four individual trees growing in the same stand in Big Thicket National Preserve were analyzed to evaluate whether they synchronously record regional climate and tropical cyclone events. Individual trees exhibited significant, but variable correlations with monthly instrumental climate records (precipitation, z-index). The average isotope chronology showed strong correlation with fall precipitation ($r = -0.71$, $p < 0.0001$) and fall Palmer z-index ($r = -0.67$, $p < 0.0001$) (short-term drought record). No correlation was found with the Palmer Drought Severity Index (PDSI, long-term drought record). Lower between-tree isotopic variability was observed in anomalously wet years (fall precipitation > 25-year average). The ability of the individual tropical cyclone models to capture and event was low (≤ 50%), and individual trees did not always record similar events. These data show that sample depth is important for properly characterizing climate variability and topical cyclone frequency through time, especially for periods prior to reliable instrumental records.

Keywords: Oxygen isotopes, tree rings, tropical cyclones, south-central U.S.

2.1 Introduction

Tree rings can provide high-resolution records of regional climate reaching well beyond instrumental records. The oxygen isotope composition of tree-ring α-cellulose in part reflects the oxygen isotope composition of the source water taken up by tree roots (Anderson et al. 1998; Roden et al. 2000; Tang and Feng 2001; Anderson et al. 2002; Waterhouse et al. 2002; Helle and Schleser 2004; McCarroll and Loader 2004). When trees utilize soil water from the upper soil column, the isotopic composition of soil water (source) is related to the isotopic composition of precipitation (Tang and Feng 2001; Anderson et al. 2002; Helle and Schleser 2004; McCarroll and Loader 2004). The α-cellulose $\delta^{18}O$ of shallow-rooted trees should therefore facilitate analyses of regional climate parameters.

Tree-ring $\delta^{18}O$ also has proven useful for characterizing tropical cyclone frequency and variability along the Gulf and Atlantic Coasts of the southeastern U.S. (Miller et al. 2006; Nelson 2008). Miller et al. (2006) developed a 221-year record of tropical cyclone events from southern Georgia, while Nelson (2008) developed two short records from coastal South Carolina and a 294-year record from Pensacola, Florida. Each of these studies utilized only one tree for any portion of the time series to characterize tropical cyclones. What remains unclear is whether individual trees in a stand respond similarly (in terms of $\delta^{18}O$) to regional climate, or record the same tropical cyclone events. Single-tree isotope chronologies may be problematic for interpreting climate variability and tropical cyclone activity. The isotopic composition of soil water being used by trees for photosynthesis may not be homogeneous across a stand. The amount of ^{18}O-depleted rainwater characteristic of tropical cyclone events may not uniformly replace the existing soil moisture across a stand. Lastly, internal and external stand disturbances may affect an individual tree rendering it incapable of capturing enough of the common climate signal to characterize the regional climate signature.

Extracting meaningful climate information from tree-ring parameters (i.e. ring width) can be difficult in semi-tropical regions, because no one climate parameter (e.g. temperature, precipitation) is limiting to tree growth (Fritts 1976). Using stable isotopes in semi-tropical areas may provide critical information regarding regional climate that is not readily evident using other tree-ring indicators (e.g. Helle and Schleser 2004). The purpose of this study is to investigate the relationship between latewood (LW) $\delta^{18}O$ of longleaf pine (*Pinus palustris* Mill.) trees and regional climate using trees growing in close proximity to each other in the same stand.

The degree to which individual isotope series in a stand record similar climate signals, trends, and tropical cyclone events is evaluated. It is unlikely that individual trees in a stand will always record the same storm event. It is also possible that isotopic variability observed among individual trees complicates the correlation with regional climate. Incorporating additional trees into the record should provide a more comprehensive analysis of regional climate and tropical cyclone frequency and variability. These data will help refine the current tree-ring tropical cyclone record.

2.2 Oxygen Isotopes in Tree Rings

The oxygen isotope ratio of tree-ring cellulose is primarily controlled by the isotopic composition of source water (rain, soil water), evaporative enrichment of water in the leaves, and biochemical fractionations (Roden et al. 2000; Anderson et al. 2002; Helle and Schleser 2004; McCarroll and Loader 2004). No fractionation occurs during uptake of water through the roots. Large fractionations can occur in the leaves due to transpiration, leaving leaf water enriched in $\delta^{18}O$ with respect to source water (Roden et al. 2000; Anderson et al. 2002). The oxygen isotopic composition of sucrose synthesized in the leaves is further modified via exchange with stem water (source water) prior to formation of cellulose (Sternberg et al. 1986; Farquhar et al. 1998; Anderson et al. 2002). These fractionations are relatively constant for trees of the same species growing in close proximity to one another, so that the year-to-year variability in cellulose $\delta^{18}O$ likely reflects isotopic changes in source water (Anderson et al. 2002).

The $\delta^{18}O$ of water in the upper portion of the soil column is related to the isotopic composition of meteoric precipitation (Tang and Feng 2001; Anderson et al. 2002). The degree to which soil water $\delta^{18}O$ reflects meteoric precipitation depends on the frequency of rainfall events and the hydrological characteristics of the soil (Tang and Feng 2001). Soil water $\delta^{18}O$ becomes increasingly enriched in the upper soil column through evapoconcentration as residence time increases (Tang and Feng 2001). Therefore, the interannual variability in cellulose $\delta^{18}O$ should reflect the variability in rainfall amount.

Tropical cyclones are capable of producing precipitation 10–20‰ depleted in ^{18}O with respect to normal precipitation (Gedzelman and Arnold 1994; Lawrence and Gedzelman 1996; Lawrence 1998). This rainfall signal is capable of remaining in the soil for several weeks after the event before is it dampened through evaporative enrichment or mixing with subsequent rainfall events (Tang and Feng 2001). Large depletions in the oxygen isotope composition of tree-ring α-cellulose likely reflect rainfall from tropical cyclone events.

2.3 Site Description

The Big Thicket National Preserve (BTNP) in southeastern Texas was established in 1974 and consists of numerous land units, typically located along creeks and rivers. The preserve is located along the southeastern Texas Coastal Plain, and has been affected by numerous tropical cyclone systems. Here we report data collected from longleaf pine trees in the northeastern portion of the Turkey Creek Unit (30.59º N, 94.33º W). The dominant soil type in the stand is the Kirbyville-Niwana Complex, which is moderately well drained (hydrologic soil group B) and contains approximately 45% sand (National Resources Conservation Service 2009). Slope throughout the stand is less than 1%, and depth to water table in the stand is approximately 80 cm (National Resources Conservation Service 2009).

The stand consisted mainly of young (60–75 yrs) longleaf pine and young (50–70 yrs) loblolly pine (*Pinus taeda* L.). Understory vegetation was sparse at the time of sampling (March 2007) because the stand had recently been burned. Significant tree mortality resulted from Hurricane Rita (2005). Several canopy trees had been either uprooted or snapped off up the stem. This, combined with low vegetation cover, significantly increased sun exposure at the soil surface.

2.4 Methods

Ten longleaf pine trees were sampled using a 12 mm increment borer. The trees were growing approximately 30 m apart, within the interior of the stand. Annual growth rings were crossdated using standard dendrochronological techniques (Stokes and Smiley 1996), and dating was statistically verified using the computer program COFECHA (Holmes 1983; Grissino-Mayer 2001). Four of these trees were randomly selected for isotopic analysis over a 25-year period (1982–2006). Annual rings were separated into their seasonal components (earlywood and latewood) and sliced into thin (50 μm) slivers using a scalpel. Alpha-cellulose was extracted using soxhlet extraction techniques (Loader et al. 1997; Rinne et al. 2005). Approximately 100 μg of latewood α-cellulose was weighed and placed into silver capsules. Oxygen isotope data were collected on a Finnigan Thermochemolysis/Elemental Analyzer (TC/EA) connected to a Finnigan Delta XL Plus mass spectrometer. All samples were run in duplicate. Standards were placed every six samples throughout each run. The data were corrected to a single standard (Sigma Cellulose) with an average $\delta^{18}O$ = 27.34‰ (VSMOW) and a standard deviation < 0.2‰ (n = 68). Results are reported in per mil (‰) notation were $\delta = (R_{sample}/R_{standard}-1)1000$.

Between-tree isotopic variability was determined using paired t-tests on the series differences. Individual latewood $\delta^{18}O$ series and monthly regional climate data (precipitation, temperature, PDSI, and z-index) were analyzed with Pearson correlation analyses using SAS® to determine which variables were significant. These analyses were repeated using the average $\delta^{18}O$ chronology. Significant months (e.g. August–October) were combined and re-evaluated to characterize the seasonal response recorded in latewood $\delta^{18}O$.

Each individual latewood isotope series was analyzed to determine their agreement in identifying tropical cyclone events. Hurricane track data were obtained from NOAA Coastal Services and Unisys Weather for all storms within 250 km of Kountze, Texas (closest town to BTNP) (NOAA Coastal Services Center 2009; Unisys Weather 2009). The 250 km radius is an arbitrary distance that was used in previous studies (Miller et al. 2006; Nelson 2008). The storm track data were verified against daily precipitation logs from Kountze, Texas (National Climatic Data Center 2009) to determine if precipitation from the storm event was recorded.

An autoregressive model (AR-1) was applied to each individual isotope series to highlight the isotopic anomalies associated with tropical cyclone events (Miller et al. 2006; Nelson 2008). The predicted values (model) were then subtracted from the observed values (isotope time series) to obtain a residual chronology. Using this method, Miller et al. found that most negative residuals ≤ –1.0 indicated anomalously light isotope values associated with confirmed storm events. Additionally, many years with negative residuals between –0.5 and –1.0

were also affected by storm events. This study uses the same criteria for identifying tropical cyclone events for comparison purposes.

2.5 Results

2.5.1 Individual isotope series variability

Individual oxygen isotope series exhibited significant variability from one another in several years over the 25-year period (Figure 2.1). Correlations of latewood $\delta^{18}O$ between individual trees ranged from 0.41 to 0.58. TC001 was highly variable (sd = 1.24) while TC003 had the lowest variability over the 25-year period (sd = 0.77). Paired t-tests on the differences of the individual series revealed that among the six possible combinations of trees, two combinations (TC002 and TC006; TC003 and TC006) were statistically different from each other at the 95% confidence interval (Table 2.1).

To determine whether the four isotope series could be used to evaluate regional climate, the expressed population signal (EPS) equation was applied;

$$EPS = (nr_{bt})/(nr_{bt}+(1-r_{bt}))$$

where n is the number of trees, and r_{bt} is the average between-tree correlation. The EPS equation is useful to determine the number of trees needed for effective climate analysis (Wigley et al. 1984; McCarroll and Loader 2004). An EPS around 0.85 indicates the number of trees is adequate. Based on the average between-tree correlations, an EPS of 0.80 was calculated for the four Turkey Creek trees.

2.5.2 δ^{18}O and regional climate

Correlations of individual LW $\delta^{18}O$ series versus instrumental monthly precipitation records showed each individual series was statistically significant with average fall (August–October) precipitation (Table 2.2). TC006 had the strongest precipitation correlation (r = –0.61, p

< 0.001), while TC002 had the lowest ($r = -0.49$, $p < 0.010$). To determine if increasing the number of trees would improve the relationship, four isotope series were averaged together to obtain one master latewood $\delta^{18}O$ chronology for the site. The average $\delta^{18}O$ chronology revealed a stronger inverse relationship with fall precipitation over the 25-year period ($r = -0.71$, $p < 0.0001$) (Figure 2.2). No correlation was observed with monthly temperature.

Two drought indices were compared to the average $\delta^{18}O$ record, PDSI and the Palmer z-index. No correlation was observed between average $\delta^{18}O$ and fall (August–October) PDSI. However, latewood $\delta^{18}O$ was positively correlated to late winter/spring (February–May) PDSI ($r = 0.48$; $p < 0.020$). This correlation was unexpected, and the positive statistical relationship to drought is atypical. Fall (August–October) z-index correlated to LW $\delta^{18}O$ ($r = -0.67$; $p < 0.0001$) and fall precipitation ($r = 0.98$; $p < 0.0001$) (Figures 2.3A, B).

2.5.3 The tropical cyclone record

Thirteen years were identified as being affected by one or more tropical cyclone events based on best-track data and local precipitation records during the 25-year period (Table 2.3). One year (Tropical Storm Allison, 2001) was not included in these analyses as the storm occurred in the earlywood portion of the growing season (6 June 2001). Hurricane Lili (2002) was not confirmed to have dropped precipitation at the Kountze, Texas climate station, but was recorded as a negative anomaly by all four trees.

The individual trees exhibited variability identifying tropical cyclone events (Figure 2.4). Three events (1986-Hurricane Bonnie Category 1, 1998-Tropical Storm Frances, 2002-Hurricane Lili) were identified by all four trees. TC001 recorded 2003, 2002, 1998, 1989, 1986, and 1983. TC002 recorded 2003, 2002, 1998, 1989, 1986, and 1985. TC003 recorded 2002, 1998, 1988, 1986, and 1985. TC006 recorded 2003, 2002, 1998, 1986, and 1985. Three events

(1987-Tropical Storm (no name), 1995- Tropical Storm Dean, and 2005- Hurricane Rita) were not detected by any of the trees. Hurricane Rita was a Category 5 hurricane that passed directly over the Turkey Creek Unit (as a Category 3), dropping over 16 cm of precipitation.
Two individual trees (TC001 and TC002) detected 6 of 12 events (50%), while two others (TC003 and TC006) detected 5 of 12 events (42%). When the AR-1 model was applied to the average isotope chronology, it identified 5 of the 12 storm events (42%) (Figure 2.5). To provide a comprehensive characterization of tropical cyclone events during the 25-year period, we combined the predictions from the four individual models into one composite tropical cyclone chronology. This practice is commonly used when developing fire history chronologies from multiple tree-ring samples (e.g. Baisin and Swetnam 1990; Grissino-Mayer 1995; Lewis 2003). If a single tree in a stand records the event, then the event is confirmed to have affected the stand, even if multiple trees in the stand fail to record it. The composite tropical cyclone chronology identified 7 of the 12 total events in the 25-year period (58%).

A number of "false positives," years with negative isotopic anomalies not related to known tropical cyclone events, were found (1996, 1994, 1993, 1991, and 1984). One year, 1996, was systematically recorded among three or four of the series. These false positives indicate either another climatic phenomenon is capable of producing significantly depleted rainfall, or the AR-1 model is not appropriate for short time series.

2.6 Discussion

2.6.1 Single-tree versus multiple-tree climate chronologies

Isotopic variability was observed among the individual isotope series. Although the trees differ in terms of isotopic value from year to year in the 25-year record, all trees display similar trends through time. The calculated EPS of 0.80 was lower than the suggested minimum of 0.85

(McCarroll and Loader 2004). However, the strong relationship between LW $\delta^{18}O$ and precipitation indicates that this minimum EPS is too stringent.

Several factors can influence the degree to which individual trees in a stand covary through time. Differences in topography, vegetation cover, soil/habitat type, or exposure, could result in heterogeneous soil water isotopic ratios throughout a stand. This variability in soil water $\delta^{18}O$ would then be transferred to tree rings resulting in a portion of the oxygen isotope record not reflecting the regional climate signal. Each tree sampled for this study was similar in age (ca. 75 years), stand and canopy position, exposure, and was sampled at equal distance above ground level (10–15 cm). Depth to water table in this portion of the Turkey Creek Unit is relatively shallow (80 cm). The relationships between the isotope series and instrumental precipitation suggests that the trees are not utilizing deeper water sources.

In years 1984, 1986, 1990, 1994, 1996, 1998, and 2002, LW $\delta^{18}O$ values of the trees were within approximately 1‰ of each other (Figure 2.1). In other years (e.g. 1985, 1987, 1989, 1991, 1993, 1995, 1997, 2000, and 2005), the isotopic difference was 2–4‰ (Figure 2.1). Most years where LW $\delta^{18}O$ was similar were years where August–October precipitation was >20 cm above the 25-year average. Only 1990 had below-average August–October precipitation. Conversely, years with high isotopic variability had below-average precipitation (except 1985 and 1997). The observed trends in these trees are likely due to soil water isotopic variability. Soil water $\delta^{18}O$ closely matches precipitation $\delta^{18}O$ in years where soil water is frequently replaced by precipitation (Darling 2004). Persistent drought (i.e. multiple months or years) results in isotopically enriched soil water. Low isotopic variability for 1990 could be attributed to prolonged drought conditions that persisted prior the current fall season. Years where these trees exhibited high variability were typically characterized by only late-summer/fall drought.

2.6.2. Climate relationship

Semi-tropical areas like the Texas Gulf Coast do not always exhibit strong relationships between tree ring indicators and rainfall, because rainfall is rarely the most limiting factor for tree growth (e.g. Fritts 1976). No other study in the southeastern or south-central U.S. shows a statistical relationship between tree-ring $\delta^{18}O$ and regional precipitation. Additionally, ring-width measurements from the Turkey Creek Unit showed no statistical relationship with monthly precipitation. The strong correlation between latewood $\delta^{18}O$ and precipitation illustrates how oxygen isotope analyses provide additional information regarding the tree-ring/climate relationship.

A statistically significant positive correlation was documented between LW $\delta^{18}O$ and February–May PDSI. No correlation was noted during the fall portion of the growing season. The fall z-index data were well correlated with LW $\delta^{18}O$ during that portion of the growing season. A positive correlation between drought and cellulose $\delta^{18}O$ is atypical, because drought (negative PDSI) will result in a corresponding enrichment in soil water $\delta^{18}O$, as well as cellulose $\delta^{18}O$. Karl (1985) suggested that the z-index was a more effective recorder of short-term moisture deficit than PDSI. Prior months are weighed more heavily in PDSI than in the z-index, which only incorporates conditions in the current month (Karl 1985). The $\delta^{18}O$ of soil water (and therefore cellulose) will respond more rapidly to changes in soil moisture status. This explains the strong correlation between LW $\delta^{18}O$ and z-index, and z-index and precipitation in the same season. The “memory effect” of PDSI, weighting the previous month(s) conditions more heavily than the current, explains the lag in correlation between LW $\delta^{18}O$ and PDSI.

2.6.3 Single-tree versus multiple-tree hurricane records

The best result obtained by individual trees at this site was 50% (6 out of 12 events). The average $\delta^{18}O$ chronology identified only 5 out of 12 events (42%). A composite chronology developed from all four trees identified 7 out of 12 tropical cyclone events (58%). Ideally, each tree in a stand should record the same negative isotopic anomalies associated with known tropical cyclone events. Results indicate that significant between-tree variability could be expected in the $\delta^{18}O$ of cellulose from trees as a result of sol water heterogeneity. Incorporating additional trees will reduce the likelihood of missing a storm because of isotopic variability. The composite tropical cyclone chronology developed for this study increased the accuracy of the record over any of the individual records.

2.6.4 False Positives in the record

One false positive year was common to three of the four series (1996). Four other false positive years were also identified by the four series (1984, 1991, 1993, and 1994). An alternative climatic phenomenon besides tropical cyclones must be capable of producing significantly depleted rainfall. Based on Southern Oscillation Index (SOI) data, El Niño conditions persisted in 1991, 1993, and 1994 (NOAA Climate Prediction Center 2009). El Niño conditions were not noted in 1984 or 1996. Nelson (2008) also detected a significant number of false positives in records from South Carolina and Florida coinciding with El Niño events. If the dominant moisture source for the region changes from the Gulf to more Pacific influence during El Niño years, then this rainfall will be isotopically depleted from normal precipitation.

Another alternative is that drought in the previous year, followed by wet conditions in the current year, approximates the negative isotopic signatures associated with tropical cyclones. The year 1996 was identified by three of the four trees, and the fourth tree exhibited a negative residual of –0.3. August–October precipitation in 1995 was 25.5 cm, approximately12 cm below the 25-year average. August–October rainfall in 1996 was 49.6 cm, approximately 12 cm above the 25-year average. The return to above-average precipitation from drought conditions in the previous year resulted in soil water $\delta^{18}O$ depleted in 1996 (with respect to 1995) mimicking the negative anomaly associated with tropical cyclones.

2.6.5 Why trees might miss a tropical cyclone event

Three tropical cyclone events (1987, 1995, and 2005) dropped precipitation near the site but were not recorded in the tree rings. Both 1987 and 1995 were tropical storms, and 2005 was a Category 5 hurricane (Rita). Hurricane Rita (Category 3 at the sample site) dropped over 16 cm of precipitation in the area causing damage to the sampled stand. Instrumental drought data (PDSI and z-index) indicated moderate drought during the latewood portion of the growing season. We hypothesize that soil water was enriched during the drought events, which dampened the ^{18}O-depleted precipitation signal by isotopic mixing. It is also possible that soil hydrological effects reduced residence time of the rainwater associated with Hurricane Rita. Tang and Feng (2001) noted that when volumetric water content of soil is low, preferential flow during rainwater infiltration my result in a large amount of pore space being bypassed by the infiltrating water. This results in incomplete replacement of the older ^{18}O-enriched soil water with the newer ^{18}O-depleted rainwater.

Tropical Storm Dean (1995) passed west/southwest of the sample area, dropping approximately 5.3 cm of precipitation near the site (NOAA Coastal Services Center; National Climatic Data Center). Significant drought was not observed in either instrumental PDSI or z-index records during1995. This storm originated in the Gulf of Mexico, and was only a tropical storm for a short period of time before weakening into a tropical depression (Unisys 2009). It is possible this system did not have time to become depleted before passing over the sample site.

The 1987 tropical storm (not named) followed a similar track as Rita, with the eyewall passing adjacent to the sample area, and dropped approximately 7.8 cm of precipitation (NOAA CSC; NCDC). Although instrumental drought records did not indicate significant drought during this year, all four trees were enriched by approximately 2–4‰ in 1987 with respect to 1986 (Figure 2.1). This storm, originating in the Gulf of Mexico, may not have had time to become depleted before raining on the site.

2.7 Conclusions

Tree rings afford the resolution needed to analyze climate variability and hurricanes on seasonal, decadal, and centennial time scales. Currently, the southeastern and south-central U.S. is lacking in isotope-based tree-ring chronologies. Obtaining longer, multi-tree isotope chronologies will result in a more robust characterization of decadal to multi-decadal scale climate variability in the southeastern U.S. The individual trees exhibited significant, but variable correlations to instrumental precipitation and drought records. An average $\delta^{18}O$ chronology revealed strong correlations with fall (August–October) precipitation and z-index (short term drought). Individual trees in the stand did not always record the same tropical cyclone events. Combining the predictions from each tree into one composite chronology resulted in 58% accuracy detecting tropical cyclones known to have impacted the sample region. The results support three major conclusions. Multiple-tree isotope chronologies provide a more robust relationship with regional climate parameters. Incorporating multiple trees also increases the accuracy of the hurricane record at this site. Observed isotopic variability between individual trees at this site is driven by heterogeneity in soil water $\delta^{18}O$, especially in anomalously dry years.

2.8 Acknowledgements

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Appendix 2

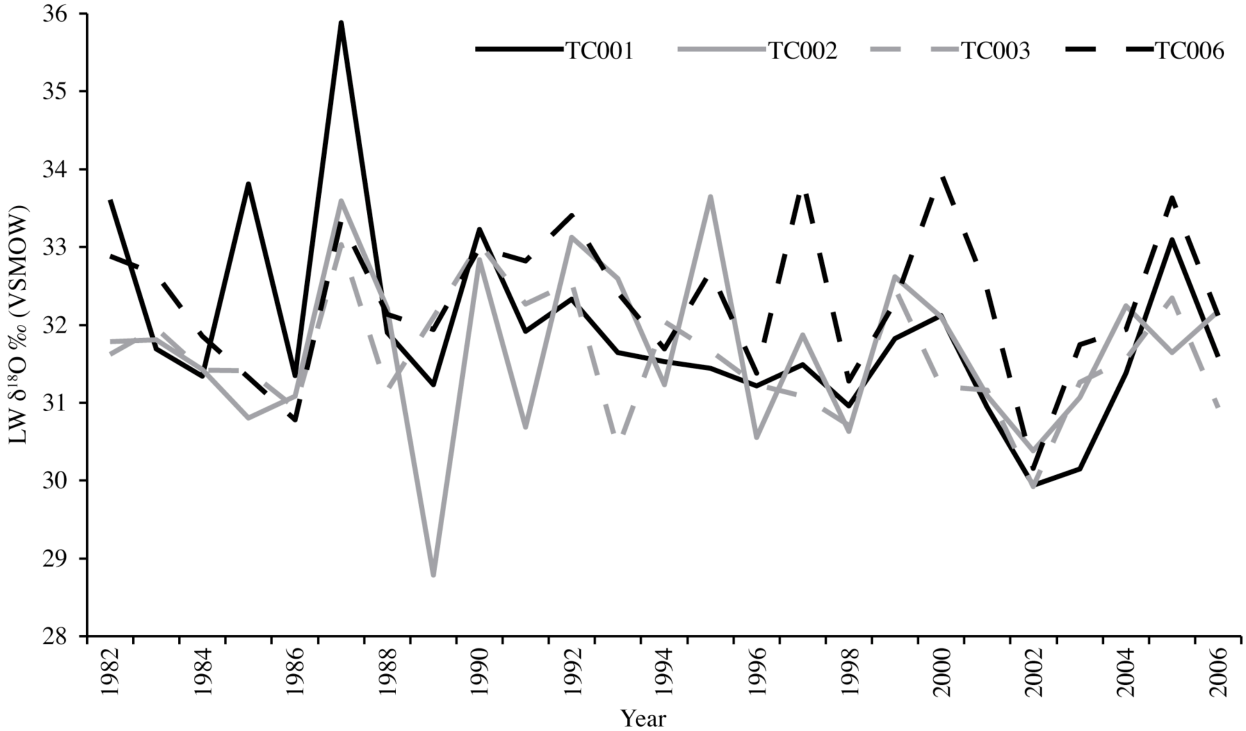

Figure 2.1. Latewood $\delta^{18}O$ for the four trees sampled for this study from 1982–2006. Although the trees differ in terms of absolute $\delta^{18}O$ values in many years, each series follows a similar trend.

Table 2.1. Results from the paired t test conducted on the differences of the individual isotopic series. Four of the six pairs are not statistically different from one another at the 95% confidence interval. Only TC002–TC006 and TC003–TC006 were statistically different from one another.

Difference	Mean	Standard Error	t value	p value
TC001–TC002	0.2240	0.2456	0.91	0.3708
TC001–TC003	0.3228	0.1940	1.66	0.1093
TC001–TC006	–0.4068	0.2251	–1.81	0.0833
TC002–TC003	0.0992	0.2215	0.45	0.6584
TC002–TC006	–0.6300	0.1972	–3.19	0.0039
TC003–TC006	–0.7288	0.1687	–4.32	0.0002

Table 2.2. Correlation values of individual and average LW $\delta^{18}O$ and regional August–October precipitation. Each individual tree was statistically significant. The average $\delta^{18}O$ chronology was well correlated to fall precipitation.

Tree ID	August–October r value	p value
TC001	–0.57	0.0030
TC002	–0.49	0.0100
TC003	–0.59	0.0020
TC006	–0.61	0.0010
Average	–0.71	0.0001

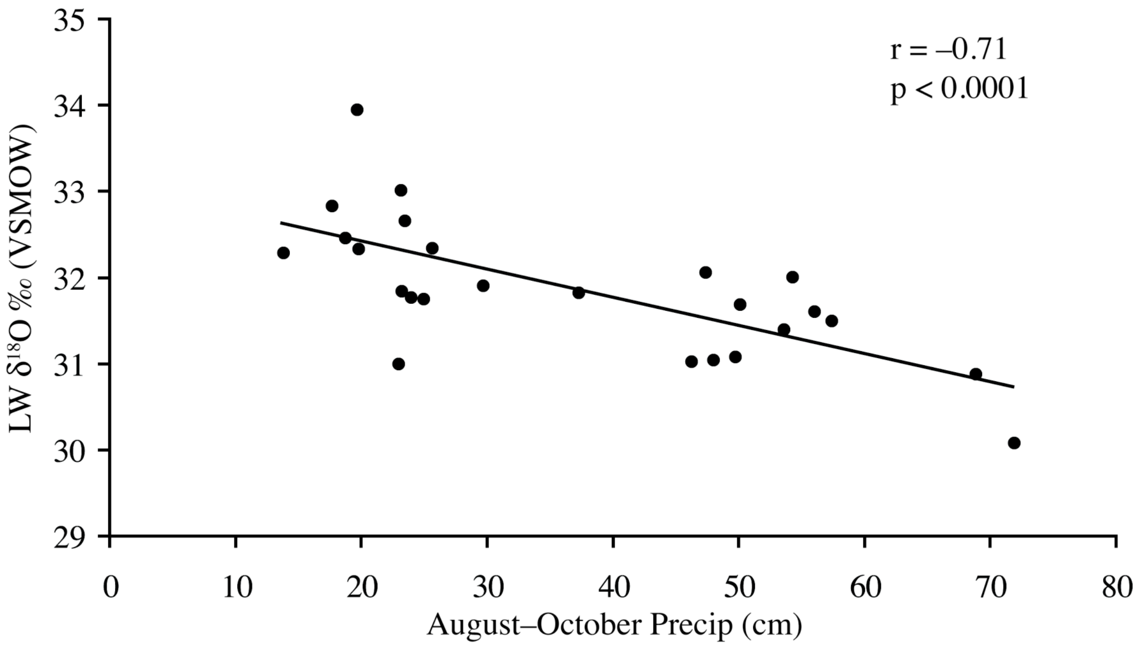

Figure 2.2. Correlation of average latewood $\delta^{18}O$ chronology versus fall (August–October) average precipitation. The black line is the best fit linear regression line fit to the data. Fall precipitation is well correlated to average $\delta^{18}O$, and explains 51% of the variation in the data.

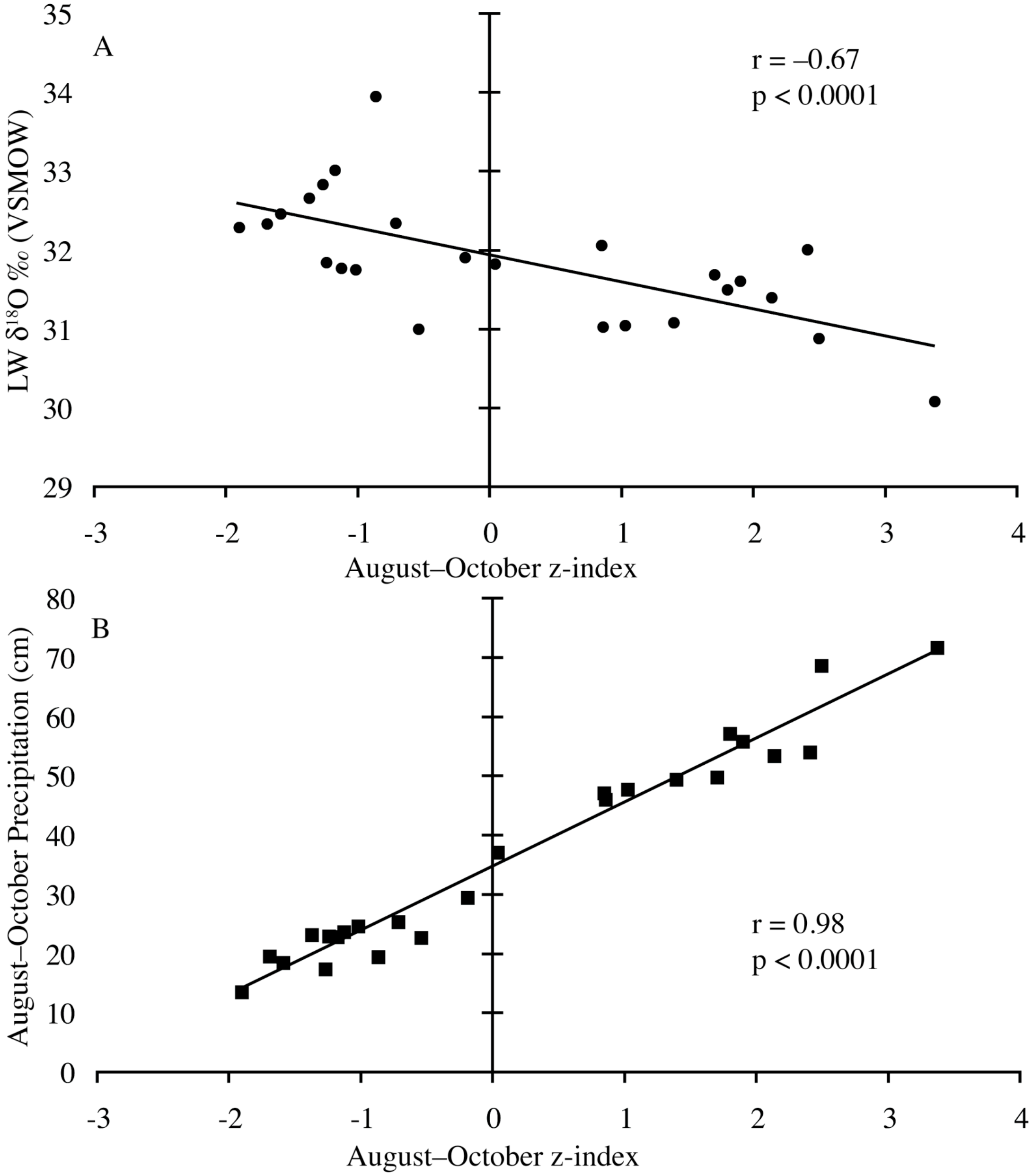

Figure 2.3. Correlation of average latewood $\delta^{18}O$ against fall z-index (A) and fall z-index versus fall precipitation (B). Fall z-index was well correlated with LW $\delta^{18}O$, and provides a much better relationship between isotopes and drought than PDSI since it closely correlates to fall rainfall.

Table 2.3. Tropical cyclone events within a 250 km radius of Kountze, TX. Bold names were confirmed with precipitation in local climate records. An (*) indicates the storm occurred in the earlywood portion of the growing season, and was not included in these analyses. Category is the maximum category during the cyclone lifespan.

Year	Storm Name	Maximum Category
1983	**Alicia**	Hurricane– Cat 3
1985	Danny	Hurricane– Cat 1
	Juan	Hurricane– Cat 1
1986	**Bonnie**	Hurricane– Cat 1
1987	**No Name**	Tropical Storm
1988	**Beryl**	Tropical Storm
1989	**Allison**	Tropical Storm
	Chantal	Hurricane– Cat 1
	Jerry	Hurricane– Cat 1
1995	**Dean**	Tropical Storm
1998	**Frances**	Tropical Storm
2001	***Allison**	Tropical Storm
2002	Lili	Hurricane– Cat 4
2003	**Grace**	Tropical Storm
2004	**Ivan**	Hurricane– Cat 5
2005	**Rita**	Hurricane– Cat 5

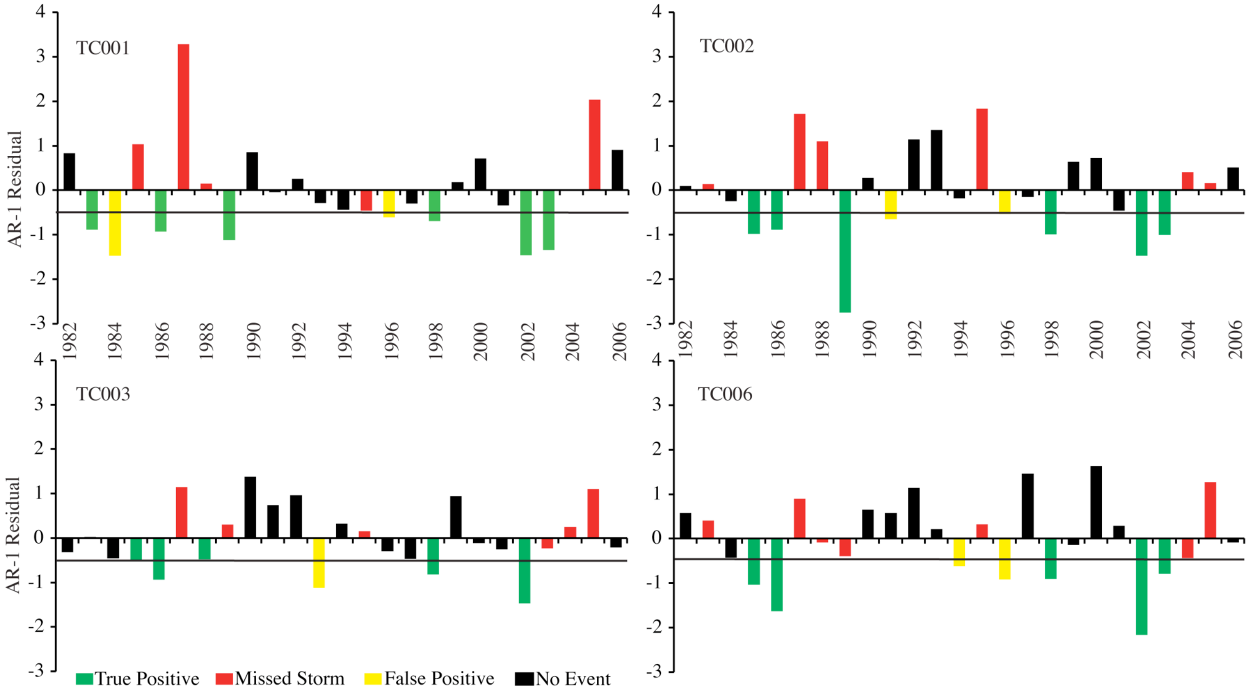

Figure 2.4. AR-1 models for all four trees analyzed for this study. Green bars indicate a storm identified by the model and confirmed to have impacted the site (true positive). Red bars indicate a storm in the climate record that was missed by the trees. Yellow bars indicate an isotopic anomaly not associated with a known storm event (false positive). The horizontal black lines represent the –0.5 AR-1 residual.

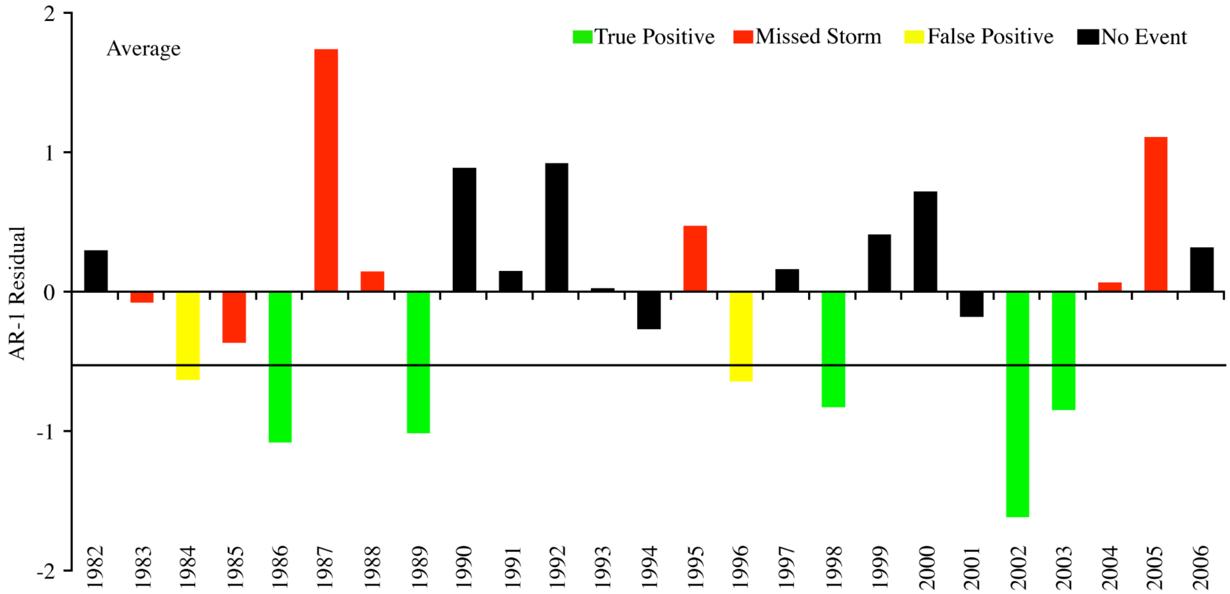

Figure 2.5. AR-1 model calculated from the average $\delta^{18}O$ chronology. Green bars indicate a storm identified by the model and confirmed to have impacted the site (true positive). Red bars indicate a storm in the climate record that was missed by the trees. Yellow bars indicate an isotopic anomaly not associated with a known storm event (false positive). The horizontal black line represents the –0.5 AR-1 residual.

Chapter 3
Evaluating the Role of the Number of Trees and Regional Climate on Tropical Cyclone Records in Tree-Ring Cellulose, Big Thicket National Preserve, Texas, USA

Abstract

Tree rings afford the temporal resolution needed to characterize extreme weather events such as tropical cyclones, the frequency and variability of. False positives and missed storm events reduce the effectiveness of tree-ring hurricane chronologies. Four trees were sampled from two sites in close proximity to each other at Big Thicket National Preserve to address the impact of these phenomena on the record. A composite chronology from the Turkey Creek Unit identified five false positive years (1984, 1991, 1993, 1994, and 1996) and missed five storms (1987, 1988, 1995, 2004, and 2005). The composite chronology from the Big Sandy Creek Unit identified five false positives (1984, 1991, 1994, 1996, and 2001) and missed four storms (1987, 1988, 1995, and 2005). Hurricane records developed from the average chronologies identified fewer storms than the composite chronologies, but contained less false positives. The most effective record with respect to true positive events versus false positive events was developed from an average LW $\delta^{18}O$ series that contained all eight trees sampled for this study. Two false positive years were characterized by above average precipitation in the current fall that followed below average precipitation in the previous year fall. This pattern mimicked the negative isotopic excursion expected from tropical cyclones. Another year (1991) was coincident with a strong El Niño event, resulting in a shift in the dominant moisture source for the Texas Gulf Coast. Drought conditions were noted in years where storms were missed, which dampened the ^{18}O-depleted signal associated with tropical cyclones. These results illustrate how the number of trees affects the tree-ring hurricane record, as well as the role of regional climate in complicating the tree-ring hurricane record.

Keywords: Tree rings, oxygen isotopes, Texas Gulf Coast, tropical cyclones, climate

3.1 Introduction

The $\delta^{18}O$ of tree-ring α-cellulose is primarily related to the $\delta^{18}O$ of source water used for photosynthesis (soil water) (Anderson et al., 1998; Roden et al., 2000; Anderson et al., 2002; Waterhouse et al., 2002). Soil water $\delta^{18}O$ is related to the $\delta^{18}O$ of precipitation, and variability depends on frequency and types of rainfall events (e.g. droughts and deluges) and soil hydrological characteristics (Tang and Feng 2001; Darling 2004). Tropical cyclone rainfall can be 10–20‰ depleted in ^{18}O compared to normal meteoric precipitation (Gedzelman and Arnold 1994; Lawrence and Gedzelman 1996; Lawrence 1998). This ^{18}O-depleted rainfall can remain in the soil for several weeks until it is dampened by evaporative enrichment or isotopic mixing (Tang and Feng, 2001). Large negative excursions in tree-ring α-cellulose likely reflect rainfall from tropical cyclones (Miller et al. 2006; Nelson 2008).

Two issues can complicate the tree-ring hurricane record. First, a false positive is a negative isotopic anomaly in the $\delta^{18}O$ of tree-ring cellulose not associated with a tropical cyclone event. Second, the $\delta^{18}O$ of cellulose may not identify tropical cyclone events known to have produced rain on the site (based on local precipitation records). Previous studies hypothesized that changes in the dominant moisture source associated with El Niño/Southern Oscillation (ENSO) could result in light isotopic anomalies in tree-ring cellulose similar to tropical cyclone events. Several mechanisms can be responsible for missed storms in the record. Tropical cyclones are dynamic systems, and the isotopic depletions associated with tropical cyclones are not homogenous within the cyclone. Rainfall associated with portions of a cyclone not significantly depleted in ^{18}O might not be significantly different from normal meteoric precipitation. Additionally, rainfall amounts are typically not even across a cyclone, so that the amount of rainfall received at a given site may be minimal. Finally, the $\delta^{18}O$ of existing soil water may be enriched so that the ^{18}O-depleted rainfall signal associated with tropical cyclones can be masked via mixing.

The purpose of this study is to use multiple trees from two sites in close proximity to each other to evaluate mechanisms that can lead to false positives and missed storm events in the tree-ring record. This study also addresses how the number of trees affects the tree-ring tropical cyclone model, and discusses whether an AR-1 model threshold of –0.5 used in previous studies is appropriate for these sites. It is likely that site characteristics (i.e. soil type, topography, soil hydrology) and tree isotopic variability will affect the tree-ring tropical cyclone record so that the model behavior is not identical across all sites.

3.2 Site Description

Big Thicket National Preserve (BTNP) is located along the southeastern Texas Coastal Plain. The preserve is made up of numerous individual land units, typically located along creeks or rivers. Two of these land units, Turkey Creek (TC) (30.59º N, 94.33º W) and Big Sandy Creek (BSC) (30.65ºN, 94.67ºW), were sampled for this study. The majority (85%) of the soils in BSC were Pinetucky fine sandy loam (hydrologic soil group B, moderately well drained) (National Resources Conservation Service, 2009). The other 15% were Pinetucky and Conroe (hydrologic soil group C, moderately well drained). Soils in TC were the Kirbyville-Nirwana Complex (hydrologic soil group B, moderately well drained). Sand content was 45–65% at both sites. Depth to water table was >2 m at BSC, and approximately 80 cm at TC (National Resources Conservation Service, 2009). Both sample sites were dominated by mature longleaf pine (*Pinus palustris* Mill.) and loblolly pine (*Pinus taeda* L.). Understory vegetation was sparse during most of the sample collection trips as a result of prescribed burning. Tree mortality (uprooting, snapped stems) resulted from Hurricane Rita (2005) and Hurricane Ike (2008).

3.3 Methods

3.3.1 Field and laboratory methods

Ten trees were sampled at TC, and twenty were sampled at BSC. Increment cores were taken with a 12 mm borer, and each core was crossdated using visual and statistical techniques (Holmes, 1983; Stokes and Smiley, 1996; Grissino-Mayer, 2001). Four trees were randomly chosen from both sites for isotopic analysis from 1982 to 2006. Annual growth rings were separated into seasonal components (earlywood and latewood) using a scalpel. Alpha-cellulose was extracted from the latewood (LW) portion (Loader et al., 1997; Rinne, 2005). Approximately 100 μg of α-cellulose was weighed and placed in silver capsules. Oxygen isotope data were collected using a Finnigan Thermochemolysis/Elemental Analyzer (TC/EA) connected to a Finnegan Delta XL Plus mass spectrometer. Results are reported as VSMOW in per mil (‰) notation where $\delta = (R_{sample}/R_{standard} - 1)*1000$. Standards were placed every six samples throughout each run (sd < 0.2‰, n = 120).

3.3.2 The hurricane record

An autoregressive model (AR-1) was applied to each individual $\delta^{18}O$ series to highlight the negative isotopic anomalies associated with tropical cyclone events (Miller et al., 2006; Nelson 2008). The modeled (predicted) values were subtracted from each time series (observed values) to obtain residual chronologies. Miller et al. (2006) and Nelson (2008) noted that most negative residuals < –0.5 corresponded to known tropical cyclone events in the climate record. Five AR-1 models were developed for each site, one for each of the four individual LW $\delta^{18}O$ series and one for the average LW $\delta^{18}O$ chronology. A composite tropical cyclone chronology was developed for each site by combining all predictions from the individual trees. An AR-1 model was also developed from a master BTNP $\delta^{18}O$ chronology that combined all eight trees sampled for this study. The composite records were then compared to the records obtained from the average $\delta^{18}O$ chronologies to characterize the differences between the two techniques.

3.4 Results

The composite chronology from TC identified seven of twelve (58%) tropical cyclone events known to have impacted the site (Figure 3.1). The BSC composite chronology identified eight of twelve cyclone events (67%) (Figure 3.1). Missed events in the TC record were 1987 (TS #1), 1988 (TS Beryl), 1995 (TS Dean), 2004 (H Ivan), and 2005 (H Rita). The BSC record missed storms in 1987, 1988, 1995, and 2005 (Figure 3.1). False positives in the TC chronology were 1984, 1991, 1993, 1994, and 1996, while BSC false positives were 1984, 1991, 1994, 1996, and 2001 (Figure 1). A 2001 storm (TS Allison) was confirmed to have dropped precipitation near the site, but the storm occurred on 6 June, prior to LW production. It is unlikely that rainwater from this event would have persisted in the soil long enough to be utilized for LW production by trees.

The AR-1 model applied to the average LW $\delta^{18}O$ chronologies from each site identified five of the twelve events (42%) (Figure 3.1). At TC, storms were missed in 1983 (H Alicia), 1985 (H Juan), 1987, 1988, 1995, 2004, and 2005. BSC missed storms were 1985, 1987, 1988, 1989 (TS Allison, H Chantal), 1995, 2002 (H Lili) and 2005. Two false positives were identified at TC using the average chronology (1984 and 1996), while four (1984, 1991, 1996, and 2001) were identified at BSC.

3.5 Discussion

3.5.1 Composite chronologies versus average chronologies

The composite chronologies from both sites detected a higher percent of known storms over the average LW $\delta^{18}O$ series. The drawback to the composite chronologies is the higher number of false positives in the record. Trees at TC and BSC identified five false positive events, nearly equal to identified storm events. The opposite was apparent using the average $\delta^{18}O$ series. Each average isotope series detected a lower number of known storms (five) over the composite chronologies, but exhibited fewer false positives (two at TC, four at BSC). These results are not unexpected. Negative isotopic anomalies recorded by only one tree in the stand will be smoothed out using the average isotope series.

The –0.5 residual worked well as a lower threshold of the previous tree-ring hurricane records. However, these records were developed using only a single tree for any portion of the time series. The models developed from individual trees at both of these sites exhibited higher standard deviation than the average isotope models. If variability in the model is reduced using the average isotope series, then the –0.5 AR-1 residual may not prove to be a useful threshold level. Lowering the threshold level to –0.3 residual resulted in improved effectiveness of the average models at TC (6 of 12) and BSC (7 of 12) with no increase in false positive events at either site (Table 3.1). Although the average site models still record slightly fewer storms than the composite chronology, they prove a more conservative approach with respect to error from false positive events.

This methodology was also applied to the BTNP average $\delta^{18}O$ chronology (developed from all eight trees) (Table 3.1). Using an AR-1 threshold of –0.3, the BTNP average AR-1 model correctly identified 8 of 12 known storms (67%), and included only three false positive years. The effectiveness of this model is equivalent to the composite chronology developed from the eight trees, but contains fewer false positives. It is difficult to ascertain whether these patterns hold true for other sites or are specific to this study. No tree-ring hurricane records exist that incorporate more than one tree. Additional studies are necessary to evaluate the results presented here.

3.5.2 Mechanisms for generating false positives in the record

Using tree-ring $\delta^{18}O$ to identify tropical cyclone events makes the assumption that only tropical cyclone precipitation generates isotopically depleted precipitation. Other climate mechanisms are capable of mimicking tropical cyclone precipitation. The TC composite chronology identified five false positive years. Of these five years, only one (1996) was identified by multiple trees in the stand. The BSC composite chronology also recorded five false positives, while three (1991, 1996, and 2001) were recorded by at least two trees. False positive years identified by multiple trees were also retained in the average site chronologies. False positives in only a single tree in a stand likely represent variability in year-to-year $\delta^{18}O$ of tree-ring cellulose. Those identified by multiple trees in a stand (i.e. average models) may be related to larger-scale climate variability.

False positives detected at the –0.3 AR-1 residual threshold at TC were 1984 and 1996, while BSC identified 1984, 1991, 1996, and 2001. The BTNP chronology identified 1984, 1996, and 2001 at the –0.3 AR-1 residual. It is possible that the negative residual in 2001 at BSC (and in the BTNP average model) is associated with a storm (Tropical Storm Allison) that occurred early in the Atlantic hurricane season (6 June), because local weather stations record rainfall from this storm. However, the likelihood that rainfall associated with this storm remained in the soil column long enough to be incorporated into LW cellulose is low. Another explanation for 2001 and 1996 false positives are their occurrence with significantly wet fall conditions following extremely dry conditions in the previous fall (e.g. 1995 and 2000, respectively). Fall (August–October) precipitation in 1995 and 2000 was approximately 20 cm or more below the

25-year (1982–2006) average (Figure 3.2A). Drought during the LW portion of the growing season results in enriched α-cellulose $\delta^{18}O$. Wet conditions following droughts will yield similar negative isotopic anomalies to those associated with tropical cyclone events.

The false positive in 1984 (TC, BSC, and BTNP) has no clear climatic explanation. Fall precipitation in 1984 was approximately 20 cm above average, but the previous fall (1983) was wet as well. Year 1991 (BSC) was coincident with a strong El Niño event this false positive year. Miller et al. (2006) and Nelson (2008) also noted false positive years coinciding with false positives in Georgia, South Carolina, and Florida records. If the dominant moisture source switches from the Gulf to more Pacific influence during El Niño years, then the resulting precipitation will be depleted in ^{18}O compared to normal meteoric precipitation.

3.5.3 A mechanism for missed storm events

Droughts can cause enriched soil water $\delta^{18}O$ and α-cellulose $\delta^{18}O$. If droughts occur simultaneous to tropical cyclone events, then the ^{18}O-depleted signal typical of tropical cyclones will be dampened in the soil. The average site models all missed storms in 1987, 1988, 1995, and 2005. Palmer z-index records revealed that all of these years were characterized by dry (negative z-index) conditions during the LW portion of the growing season (Figure 3.2B). Regional PDSI records (long-term drought) exhibited dry conditions (negative PDSI) in all these years. The magnitude of the drought had no effect on the recording of storms, only that conditions concurrent with the tropical cyclone were dry, and storm magnitude was not significant. Hurricane Rita (2005) dropped over 16 cm of rainfall near the site, but was not detected in α-cellulose $\delta^{18}O$.

It is possible that missed storms in these records were a product of sample bias. Oxygen isotope records used for this study were collected to characterize both regional climate as well as tropical cyclone events. To characterize regional climate, the entire latewood portion of each ring was collected for isotopic analyses. Tropical cyclone rainfall represents a small portion of the total LW ring, especially when growth rates are higher than normal (large ring width). In certain circumstances, finer-scale sampling of the LW ring can reveal negative isotopic depletions not evident in the entire LW ring (Miller et al. 2006). The only year subsampled for this study was 2005 (Hurricane Rita), and the storm was not identified even when the 2005 LW ring was sampled at subseasonal resolution.

3.6 Conclusions

The $\delta^{18}O$ of tree-ring cellulose can be a useful tool for characterizing tropical cyclone frequency and variability. This study demonstrates that although tree rings do record tropical cyclone events, climatic variability may complicate the ability of trees to record extreme weather events such as hurricanes. At this site, climatic extremes (wet and dry periods) exerted a significant influence on the tree-ring hurricane record. Wet years that followed drought years mimicked tropical cyclone events. Droughts dampened the isotopic signal of tropical cyclones such that trees did not identify all known storm events. These results may not be typical of every tree-ring hurricane chronology. Individual sites need to be evaluated to determine the degree to which local climatic variability affects the record.

The composite hurricane chronology identified more cyclone events than the average chronologies, but included more false positive than the average chronologies. False positives are more problematic for periods where instrumental records are not available to verify events identified by tree-ring records. Using average $\delta^{18}O$ chronologies for tropical cyclone characterization affords a more conservative approach for periods prior to sufficient instrumental records. At this site, an AR-1 model applied to the average $\delta^{18}O$ chronology developed from all eight trees was as effective as the composite chronology with respect to identifying known storms. The BTNP model was superior to the composite chronology in terms of false positive events. The lack of data sets suitable for comparison makes it difficult to ascertain if the patterns characteristic of this hold true at other sites. The goal of characterizing tropical cyclones using tree rings is to obtain information about long-term changes in frequency and variability of tropical cyclones. Developing a 200-year (or more) isotope chronology using the number of trees presented here is not feasible because of the time-intensive nature of collecting tree-ring isotope data. Future studies should evaluate the characteristics of the individual trees at the site to characterize the suitable number of trees to include for comprehensive analysis.

3.7 Acknowledgements

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Appendix 3

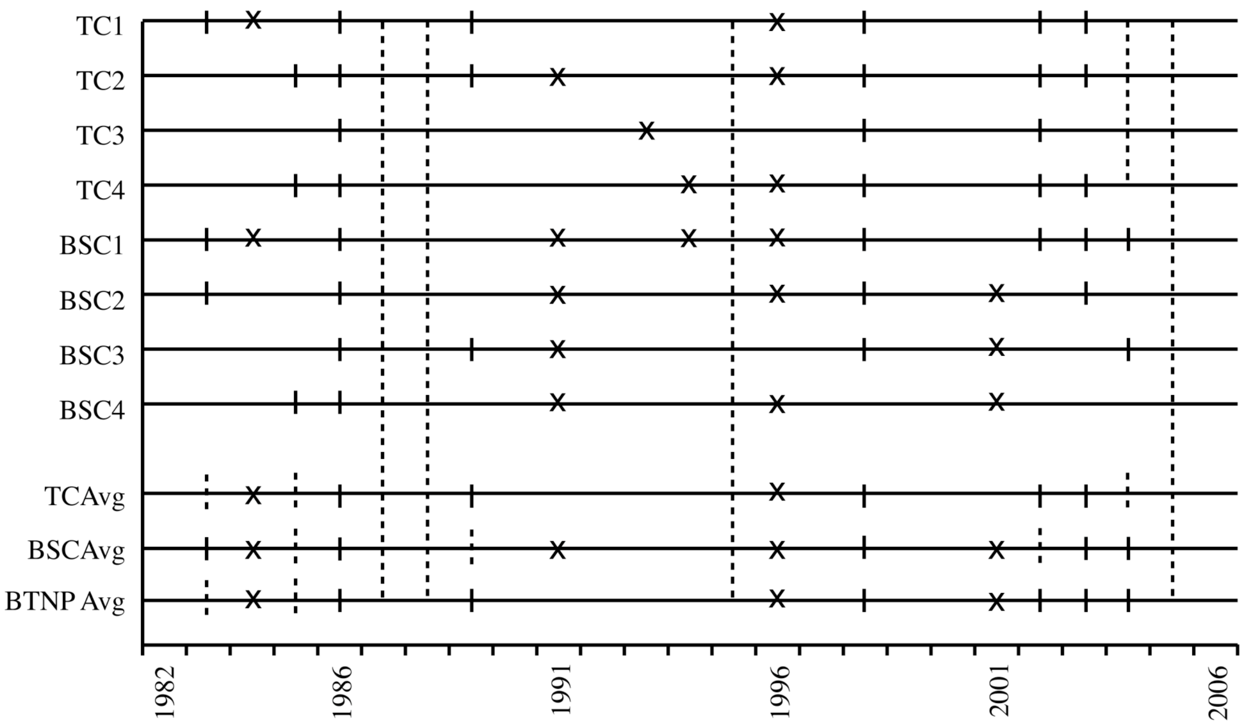

Figure 3.1. Composite and average tropical cyclone chronologies for the Turkey Creek Unit (TC, top) and Big Sandy Creek Unit (BSC, bottom) at Big Thicket National Preserve. A vertical tick mark (|) indicates a true positive, an (X) indicates a false positive, and the dashed lines indicate missed storms in the record. TC average, BSC average, and BTNP average are the AR-1 models applied to the average LW $\delta^{18}O$ series. All residuals represent those ≤ –0.5.

Table 3.1. Table of true and false positives and missed storms. Using –0.3 instead of –0.5 as the AR-1 model threshold, the effectiveness of the models was improved without an increase in false positives. The BTNP average record exhibited the best result.

	–0.5 AR-1 Residual		
	True Positive Years	False Positive Years	Missed Storm Years
TC Average	1986, 1989, 1998, 2002, 2003	1984, 1996	1983, 1985, 1987, 1988, 1995, 2004, 2005
BSC Average	1983, 1986, 1998, 2003, 2004	1984, 1991, 1996, 2001	1985, 1987, 1988, 1989, 1995, 2002, 2005
BTNP average	1986, 1989, 1998, 2002, 2003, 2004	1984, 1996, 2001	1983, 1985, 1987, 1988, 1995, 2005
	–0.3 AR-1 Residual		
TC Average	1985, 1986, 1989, 1998, 2002, 2003	1984, 1996	1987, 1988, 1995, 2004, 2005
BSC Average	1983, 1985, 1989, 1988, 2002, 2003, 2004	1984, 1991, 1996, 2001	1987, 1988, 1995, 2005
BTNP Average	1983, 1985, 1986, 1989, 1998, 2002, 2003, 2004	1984, 1996, 2001	1987, 1988, 1995, 2005

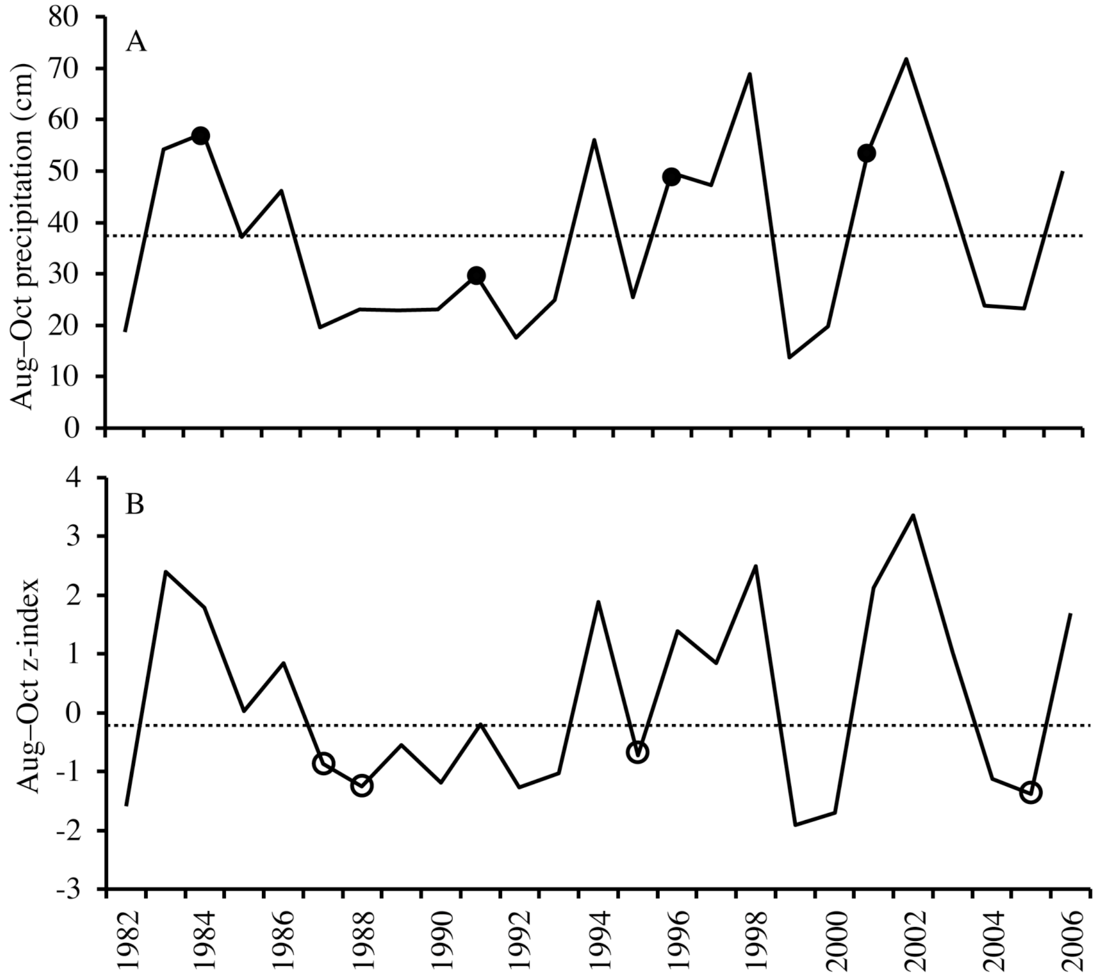

Figure 3.2. False positives (solid black dots) compared to fall (August–October) precipitation (A) and missed storms (open circles) compared to fall drought (z-index) records (B). False positives in 1996 and 2001 resulted from above average precipitation following years of below average precipitation. Average fall precipitation for the 25-year period is represented by the dashed line (approximately 36 cm). Missed storms were coincident with dry (negative z-index) conditions during the fall (August–October) portion of the growing season. The dashed line represents average z-index for the 25-year period.

Chapter 4

Characterizing Climate Using Ring Width, Carbon, and Oxygen Isotopes in Latewood Tree-Ring Cellulose, Big Thicket National Preserve, Texas, USA

Abstract

Tree ring indicators such as ring width and stable isotopes offer suitable resolution to analyze climate variability. However, when tree growth is not limited by one specific climate variable (i.e. temperature, precipitation), ring width chronologies may not show correlation with regional climate variables. Stable isotopes may improve the tree-ring climate relationship in areas where ring width analyses are not effective. This study combines tree-ring width, $\delta^{18}O$, and $\delta^{13}C$ to quantify the relationship with regional climate parameters (i.e. precipitation and z-index) over a 26-year period (1982–2007) at Big Thicket National Preserve, Texas. The latewood (LW) ring width chronology showed strong interseries correlation among the individual trees ($r = 0.71$), which indicated that the trees were all responding to the same environmental signal. However, the ring width chronology was not correlated to any regional climate parameter. LW ring width was also not correlated to either LW $\delta^{18}O$ or LW $\delta^{13}C$, except for a short period from 1982–1991. The average LW $\delta^{18}O$ chronology showed strong inverse correlations with precipitation ($r = -0.62$, $p < 0.001$) and z-index ($r = -0.63$, $p < 0.001$). The average LW $\delta^{13}C$ chronology was also inversely correlated to precipitation ($r = -0.59$, $p < 0.001$) and z-index ($r = -0.57$, $p < 0.003$). Combining LW $\delta^{18}O$ and $\delta^{13}C$ resulted in better correlations between precipitation ($r = 0.64$) and z-index ($r = 0.66$) over the individual chronologies. The data show that there is no single climatic variable that imparts a significant influence on cambial growth at this site. However, moisture availability explains 33–40% of the variance in LW $\delta^{18}O$ and LW $\delta^{13}C$. Combining $\delta^{18}O$ and $\delta^{13}C$ explained 41% of the variance with precipitation and 43% with z-index. These results highlight the usefulness of tree-ring chemistry in areas where ring width may be problematic.

Keywords: Carbon isotopes, oxygen isotopes, tree rings, precipitation, z-index

4.1 Introduction

Tree-ring width is a proven archive of climatic variability (e.g. Fritts 1976; Grissino-Mayer 1995; Cook et al. 1999; Gray et al. 2004, Stahle et al. 2009). In regions where a climate parameter is limiting to growth (i.e. precipitation, temperature, moisture availability), cambial growth will only proceed as fast as the limiting variable will allow (Fritts 1976). However, trees growing in areas where regional climate is not limiting to growth may not exhibit relationships with regional climate variables. The analysis of stable isotopes ($\delta^{18}O$, $\delta^{13}C$, δD) in tree-ring cellulose provides important climatic information in areas where ring width parameters are not effective (Anderson et al 1998, Helle and Schleser 2004; McCarroll and Loader 2004).

The $\delta^{18}O$ and $\delta^{13}C$ of tree-ring cellulose have been used to characterize precipitation (e.g. Anderson et al. 1998; McCarroll and Pawellek 2001; Anderson et al 2002; Roden and Ehleringer 2007), temperature (e.g. Anderson et al. 1998; Rebetez et al. 2003; Gagen et al. 2006; Lewis et al. in review), and drought (e.g. Lewis et al. in review). However, few tree-ring isotope records exist for the south-central or southeastern United States. Anderson et al. (2005) noted significant correlation between $\delta^{13}C$ of two cypress species (*Taxodium* spp.) and precipitation from Florida, but the relationships were strongly influenced by local site characteristics. Other isotope chronologies from the Southeast focused on using LW $\delta^{18}O$ to analyze tropical cyclone events (Miller et al. 2006; Nelson 2008).

Previous work at Big Thicket National Preserve (BTNP) has shown that oxygen isotopes and ring width parameters correlate with several regional climate parameters. LW $\delta^{18}O$ analyses from the Turkey Creek Unit at BTNP indicated strong correlations with regional fall (August–October) precipitation and z-index (short-term drought) (Lewis et al. in review). Ring width analyses from several locations at BTNP indicated strong correlations with precipitation and

PDSI (long-term drought) (Henderson and Grissino-Mayer 2009). The purpose of this study is to quantify the relationship between multiple tree-ring properties (ring width, $\delta^{18}O$, $\delta^{13}C$) and regional climate at BTNP. Characterizing both $\delta^{18}O$ and $\delta^{13}C$ together with ring width measurements will provide a more comprehensive analysis of the tree-ring/climate relationship, and an understanding of how each of these indicators covary with each other through time.

Several studies have demonstrated the utility of combining multiple tree-ring indicators for climate analyses (e.g. McCarroll et al. 2003; Gagen et al. 2006; Cullen et al. 2008; Loader at al. 2008). When significant correlations exist between two or more tree-ring indicators and a particular climate parameter (i.e. precipitation), multiple tree-ring components can be combined to enhance the correlation with that climate parameter (McCarroll et al. 2003). This study will address if combined tree-ring records at this site improves the relationship with regional climate.

4.2 Isotope Theory

4.2.1 Oxygen

The oxygen isotope composition of tree-ring α-cellulose is primarily controlled by the isotopic composition of source water (precipitation, soil water) and biochemical fractionations (Roden et al. 2000; Anderson et al. 2002; Helle and Schleser 2004; McCarroll and Loader 2004). Isotopic fractionation of soil water does not occur during uptake through tree roots, but large fractionations occur in the leaves resulting in leaf water that is enriched in $\delta^{18}O$ relative to source water (Roden et al. 2000; Anderson et al. 2002). The $\delta^{18}O$ of sucrose formed by photosynthesis is further modified by exchange with stem water (source) prior to cellulose synthesis (Sternberg et al. 1986; Farquhar et al. 1998; Anderson et al. 2002). Biochemical fractionations are relatively constant for trees of the same species in a stand, so that fluctuations in α-cellulose $\delta^{18}O$ likely reflect changes in source water (Anderson et al. 2002).

4.2.2 Carbon

The carbon isotope composition ($\delta^{13}C$) of tree-ring α-cellulose is primarily a product of the concentration of atmospheric CO_2 (c_a), the concentration of CO_2 inside the leaf (c_i), and fractionation as a result of carboxylation. Diffusion of CO_2 through leaf stomata results in an approximately –4.4‰ discrimination, while carboxylation results in an approximately –27‰ fractionation (Farquhar et al. 1982). When c_i/c_a is high, stomatal conductance is high, which causes a strong discrimination during carboxylation. Low c_i/c_a related to decreased stomatal conductance results in decreased discrimination, leading to enriched $\delta^{13}C$ values in tree-ring cellulose.

4.3 Site Description

Big Thicket National Preserve is located along the southeast Texas Gulf Coast, and is comprised of several individual land units. The trees used for this study were collected from the Big Sandy Creek Unit (BSC) (30.65°N, 94.67°W). Two soil types dominated the unit, Pinetucky fine sandy loam (85%, hydrologic soil group B) and Pinetucky and Conroe (15%, hydrologic soil group C) (National Resources Conservation Service 2009). Both soil types are moderately well drained and contain approximately 60–65% sand (National Resources Conservation Service 2009). Depth to water table was >2 m throughout the stand. The stand was dominated by mature longleaf pine (*Pinus palustris* Mill.) and loblolly pine (*Pinus taeda* L.). Understory vegetation was sparse during sampling as a result of prescribed burning. Tree mortality was observed as a result of Hurricane Rita (2005) and Hurricane Ike (2008).

4.4 Methods

Living longleaf pine trees were sampled using a standard 12 mm increment borer. Each core was crossdated using standard visual and statistical dendrochronological techniques (Stokes and Smiley 1996; Grissino-Mayer 2001). Four trees were randomly chosen for isotopic analyses. Annual growth rings were separated into earlywood (EW) and latewood (LW) components using a scalpel. Alpha-cellulose was extracted from LW rings following Loader et al. (1997) and Rinne (2005) from 1982–2007. Approximately 100 μg of α-cellulose was weighed in silver capsules for oxygen isotope analyses. Oxygen data were collected on a Finnigan Thermochemolysis/Elemental Analyzer (TC/EA) connected to a Finnigan Delta XL Plus mass spectrometer. Approximately 1 mg of α-cellulose was weighed in tin capsules for carbon isotope analyses. Carbon data were collected on a Costech Elemental Analyzer (EA) connected to a Finnigan Delta XL Plus mass spectrometer. Oxygen and carbon isotope data are presented in per mil (‰) notation, were $\delta = (R_{sample}/R_{standard}-1)*1000$. The $\delta^{18}O$ data were standardized to VSMOW using internal standards (SD = 0.13, n = 51), and $\delta^{13}C$ data were standardized to PDB using internal standards (SD < 0.10, n = 35).

The LW ring width chronology was developed from raw ring measurements using the computer program ARSTAN. Average LW $\delta^{18}O$ and $\delta^{13}C$ chronologies were calculated from the individual LW isotope series. The $\delta^{13}C$ values were corrected for atmospheric CO_2 change from 1950 by subtracting from the CO_2 curve (–0.025‰ per year) (Saurer et al. 1997). To determine the coherency of the individual trees for climate analysis, the expressed population signal (EPS) equation was calculated;

$$EPS = (nr_{bt})/(nr_{bt}+(1-r_{bt}))$$

where n is the number of trees, and r_{bt} is the average between-tree correlation. The EPS equation is a useful tool to determine the number of trees needed for effective climate analysis (Wigley et al. 1984; McCarroll and Loader 2004). An EPS around 0.85 indicates the number of trees is adequate.

Monthly regional climate data (temperature, precipitation, PDSI, z-index) were obtained for Texas Region 8 (Upper Coast) from the National Climatic Data Center (NCDC 2009). Monthly data were seasonalized to correspond with the latewood (LW) portion of the growing season (August–October). Peasrson correlation analyses were conducted with each climate variable using the individual LW tree-ring parameters ($\delta^{18}O$, $\delta^{13}C$, ring width). When more than one tree-ring parameter exhibited significant ($p < 0.05$) correlations with a single climate parameter, we employed stepwise multiple regression (SAS®), principal component analyses (SAS®), and a multiproxy approach developed by McCarroll et al. (2003) to quantify whether combined analyses improved the statistical relationship.

4.5 Results

4.5.1 Isotope and ring width chronologies

The individual trees showed some differences in annual $\delta^{18}O$, but exhibited similar trends in $\delta^{18}O$ over the 25-year period (Figure 4.1). Correlation between the individual LW $\delta^{18}O$ series ranged from 0.84 (BSC1-BSC2) to 0.53 (BSC2-BSC3). BSC1 and BSC2 were growing approximately 10 m apart, while BSC2 and BSC3 were growing approximately 50 m apart. Standard deviation of the individual series ranged from 1.09 (BSC3) to 0.78 (BSC4). BSC3 exhibited the lowest correlation to the other trees, so it was removed from the average LW $\delta^{18}O$ chronology for climate analysis. An EPS of 0.86 was achieved using the remaining three series.

The detrended individual LW $\delta^{13}C$ chronologies showed a similar trend to each other, with the exception of BSC4 (Figure 4.2). Between-tree correlations in LW $\delta^{13}C$ ranged from 0.72 (BSC2-BSC3) to –0.01 (BSC2-BSC4). BSC4 became enriched in ^{13}C versus the other three trees by more than 1‰ beginning in 1991 and remained enriched through the end of the time series.

Because of the low correlation of BSC4 to the other series, it was removed from the average LW $\delta^{13}C$ chronology for climate analysis resulting in an EPS of 0.85.

Sixteen measured series from eight trees were included into the master LW ring-width chronology. The LW width chronology from BSC spanned 1864–2007, but the period 1982–2007 is shown here for comparison purposes (Figure 4.3). The chronology was characterized by strong interseries correlation ($r = 0.71$), high mean sensitivity (measure of ring width variability) (0.46), and achieved an EPS of 0.95 over the period 1982–2007. Low year-to-year variability in ring width was observed from 1982 to 1991. A negative trend was apparent in the ring width chronology from 1995 through 2007.

LW ring width exhibited no correlation with average LW $\delta^{18}O$ or LW $\delta^{13}C$ (Figure 4.4). Conversely, average LW $\delta^{18}O$ and average LW $\delta^{13}C$ were well correlated over the 25-year period ($r = 0.67$) (Figure 4.5). A closer look at the three chronologies revealed an interesting result. LW ring width was inversely correlated to LW $\delta^{18}O$ from 1982–1991 ($r = -0.56$), but poorly correlated from 1992–2007 ($r = 0.27$) (Figure 4.6A). LW ring width exhibited even stronger inverse correlation to LW $\delta^{13}C$ from 1982–1991 ($r = -0.88$), and was also poorly correlated from 1992–2007 ($r = 0.06$) (Figure 4.6B). The expected correlation between ring width and both isotopes is negative, because increased ring width (wet conditions) should result in decreased moisture stress (depleted ^{18}O and ^{13}C).

4.5.2 Climate relationships

LW ring width exhibited no significant relationship with fall precipitation, PDSI (long-term drought), z-index (short-term drought) or temperature. Average LW $\delta^{18}O$ exhibited a strong inverse correlation with fall (August–October) precipitation ($r = -0.62$, $r^2 = 0.38$, $p < 0.001$) and fall z-index ($r = -0.63$, $r^2 = 0.40$, $p < 0.001$) (short-term drought record) (Figure 4.7A, B).

Average LW $\delta^{13}C$ was also inversely correlated to fall precipitation ($r = -0.59$, $r^2 = 0.35$, $p < 0.001$) and z-index ($r = -0.56$, $r^2 = 0.31$, $p < 0.002$) (Figure 4.8A, B). Step-wise multiple regression analyses using LW $\delta^{18}O$ and $\delta^{13}C$ chronologies did not explain additional variation with respect to precipitation or z-index. The first principal component between LW $\delta^{18}O$ and $\delta^{13}C$ explained equal variation to the LW $\delta^{18}O$ Pearson correlation analyses for both precipitation and z-index. The multiproxy approach (combining $\delta^{18}O$ and $\delta^{13}C$) yielded slightly higher explained variance over $\delta^{18}O$ or $\delta^{13}C$ alone for fall precipitation ($r = 0.64$, $r^2 = 0.41$) and z-index ($r = 0.66$, $r^2 = 0.43$) (Figure 4.9A, B).

4.6 Discussion

Henderson and Grissino-Mayer (2009) noted significant correlations between LW ring width and climate variables (precipitation, PDSI) at BTNP, but trees from BSC revealed no correlations with any climate parameter. BTNP is composed of a number of individual land units, all with varying ecological characteristics. BSC has ideal site characteristics (deep water table, well-drained sandy soils, etc.) for dendroclimatological analyses, and the ring-width chronology was well correlated between individual trees. Mean sensitivity was high for southeastern tree-ring chronologies, indicating adequate ring width variability.

LW ring width exhibited poor correlation to LW $\delta^{18}O$ or LW $\delta^{13}C$ over the entire period (1982–2007) (Figures 4.4; 4.6A, B). However, the three chronologies were correlated from 1982–1991, an interval that was also characterized by low year-to-year variability in ring width. It is unclear why the time series would diverge at this time. The ring width chronology indicates significant reduction in ring width from 1991 to 1993, an increase of equal magnitude from 1993 to 1995, then a negative trend from 1995 through 2007 (Figure 4.3). After 1991, three of the four trees also exhibited a negative trend in $\delta^{13}C$ (Figure 4.2). A similar trend was not apparent in

$\delta^{18}O$. These results indicate a change in growth rate and/or carbon isotope assimilation not related to moisture availability, because oxygen in the four trees was unaffected. A possible explanation is senescence, as the majority of the trees in this stand exceed 150 years. The carbon isotope composition of tree-ring cellulose is directly affected by the intercellular/atmospheric concentration of CO_2 (c_i/c_a) (Farquhar et al. 1982). If stomatal aperture remains high but photosynthetic rate slows as a result of decreased growth, the (c_i/c_a) ratio will remain high, resulting in decreased (more negative) $\delta^{13}C$ of cellulose.

Carbon and oxygen isotopes at this site were superior to ring width analyses for characterizing climate variables. Carbon and oxygen isotopes are significantly correlated to each other and exhibited strong inverse correlations with regional fall precipitation and fall z-index (Figures 4.7A, B; 4.8A, B). The degree to which carbon and oxygen isotopes in tree-ring cellulose typically correlate has not been widely addressed in the literature. Anderson et al. (1998) found no significant relationship between $\delta^{13}C$ and $\delta^{18}O$ from central Switzerland. Cullen et al. (2008) and Hilasvouri et al. (2009) demonstrated that the relationship between cellulose $\delta^{18}O$ and $\delta^{13}C$ can vary through time. The correlation between carbon and oxygen in these trees is explained through the common climate response. During periods of low precipitation (dry conditions), stomatal aperture would decrease, resulting in enriched cellulose $\delta^{13}C$. Similarly, increased evaporation during periods of low precipitation results in enriched $\delta^{18}O$ of soil water, and therefore enriched cellulose $\delta^{18}O$. Wet conditions would have the opposite effect on each isotope system.

Stepwise multiple regression techniques and principal component analyses did not yield additional variance explained over LW $\delta^{18}O$ alone for fall precipitation and z-index. When both $\delta^{18}O$ and $\delta^{13}C$ were included in the stepwise multiple regression, only LW $\delta^{18}O$ was retained in model because $\delta^{18}O$ exhibited superior Pearson correlations to both climate parameters. Likewise, the first principal component between $\delta^{18}O$ and $\delta^{13}O$ explained equal variance as $\delta^{18}O$ alone for both climate parameters. Combining $\delta^{18}O$ and $\delta^{13}C$ yielded slightly higher correlations with precipitation (r = 0.64) and z-index (r = 0.66) (Figure 4.9A, B), but reconstructed variables for both typically underestimated the instrumental data. McCarroll and Pawellek (2001) suggested an r-value of 0.71 ($r^2 = 0.50$) be the minimum threshold for use as a climate proxy. Although correlations for these trees do not meet this threshold, they highlight the utility of combining multiple tree-ring components for climate analyses.

4.7 Conclusions

Tree-ring isotopes can be useful recorders of regional climate, even if tree ring widths are not. These results are especially important for areas such as the Gulf Coast, where ring width analyses can be problematic because cambial growth may not limited by climate (Helle and Schleser 2004; Henderson and Grissino-Mayer 2009). These results highlight the utility of incorporating multiple tree-ring indicators as it may provide a more comprehensive understanding of the tree growth/climate relationship (e.g. McCarroll et al. 2003; Gagen et al. 2006). Currently, the south central U.S. is lacking in tree-ring isotope chronologies.

The results presented here represent the first attempt at characterizing $\delta^{13}C$, $\delta^{18}O$, and ring width in the south-central United States. Oxygen isotopes exhibited significant inverse correlations to fall (August–October) precipitation ($r = –0.62$, $p < 0.001$) and z-index ($r = –0.63$, $p < 0.001$). Carbon isotopes were also inversely correlated to fall precipitation ($r = –0.59$, $p < 0.001$) and z-index ($r = –0.59$, $p < 0.003$). Conversely, ring width measurements displayed no correlation to regional climate parameters. Combining $\delta^{18}O$ and $\delta^{13}C$ resulted in a more comprehensive characterization of fall precipitation and z-index. Carbon and oxygen isotopes in these trees were not correlated with ring width, except for the period 1982–1991. The combined carbon and ring width analyses indicated changes in growth rates and/or carbon assimilation beginning around 1991 and continuing through 2007. That oxygen isotopes were unaffected by this change indicated the reduction in growth rate was not associated with moisture stress or a shift in moisture availability.

4.8 Acknowledgements

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Appendix 4

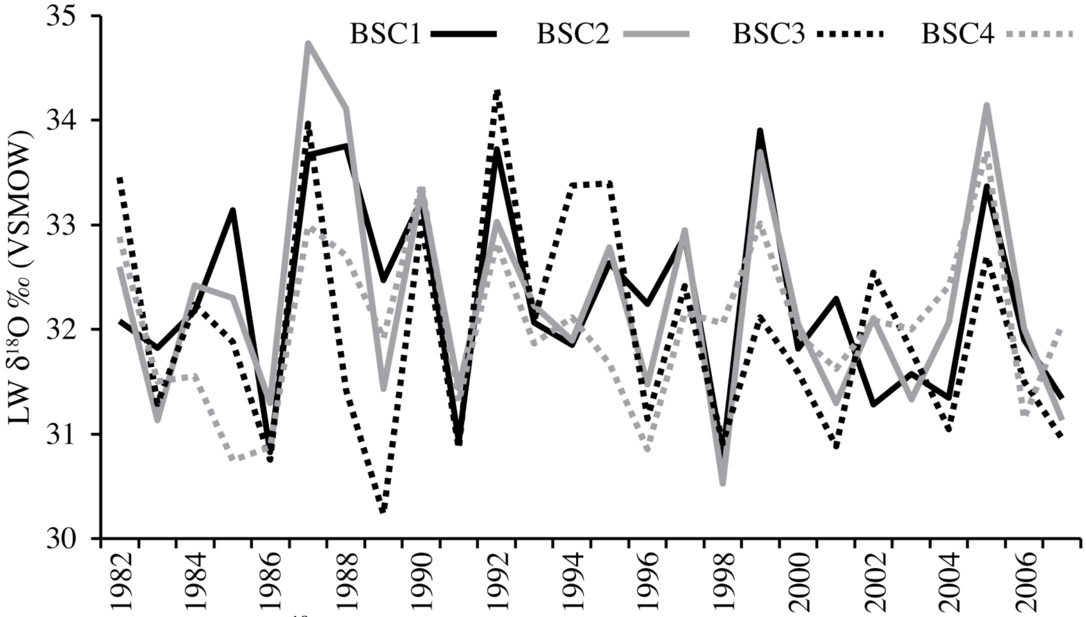

Figure 4.1. Latewood $\delta^{18}O$ values for the four trees analyzed for this study. All four trees follow similar trends over the 26-year period. BSC3 was not included in the average $\delta^{18}O$ chronology because it had the lowest correlation to the other trees.

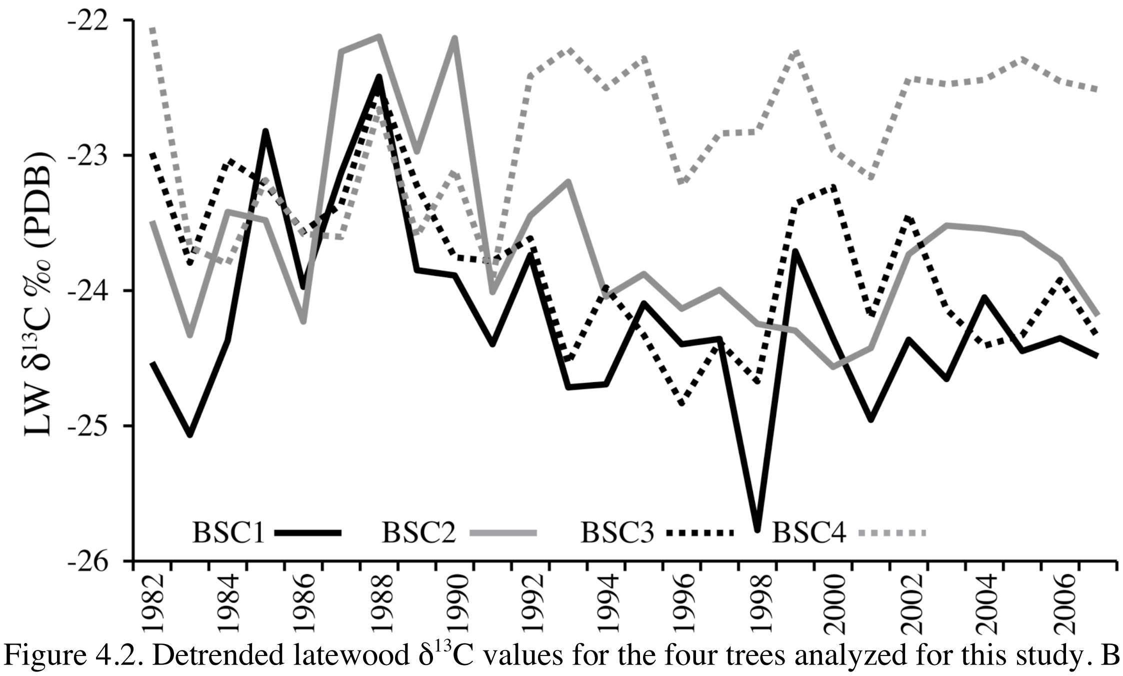

Figure 4.2. Detrended latewood $\delta^{13}C$ values for the four trees analyzed for this study. BSC4 diverged from the other three trees after 1991 so it was not included in the average $\delta^{13}C$ chronology.

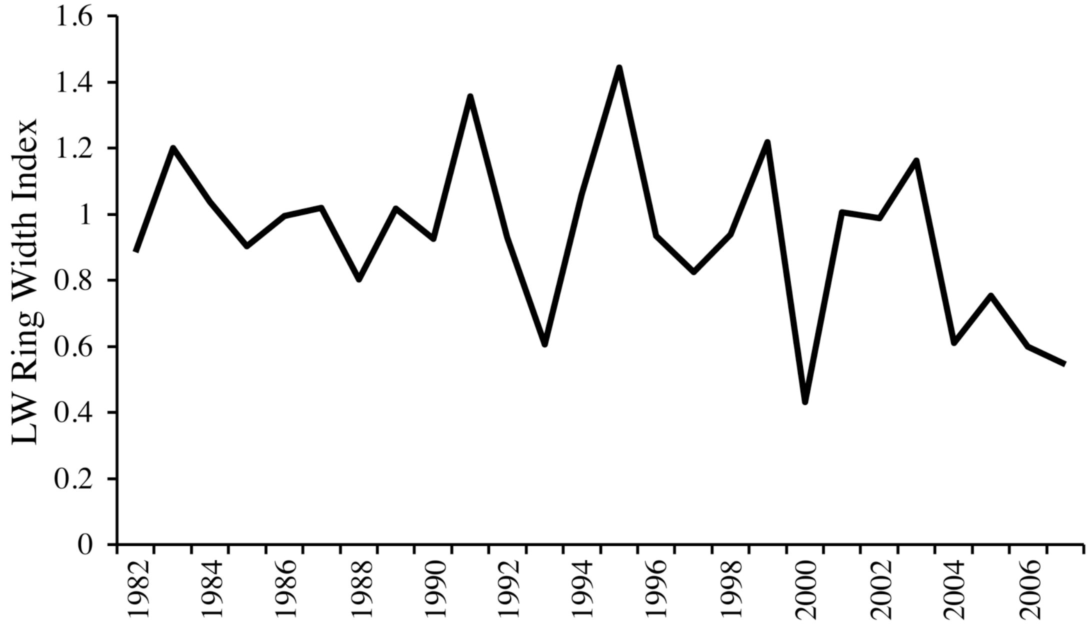

Figure 4.3. Master LW tree-ring chronology from BSC. Low ring variability is apparent from 1982 through 1990. A negative growth trend is also visible after 1995. The chronology includes 16 tree-ring series from eight individual trees, and has an EPS of 0.95.

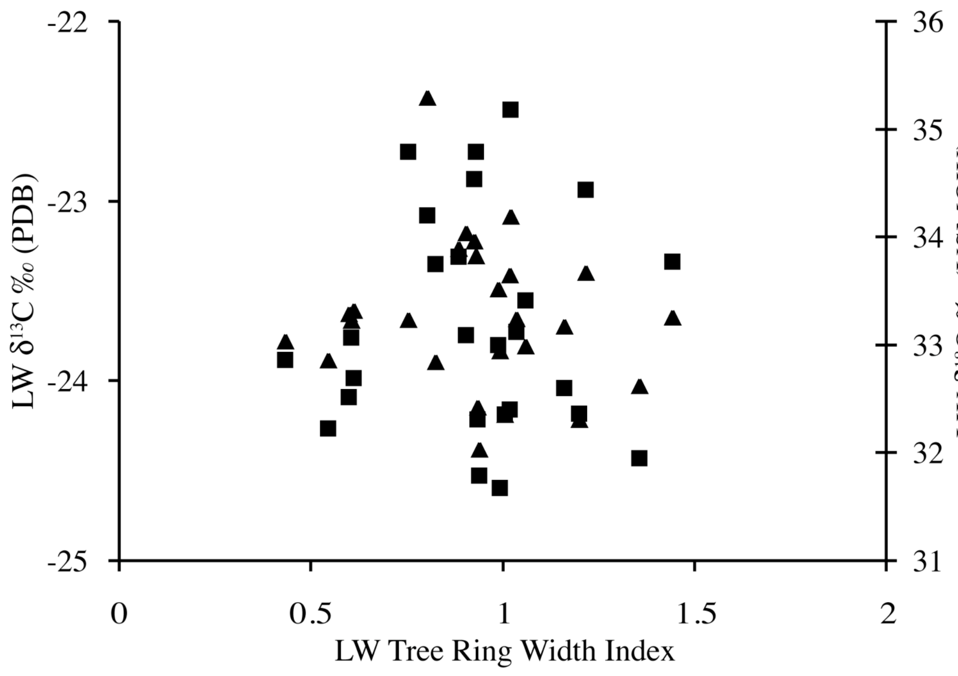

Figure 4.4. Scatter plot of latewood ring width versus $\delta^{13}C$ (black triangles) and $\delta^{18}O$ (black squares). No relationship exists between ring width and either isotope species.

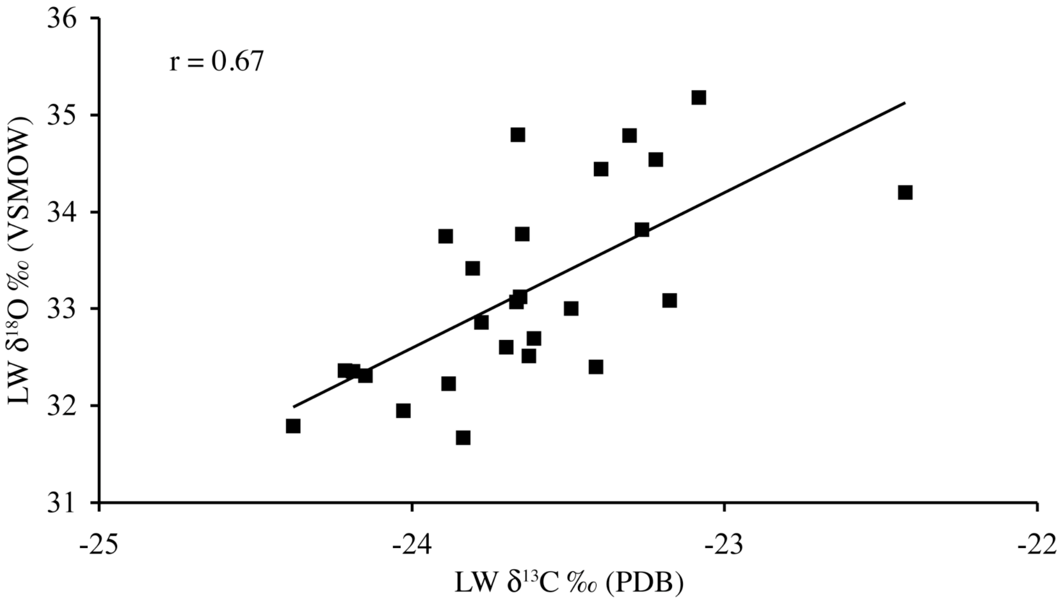

Figure 4.5. Scatter plot of LW $\delta^{18}O$ versus LW $\delta^{13}C$. Correlation between the two series is 0.67 and the relationship is positive.

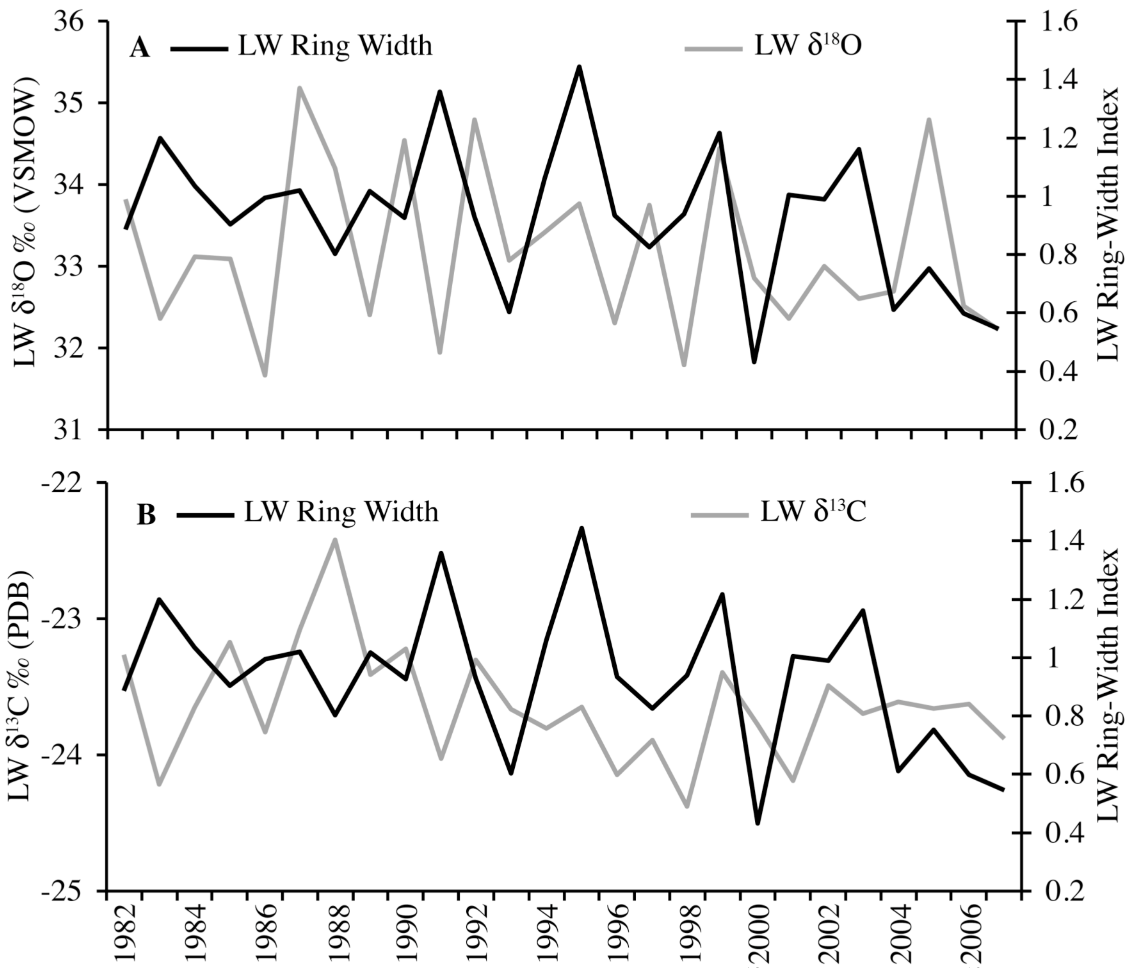

Figure 4.6. LW ring-width chronology graphed with LW $\delta^{18}O$ (a) and LW $\delta^{13}C$ (b). Ring width exhibits correlation with $\delta^{18}O$ from 1982–1991, but not from 1992–2007. A similar pattern is evident in $\delta^{13}C$.

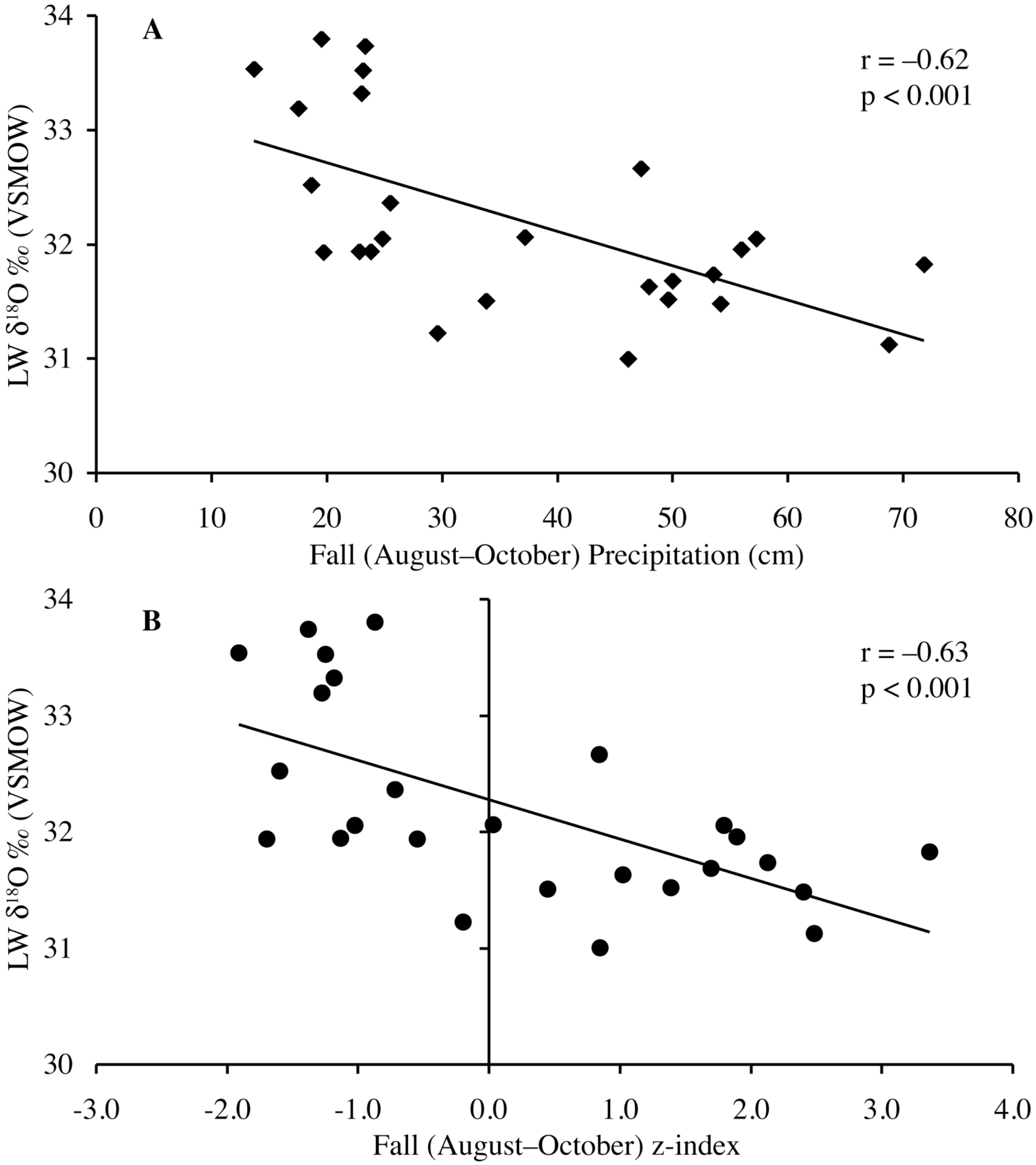

Figure 4.7. Latewood $\delta^{18}O$ correlations with regional fall (August–October) precipitation (A) and z-index (B). Fall precipitation explains 38% of the variation in $\delta^{18}O$, while fall z-index explains 40% of the variation in $\delta^{18}O$.

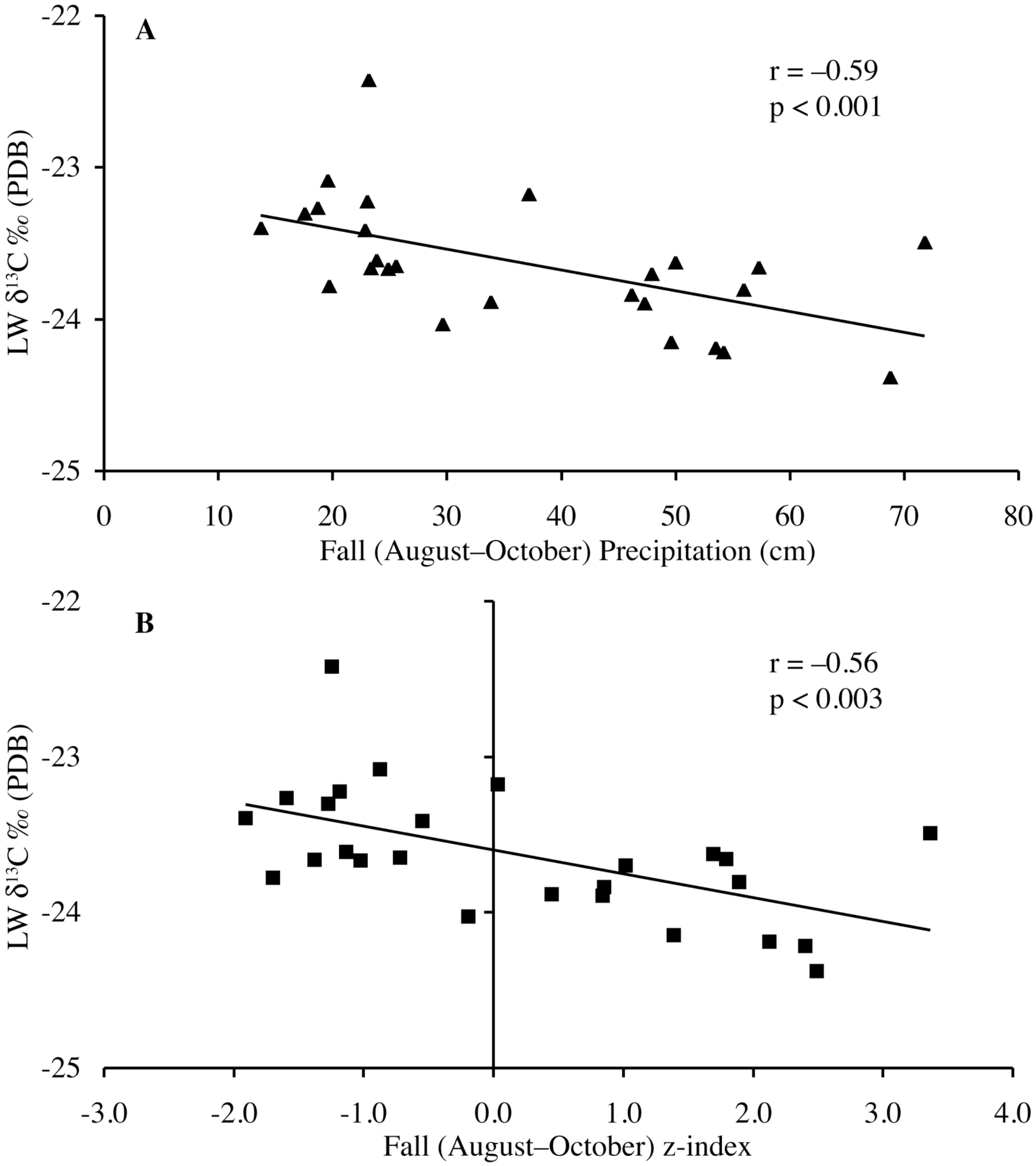

Figure 4.8. Latewood $\delta^{13}C$ correlations with regional fall (August–October) precipitation (A) and z-index (B). Fall precipitation explains 35% of the variation in $\delta^{13}C$, while fall z-index explains 31% of the variation in $\delta^{13}C$.

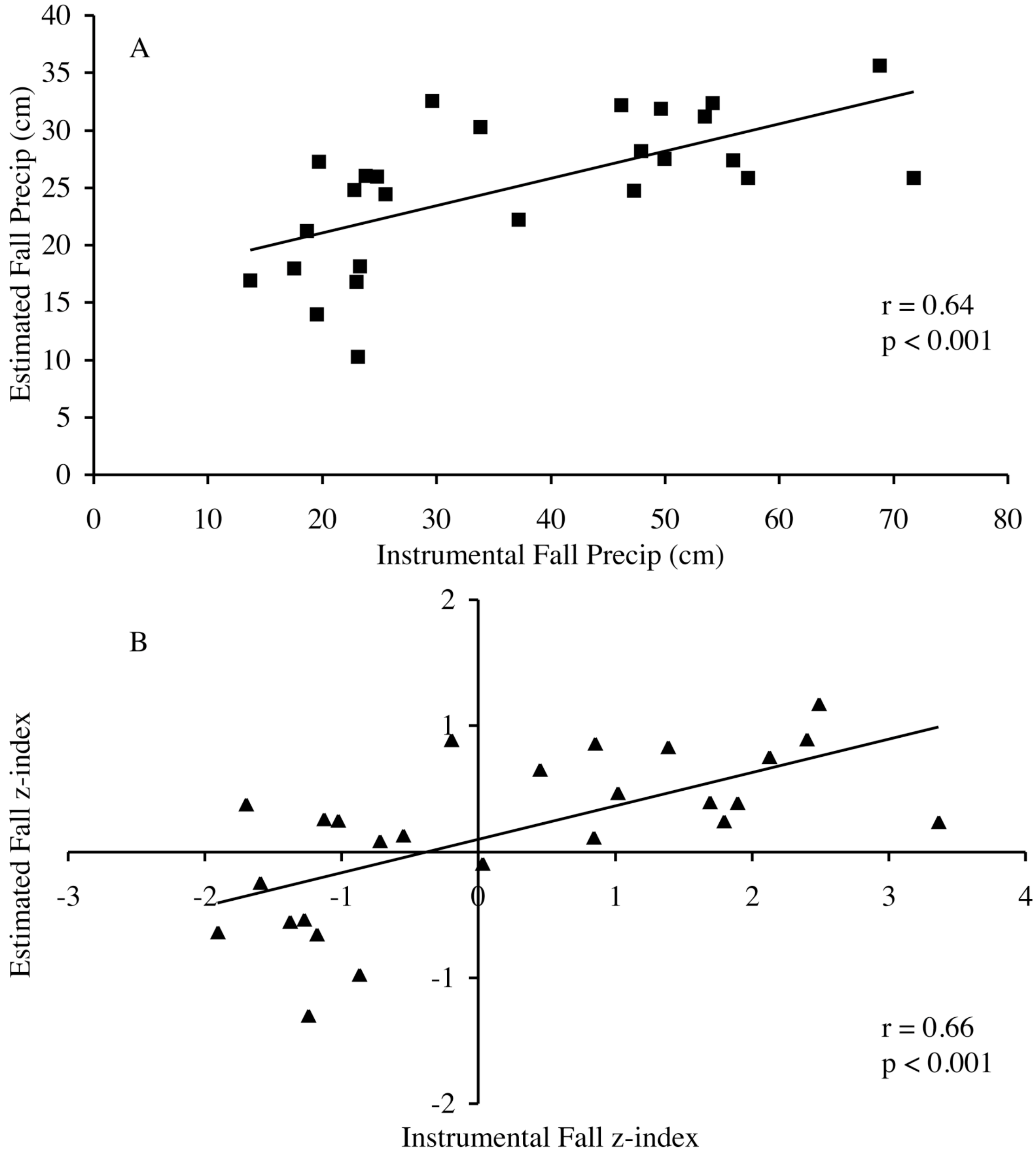

Figure 4.9. Estimated versus instrumental precipitation (A) and z-index (B). Combining LW $\delta^{18}O$ and $\delta^{13}C$ yielded higher variance explained for precipitation (0.41) and z-index (0.43) over $\delta^{18}O$ or $\delta^{13}C$ alone.

Chapter 5
Conclusions

5.1 Major conclusions

5.1.1 A multi-tree perspective of oxygen isotope variability

Individual trees at both sites exhibited significant variability from each other with respect to yearly $\delta^{18}O$ values of α-cellulose. Statistical analyses determined that two of the six possible combinations of trees analyzed for this study were statistically different at the 95% confidence interval. The isotopic variability at this site was driven by soil moisture heterogeneity (primarily in dry yeasrs), and affected the correlation of individual trees to regional instrumental climate data as well as consistency in detecting tropical cyclone events known to have impacted the stand. Individual trees did not always record the same tropical cyclone events, and only three of twelve known storms events during the 25-year study period (1982–2006) were identified by all four trees in the stand.

Incorporating multiple trees resulted in a more robust characterization of regional climate and tropical cyclones. The highest correlation of an individual tree to regional precipitation was –0.61 ($p < 0.001$). An average $\delta^{18}O$ chronology developed from all four trees revealed improved correlation ($r = –0.71$, $p < 0.0001$). The average $\delta^{18}O$ chronology was also correlated to z-index (short-term drought record) ($r = –0.67$, $p < 0.0001$). The best result identifying tropical cyclone events from an individual tree was 50% (6 of 12 storms). However, a composite tropical cyclone chronology developed from the predictions from all four trees identified 58% (7 of 12) of known tropical cyclone events.

5.1.2 Effects of sample depth and regional climate on the tropical cyclone record

Two problems influence the effectiveness of tree-ring hurricane records, events identified by the tree-ring record not associated with a storm event (false positive) and missing storms known to have dropped precipitation on the study area (missed storms). Using multiple trees from two sites at BTNP, the effect of sample depth on the tree-ring hurricane record was evaluated. Average site $\delta^{18}O$ chronologies resulted in fewer false positive events over the individual tree chronologies. These results are not surprising because a number of false positives occurred only in individual trees in a stand, and these events would be smoothed out via averaging of multiple trees. Using the previously documented –0.5 AR-1 residual as the threshold level for identifying hurricanes, the average chronologies only identified 42–50% of the known storm events. However, because the average isotope series and average AR-1 models exhibited lower standard deviation over the individual series, the residual threshold was raised to –0.3, which improved the effectiveness of all the average models without additional false positives appearing in the records. A model developed from the BTNP $\delta^{18}O$ chronology equaled the effectiveness of the composite chronology (sum of all individual predictions) but contained fewer false positives. These results indicate that the –0.5 AR-1 threshold level may not be useful for every site.

A closer evaluation of the tropical cyclone records with regional climate variability revealed possible climate mechanisms for false positives and missed storms. Most false positive events in the average chronologies were explained by wet fall seasons that followed dry falls. Droughts result in enriched $\delta^{18}O$ in tree-ring cellulose, while wetter than average years result in depleted $\delta^{18}O$ in tree-ring cellulose. The large year-to-year change in $\delta^{18}O$ mimics the ^{18}O-depleted signal associated with tropical cyclone events. Another false positive year was characterized by a large El Niño event. El Niño exerts an influence on rainfall along the Gulf Coast, typically resulting in increased precipitation. The dominant moisture source for the region likely shifts from the Gulf of Mexico to more Pacific influence during El Niño years. Pacific moisture is depleted in $\delta^{18}O$ versus Gulf of Mexico moisture.

Drought events concurrent with tropical cyclones dampened the characteristic ^{18}O-depleted rainfall signal via mixing with ^{18}O-enriched soil moisture. Results from this study indicated that the amount of rainfall associated with a tropical cyclone did not affect the trees' ability to identify the storm. Hurricane Rita (2005) dropped over 16 cm of rainfall near the site. However, drought conditions during the summer and fall season resulted in the storm being missed by trees at both sites. During the 25-year period, no tropical cyclone concurrent with drought conditions was recorded at either site.

5.1.3 Using multiple tree-ring indicators to characterize climate

Combining ring width, $\delta^{18}O$, and $\delta^{13}C$ from the same site provided a comprehensive analysis of the tree-ring/climate relationship. An average $\delta^{18}O$ chronology from the Big Sandy Creek Unit was correlated to fall (August–October) precipitation ($r = -0.62$, $p < 0.001$) and z-index ($r = -0.63$, $p < 0.001$) (1982–2007). An average $\delta^{13}C$ chronology revealed similar correlations between fall precipitation ($r = -0.59$, $p < 0.001$) and z-index ($r = -0.56$, $p < 0.003$) over the same period. Step-wise multiple regression techniques and principal component analyses conducted on the multiple chronologies did not improve the tree-ring/climate relationship over $\delta^{18}O$ alone. However, combining tree-ring parameters with similar climate responses ($\delta^{18}O$ and $\delta^{13}C$) resulted in improved correlations with fall precipitation ($r = 0.64$, $p < 0.001$) and fall z-index ($r = 0.66$, $p < 0.001$).

The combined ring width and $\delta^{13}C$ chronologies revealed changes in growth rate and/or carbon assimilation in the stand beginning ca. 1991. The corresponding $\delta^{18}O$ chronology did not indicate a change in moisture availability in the area coincident with this event. The decrease in ring growth and $\delta^{13}C$ is likely a result of decreased growth and photosynthetic rate related to tree senescence (age), because the majority of the trees in the stand exceed 150 years of age.

5.2 Summary

The tree-ring hurricane record is complex, and is directly affected by isotopic variability among individual trees in a stand. The $\delta^{18}O$ of tree-ring cellulose is related to the $\delta^{18}O$ of soil moisture used for photosynthesis, so that soil moisture heterogeneity will be expressed in tree-ring cellulose. Incorporating multiple trees into the hurricane record will improve the effectiveness of the record and allow for a more comprehensive characterization of tropical cyclone frequency and variability. Climatic variability can mimic or mask the ^{18}O-depleted rainfall signal associated with tropical cyclones, which further complicates the record. Individual sites should be evaluated to determine the amount of isotopic heterogeneity among individual trees and the degree to which climate variability influences the trees' ability to record tropical cyclone events.

Stable isotopes in tree-ring cellulose can provide information regarding the tree-ring/climate relationship even when ring width analyses are not useful. At these sites, oxygen and carbon isotopes proved superior for analyzing regional precipitation and drought over ring width analyses. However, ring width analyses, in conjunction with stable isotope records, can provide a comprehensive characterization of tree growth even in areas where ring width is not correlated to regional climate. The south-central and southeastern US are lacking in tree-ring isotope records. The results presented in this dissertation highlight the usefulness of tree-ring parameters for climate research, and the high potential for climate reconstructions from trees in the south-central US.

5.3 Future research objectives

This dissertation is the first to incorporate multiple trees into the tree-ring hurricane record. The results presented here provided crucial information for refining this new and innovative technique. Comparison of these data with other studies is impossible because of the lack of available data. Using the results presented here, a detailed mechanistic evaluation of the tropical cyclone record could be accomplished using multiple trees from the original site (Valdosta, Georgia). A 220-year record exists for this site, and a multi-tree comparison during the instrumental period could be accomplished using existing tree-ring specimens. It is likely that there is no “magic number” of trees necessary for a comprehensive analysis of the tree-ring hurricane record. Instead, site-specific characteristics will require that other sample areas be evaluated individually.

The AR-1 model was originally implemented to highlight the negative isotopic anomalies thought to be associated with tropical cyclone rainfall. Although the model has proven useful in that respect, no study has exceeded approximately 65% effectiveness when evaluating the models versus instrumental records. One possible shortcoming of the AR-1 model for the data presented here is that these series were short (25 to 26 years), and were intended to evaluate how variability affects the hurricane record in trees. The AR-1 model is time dependent, and may not be suitable for shorter time series. Regional climate variability can also introduce error into the models by masking or mimicking the negative isotopic anomalies associated with hurricanes. Re-evaluating the previously employed –0.5 AR-1 threshold proved useful for these data where multiple trees were available, but future studies should focus on developing alternative methods for characterizing tropical cyclones from tree-ring $\delta^{18}O$ records.

Appendix 5- Isotope Data

Turkey Creek LW Oxygen Isotope Data (‰ VSMOW)

	TC001	TC002	TC003	TC006	TC avg
1982	31.90	32.71	33.54	33.52	32.92
1983	32.12	32.82	31.31	32.74	32.25
1984	31.72	32.36	32.45	31.36	31.97
1985	31.61	31.47	33.45	31.48	32.01
1986	31.01	31.75	31.28	30.97	31.25
1987	33.25	34.96	35.39	33.26	34.21
1988	31.10	33.21	31.70	32.17	32.04
1989	32.29	29.10	30.44	32.18	31.00
1990	33.32	33.79	33.10	33.03	33.31
1991	32.54	31.51	31.98	32.62	32.16
1992	32.71	34.38	32.03	33.67	33.20
1993	30.64	33.40	31.92	32.54	32.13
1994	32.04	32.06	31.39	31.95	31.86
1995	31.84	35.07	31.54	32.44	32.72
1996	31.53	31.23	30.80	31.34	31.23
1997	31.19	32.85	30.93	33.95	32.23
1998	31.00	31.22	30.37	30.94	30.88
1999	32.47	33.79	31.53	32.35	32.53
2000	31.47	33.25	31.92	33.80	32.61
2001	31.46	31.92	30.97	32.68	31.76
2002	30.17	30.77	29.95	30.41	30.32
2003	31.13	31.68	30.57	32.02	31.35
2004	31.84	33.21	30.69	31.81	31.89
2005	32.47	32.57	32.63	33.74	32.85
2006	31.17	30.85	31.75	32.09	31.47

Big Sandy Creek LW Isotope Data (‰ VSMOW)

	BSC 002	BSC 005	BSC 010	BSC 015	BSC Avg
1982	33.03	33.67	34.63	33.92	33.82
1983	32.81	32.06	32.19	32.37	32.36
1984	33.17	33.51	33.30	32.50	33.12
1985	34.48	33.30	33.01	31.56	33.09
1986	31.60	32.13	31.40	31.55	31.67
1987	34.93	36.20	35.49	34.10	35.18
1988	34.95	35.53	32.40	33.92	34.20
1989	33.53	32.32	30.97	32.79	32.40
1990	34.56	34.67	34.36	34.57	34.54
1991	31.64	32.26	31.70	32.19	31.95
1992	35.07	34.21	35.83	34.06	34.79
1993	33.08	33.28	33.12	32.8o	33.07
1994	32.86	32.83	34.81	33.15	33.41
1995	33.74	33.84	34.81	32.68	33.77
1996	33.24	32.44	31.94	31.61	32.31
1997	34.19	34.09	33.63	33.09	33.75
1998	31.47	31.21	31.53	32.96	31.79
1999	35.31	35.05	33.10	34.29	34.44
2000	32.76	33.02	32.63	33.01	32.86
2001	33.44	32.15	31.41	32.43	32.36
2002	32.16	33.11	33.70	33.02	33.00
2003	32.43	32.15	32.77	33.05	32.60
2004	32.33	33.11	31.94	33.39	32.69
2005	34.63	35.53	33.15	35.02	34.58
2006	32.79	32.92	32.32	32.04	32.52
2007	32.20	31.87	31.88	32.95	32.23

LW Carbon (‰ PDB, No Seuss Correction)

	BSC002	BSC005	BSC010	BSC015	BSC Avg
1982	-25.35	-24.31	-23.81	-22.88	-24.09
1983	-25.91	-25.18	-24.64	-24.52	-25.06
1984	-25.24	-24.29	-23.91	-24.68	-24.53
1985	-23.72	-24.38	-24.11	-24.09	-24.07
1986	-24.90	-25.15	-24.49	-24.50	-24.76
1987	-24.08	-23.18	-24.31	-24.55	-24.03
1988	-23.40	-23.10	-23.46	-23.63	-23.40
1989	-24.85	-23.97	-24.23	-24.60	-24.41
1990	-24.91	-23.16	-24.78	-24.13	-24.25
1991	-25.45	-25.06	-24.83	-24.97	-25.08
1992	-24.81	-24.52	-24.69	-23.49	-24.38
1993	-25.81	-24.30	-25.64	-23.31	-24.77
1994	-25.82	-25.17	-25.11	-23.63	-24.93
1995	-25.24	-25.02	-25.48	-23.44	-24.80
1996	-25.57	-25.31	-26.01	-24.40	-25.32
1997	-25.56	-25.19	-25.58	-24.04	-25.09
1998	-27.00	-25.47	-25.90	-24.05	-25.60
1999	-24.96	-25.55	-24.61	-23.47	-24.65
2000	-25.63	-25.84	-24.51	-24.24	-25.05
2001	-26.26	-25.72	-25.50	-24.46	-25.49
2002	-25.69	-25.06	-24.76	-23.75	-24.81
2003	-26.01	-24.87	-25.49	-23.83	-25.05
2004	-25.42	-24.92	-25.78	-23.82	-24.98
2005	-25.85	-24.98	-25.73	-23.69	-25.06
2006	-25.78	-25.19	-25.35	-23.88	-25.05
2007	-25.94	-25.63	-25.80	-23.96	-25.33

LW Carbon Isotope Data (‰ PDB, Seuss corrected)

	BSC002	BSC005	BSC010	BSC015	BSC Avg
1982	-24.53	-23.49	-22.98	-22.06	-23.26
1983	-25.06	-24.33	-23.79	-23.67	-24.21
1984	-24.37	-23.42	-23.03	-23.80	-23.65
1985	-22.82	-23.48	-23.21	-23.19	-23.17
1986	-23.97	-24.23	-23.56	-23.58	-23.84
1987	-23.13	-22.23	-23.36	-23.60	-23.08
1988	-22.42	-22.12	-22.48	-22.66	-22.42
1989	-23.85	-22.97	-23.23	-23.60	-23.41
1990	-23.89	-22.14	-23.75	-23.11	-23.22
1991	-24.40	-24.01	-23.78	-23.92	-24.03
1992	-23.74	-23.45	-23.62	-22.41	-23.30
1993	-24.71	-23.20	-24.54	-22.21	-23.67
1994	-24.69	-24.04	-23.98	-22.50	-23.80
1995	-24.09	-23.87	-24.33	-22.29	-23.65
1996	-24.40	-24.14	-24.83	-23.22	-24.15
1997	-24.36	-23.99	-24.38	-22.84	-23.89
1998	-25.77	-24.25	-24.67	-22.82	-24.38
1999	-23.71	-24.30	-23.36	-22.22	-23.40
2000	-24.35	-24.56	-23.24	-22.96	-23.78
2001	-24.96	-24.42	-24.20	-23.16	-24.19
2002	-24.36	-23.73	-23.44	-22.43	-23.49
2003	-24.66	-23.52	-24.14	-22.48	-23.70
2004	-24.05	-23.54	-24.41	-22.44	-23.61
2005	-24.45	-23.58	-24.33	-22.29	-23.66
2006	-24.35	-23.77	-23.92	-22.45	-23.63
2007	-24.49	-24.18	-24.35	-22.51	-23.88

Appendix 6- AR-1 Residuals
Turkey Creek AR-1 Residuals

	TC001	TC002	TC003	TC006	TC Avg
1982	0.83	0.10	-0.30	0.59	0.31
1983	-0.87	0.14	0.03	0.40	-0.07
1984	-1.46	-0.23	-0.44	-0.41	-0.63
1985	1.03	-0.96	-0.48	-1.02	-0.36
1986	-0.92	-0.87	-0.92	-1.62	-1.07
1987	3.28	1.72	1.16	0.90	1.75
1988	0.16	1.11	-0.46	-0.07	0.15
1989	-1.11	-2.73	0.31	-0.38	-1.01
1990	0.86	0.28	1.39	0.66	0.90
1991	-0.02	-0.64	0.74	0.58	0.16
1992	0.26	1.15	0.97	1.14	0.93
1993	-0.27	1.36	-1.10	0.21	0.03
1994	-0.42	-0.17	0.33	-0.60	-0.26
1995	-0.44	1.84	0.16	0.32	0.48
1996	-0.60	-0.52	-0.28	-0.90	-0.64
1997	-0.28	-0.14	-0.45	1.47	0.17
1998	-0.67	-0.97	-0.80	-0.89	-0.82
1999	0.19	0.64	0.95	-0.12	0.42
2000	0.71	0.73	-0.09	1.64	0.72
2001	-0.33	-0.44	-0.24	0.29	-0.17
2002	-1.45	-1.46	-1.46	-2.14	-1.61
2003	-1.32	-0.98	-0.21	-0.77	-0.84
2004	0.03	0.41	0.25	-0.43	0.07
2005	2.04	0.16	1.10	1.28	1.12
2006	0.91	0.52	-0.19	-0.07	0.33

Big Sandy Creek AR-1 Residuals

	BSC 002	BSC005	BSC 010	BSC 015	BSC Avg
1982	-0.47	0.14	1.24	1.02	0.50
1983	-0.91	-1.28	-0.45	-0.24	-0.58
1984	-0.63	-0.39	-0.30	-0.39	-0.54
1985	0.51	-0.13	-0.27	-1.21	-0.29
1986	-1.38	-1.16	-1.51	-1.21	-1.40
1987	0.53	2.01	1.30	0.91	1.00
1988	1.82	2.38	-0.02	0.89	1.55
1989	0.60	-0.47	-2.14	0.04	-0.33
1990	0.87	0.69	0.23	1.39	0.70
1991	-1.10	-0.65	-0.86	-0.51	-0.57
1992	0.76	0.41	1.78	0.71	0.77
1993	0.29	0.08	0.89	-0.06	0.48
1994	-0.58	-0.47	1.36	0.04	0.06
1995	0.14	0.33	1.90	-0.39	0.51
1996	0.10	-0.72	-0.32	-1.29	-0.53
1997	0.62	0.41	0.11	-0.11	0.08
1998	-1.19	-1.59	-0.89	-0.05	-0.88
1999	1.08	0.91	-0.23	0.87	0.51
2000	0.32	0.17	-0.28	-0.08	0.19
2001	-0.05	-1.03	-1.16	-0.57	-0.76
2002	-0.84	-0.42	0.25	-0.17	-0.43
2003	-0.94	-0.96	0.16	-0.21	-0.52
2004	-1.01	-0.43	-0.85	0.17	-0.62
2005	0.95	1.87	0.54	1.50	1.17
2006	0.35	0.34	-0.01	-0.90	0.18

Appendix 7- Monthly Regional Climate Data
Region 8 Texas Monthly Precipitation (cm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1982	4.1	11.2	4.0	7.6	16.8	7.5	4.3	5.6	4.3	8.1	20.5	13.6
1983	7.9	13.8	9.8	1.0	12.0	11.5	22.2	20.0	24.1	8.1	8.8	7.5
1984	10.8	5.9	3.7	0.9	11.7	3.7	9.0	9.2	13.4	32.7	7.7	6.5
1985	8.0	12.0	15.5	7.6	5.1	11.7	9.8	6.9	14.7	14.2	8.9	6.5
1986	3.7	4.9	3.5	3.9	14.6	19.9	2.5	8.5	12.5	23.5	18.9	15.5
1987	9.7	12.6	1.8	0.5	13.4	25.4	14.8	6.3	11.5	1.1	12.1	9.5
1988	5.0	4.0	10.8	6.9	2.4	5.9	10.0	6.9	11.5	4.0	1.7	6.7
1989	15.9	1.9	6.6	3.8	16.4	30.9	10.2	11.5	4.0	6.6	6.6	2.5
1990	12.2	8.6	13.0	11.0	9.7	4.7	13.1	3.7	11.2	7.3	7.0	6.3
1991	25.6	13.0	6.5	20.8	15.8	17.2	9.3	8.5	14.0	6.0	10.6	19.1
1992	19.5	19.5	10.1	13.1	17.1	14.9	10.5	6.3	6.5	4.1	18.2	9.9
1993	15.8	8.4	15.4	12.8	19.0	22.3	2.7	4.9	4.9	14.2	10.8	7.4
1994	7.4	4.0	6.6	6.7	15.2	13.5	3.6	13.7	7.7	32.5	2.6	14.8
1995	11.5	6.3	12.4	10.6	15.5	13.1	9.5	10.0	5.8	8.8	9.4	17.1
1996	5.2	1.9	1.8	4.4	1.4	18.4	4.5	22.2	18.5	7.2	6.1	7.7
1997	11.3	12.1	19.7	19.5	15.3	8.3	5.5	5.2	21.2	19.2	9.7	10.7
1998	15.6	12.8	6.0	2.0	0.1	8.0	4.7	14.6	32.2	19.5	15.9	8.1
1999	6.5	3.2	7.9	2.5	12.5	14.6	11.4	2.1	8.1	3.0	2.3	6.9
2000	4.8	3.1	7.6	10.9	18.5	8.0	2.2	4.2	7.1	7.6	23.4	6.1
2001	12.3	1.8	13.8	2.4	9.4	28.3	7.1	21.3	17.2	13.1	13.1	11.9
2002	4.2	2.2	4.2	9.0	5.6	13.5	14.1	17.0	21.6	30.7	11.8	17.0
2003	6.1	8.4	4.0	2.2	0.1	14.9	16.1	10.4	23.5	12.3	9.9	8.4
2004	12.3	12.9	4.9	11.1	21.3	30.0	6.3	5.4	4.9	12.7	30.7	5.7
2005	5.4	12.4	9.5	3.0	10.0	1.9	16.2	6.2	10.3	6.0	8.7	5.8
2006	5.0	4.0	4.2	5.0	13.0	18.4	26.0	6.9	11.8	29.5	2.1	10.0
2007	18.4	3.0	13.8	11.9	14.7	11.0	33.6	14.2	12.1	6.4	8.8	3.8
2008	13.3	7.1	6.5	5.2	4.3	6.9	9.3	18.0	14.0	6.5	9.2	3.3

Region 8 Texas Monthly Temperature (ºF)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1982	53.1	53.1	64.3	68.2	75.2	82.2	84.3	84.2	79.7	70.3	62.3	57.0
1983	51.5	54.5	59.7	65.0	73.7	79.3	82.4	82.9	77.1	71.0	64.3	47.5
1984	48.3	55.9	62.5	69.5	75.4	80.4	82.5	82.4	76.9	73.7	61.8	63.6
1985	47.2	50.9	65.4	70.8	76.6	81.0	81.9	84.2	79.6	72.2	67.1	51.7
1986	55.0	60.1	63.3	71.5	75.4	81.3	84.4	83.0	81.7	70.0	62.7	52.6
1987	51.8	56.7	60.0	66.9	76.6	80.4	82.7	84.8	78.5	68.3	61.1	56.5
1988	48.5	54.1	61.7	68.1	73.5	79.4	83.2	84.5	79.5	71.6	65.7	56.4
1989	58.4	52.8	61.3	68.8	77.6	80.0	82.3	81.8	77.0	70.8	63.9	45.4
1990	57.5	60.6	63.7	69.2	77.4	83.8	82.1	84.0	79.8	68.8	64.4	54.8
1991	50.6	57.7	64.7	72.3	77.3	81.5	83.3	83.0	77.3	72.6	57.2	58.3
1992	51.8	59.4	64.3	68.6	73.6	81.7	83.4	80.3	79.5	71.4	57.7	57.2
1993	53.9	56.8	61.7	66.1	73.1	80.7	84.2	84.9	80.1	70.2	58.5	56.7
1994	53.3	55.6	62.7	69.1	75.0	82.0	83.8	81.8	77.7	71.6	66.7	57.9
1995	54.8	59.1	62.7	68.2	76.7	80.0	84.1	84.0	80.8	70.6	61.6	56.8
1996	53.2	57.7	57.6	67.5	79.1	81.6	84.6	82.5	79.0	71.1	64.0	58.4
1997	52.0	56.7	66.1	65.1	74.2	80.7	84.4	84.3	80.4	70.3	58.4	52.6
1998	58.5	57.5	61.4	67.7	78.7	84.6	86.1	84.6	82.1	73.3	65.5	56.6
1999	58.1	62.7	63.8	72.5	76.3	81.7	82.8	86.1	78.8	69.9	64.4	55.6
2000	58.4	63.0	66.3	69.5	78.4	81.8	85.0	84.7	80.2	71.6	59.8	49.7
2001	50.3	60.4	58.6	72.2	76.5	81.0	84.0	83.7	77.8	68.8	64.8	57.4
2002	56.1	53.0	62.5	73.4	76.8	81.1	83.2	83.4	79.2	72.0	59.8	55.3
2003	51.3	55.1	62.0	70.0	79.7	82.1	82.4	83.8	77.6	71.3	66.2	54.6
2004	55.4	53.8	67.1	69.0	75.6	80.7	83.0	82.3	80.3	76.5	63.8	54.1
2005	57.3	58.4	62.4	68.5	74.8	82.4	84.1	84.6	83.2	71.1	65.2	53.5
2006	58.9	56.2	66.3	73.2	76.6	80.6	82.4	84.2	78.7	72.5	63.9	56.1
2007	51.1	55.3	66.5	66.6	75.8	81.3	80.9	84.1	80.2	72.5	63.7	58.9
2008	53.1	60.4	63.9	69.8	77.3	83.3	83.0	83.1	78.0	69.5	63.4	55.8

Region 8 Texas Monthly z-index

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1982	-1.3	1.6	-1.1	0.1	1.8	-0.6	-1.8	-1.9	-2.5	-0.4	3.1	1.9
1983	0.1	2.4	1.5	-1.7	0.4	0.5	3.5	3.9	3.5	-0.2	0.3	0.4
1984	1.2	-0.6	-1.0	-2.3	-0.1	-2.0	-1.1	-0.7	0.2	5.9	0.2	-1.2
1985	0.3	2.0	2.9	-0.2	-1.6	0.0	-0.4	-1.3	0.2	1.2	-0.4	-0.6
1986	-1.6	-1.3	-1.2	-1.6	0.8	2.4	-1.6	-0.7	-0.6	3.8	3.6	2.9
1987	0.7	1.8	-1.4	-2.2	0.2	3.7	1.9	-0.4	-0.3	-2.0	0.8	0.1
1988	-0.7	-1.2	1.6	-0.1	-1.9	-1.3	-0.7	-1.5	-0.6	-1.6	-3.1	-1.9
1989	1.0	-1.9	0.2	-1.2	1.2	5.5	0.7	1.0	-1.9	-0.8	-1.1	-2.2
1990	0.3	0.0	2.2	1.2	-0.4	-1.6	0.2	-2.4	-0.8	-0.4	-1.3	-1.6
1991	5.2	1.9	-0.2	4.1	1.3	1.9	0.3	-0.1	0.5	-1.0	0.7	3.4
1992	4.0	4.1	1.1	2.0	2.1	1.3	0.6	-0.6	-1.7	-1.5	2.9	0.6
1993	2.6	0.2	3.3	2.1	2.7	3.3	-1.5	-1.9	-2.4	1.3	0.9	-0.4
1994	-0.2	-1.3	0.0	-0.2	1.4	0.9	-1.4	0.9	-1.3	6.1	-1.9	2.0
1995	1.1	-0.7	2.1	1.2	1.3	1.0	0.2	0.1	-2.1	-0.2	-0.1	2.5
1996	-0.9	-2.3	-1.3	-0.9	-3.1	1.1	-2.2	3.2	1.5	-0.5	-0.8	-0.6
1997	1.2	1.6	4.3	4.5	1.5	-0.3	-1.4	-1.9	1.7	2.8	1.1	1.2
1998	2.2	1.8	-0.1	-1.6	-3.4	-1.9	-2.8	0.5	4.3	2.6	2.4	0.0
1999	-0.9	-2.2	0.2	-2.1	0.1	0.8	0.3	-2.6	-1.4	-1.7	-2.8	-1.8
2000	-2.7	-3.8	-1.6	0.5	1.3	-0.7	-2.6	-2.5	-1.9	-0.6	4.2	-0.2
2001	1.6	-2.5	2.8	-2.1	-0.8	4.2	-0.3	3.6	1.5	1.3	1.6	1.3
2002	-1.5	-1.7	-0.8	0.0	-1.5	0.5	0.8	2.1	2.3	5.8	1.6	3.2
2003	-0.5	0.4	-0.8	-1.9	-3.7	0.0	0.7	-0.5	2.7	0.9	0.4	0.3
2004	1.3	2.1	-1.1	1.2	3.0	5.3	-0.5	-1.2	-2.4	0.2	6.3	-0.6
2005	-1.2	1.6	1.1	-1.4	-0.2	-2.4	0.6	-1.8	-1.3	-1.0	-0.9	-1.7
2006	-2.4	-2.3	-1.9	-1.9	-0.2	1.5	4.3	-0.1	-0.1	5.3	-1.8	0.5
2007	3.7	-1.6	2.1	1.8	1.2	0.3	6.8	2.2	0.0	-0.8	0.0	-1.8
2008	1.8	-0.6	-0.2	-0.8	-2.0	-1.6	-1.1	1.9	0.3	-0.6	-0.3	-2.2

Region 8 Texas Monthly Palmer Drought Severity Index (PDSI)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1982	1.9	2.2	1.6	1.5	1.9	-0.2	-0.8	-1.4	-2.1	-2.0	1.0	1.6
1983	1.4	2.1	2.4	1.6	1.5	1.5	2.5	3.6	4.4	3.8	3.5	3.3
1984	3.4	-0.2	-0.5	-1.2	-1.1	-1.7	-1.9	-1.9	0.1	2.0	1.9	1.3
1985	1.3	1.8	2.6	-0.1	-0.6	-0.5	-0.6	-1.0	-0.8	-0.3	-0.4	-0.6
1986	-1.0	-1.4	-1.6	-2.0	0.3	1.0	-0.5	-0.7	-0.8	1.3	2.3	3.0
1987	3.0	3.3	2.4	1.5	1.4	2.4	2.8	-0.1	-0.2	-0.8	-0.5	-0.4
1988	-0.6	-0.9	-0.3	-0.3	-0.9	-1.2	-1.3	-1.7	-1.7	-2.1	-2.9	-3.2
1989	-2.6	-2.9	-2.6	-2.7	0.4	2.2	2.2	2.3	-0.6	-0.8	-1.1	-1.7
1990	0.1	0.1	0.8	1.1	-0.1	-0.6	-0.5	-1.2	-1.4	-1.4	-1.6	-2.0
1991	1.7	2.2	1.9	3.0	3.2	3.5	3.2	2.9	2.7	2.1	2.2	3.1
1992	4.1	5.0	4.9	5.0	5.2	5.1	4.8	4.1	3.1	2.3	3.0	2.9
1993	3.5	3.2	4.0	4.3	4.7	5.3	-0.5	-1.1	-1.8	-1.2	-0.8	-0.8
1994	-0.8	-1.1	-1.0	-1.0	-0.4	-0.1	-0.6	-0.2	-0.6	2.0	1.2	1.7
1995	1.9	1.5	2.0	2.2	2.4	2.5	2.3	0.0	-0.7	-0.7	-0.6	0.8
1996	-0.3	-1.0	-1.4	-1.5	-2.4	-1.8	-2.4	1.1	1.4	-0.2	-0.4	-0.6
1997	0.4	0.9	2.3	3.5	3.7	3.2	2.4	1.5	1.9	2.6	2.7	2.8
1998	3.3	3.5	0.0	-0.6	-1.7	-2.1	-2.9	0.2	1.6	2.3	2.9	0.0
1999	-0.3	-1.0	-0.8	-1.4	-1.3	-0.9	-0.7	-1.5	-1.8	-2.2	-2.9	-3.2
2000	-3.8	-4.6	-4.7	-4.1	-3.2	-3.1	-3.7	-4.1	-4.3	-4.1	1.4	1.2
2001	1.6	0.6	1.5	0.6	0.3	1.7	1.4	2.5	2.7	2.9	3.1	3.2
2002	-0.5	-1.0	-1.2	-1.1	-1.5	0.2	0.4	1.1	1.7	3.5	3.6	4.3
2003	-0.2	0.0	-0.3	-0.9	-2.1	0.0	0.2	0.1	0.9	1.1	1.2	1.1
2004	1.5	2.0	1.5	1.7	2.5	4.0	3.4	2.7	1.6	1.5	3.5	2.9
2005	2.2	2.5	2.6	-0.5	-0.5	-1.3	-0.9	-1.4	-1.7	-1.9	-2.0	-2.3
2006	-2.9	-3.3	-3.6	-3.9	-3.5	0.5	1.9	1.7	1.5	3.1	2.2	2.1
2007	3.1	2.3	2.8	3.1	3.1	2.9	4.9	5.1	0.0	-0.3	-0.3	-0.8
2008	-0.1	-0.3	-0.3	-0.6	-1.2	-1.6	-1.8	-1.0	-0.8	-0.9	-0.9	-1.5

Appendix 8- Ring Width Statistical Dating

```
[]  Dendrochronology Program Library                                        Run BSCLW  Program COF  14:21  Thu 19 Nov 2009  Page   1
[]  P R O G R A M      C O F E C H A                                                                        Version 6.06P    27353
-----------------------------------------------------------------------------------------------------------------------------------

 QUALITY CONTROL AND DATING CHECK OF TREE-RING MEASUREMENTS

 Title of run:           BSCLW
 File of DATED series:   BSCLW.txt

 CONTENTS:

    Part 1:  Title page, options selected, summary, absent rings by series
    Part 2:  Histogram of time spans
    Part 3:  Master series with sample depth and absent rings by year
    Part 4:  Bar plot of Master Dating Series
    Part 5:  Correlation by segment of each series with Master
    Part 6:  Potential problems: low correlation, divergent year-to-year changes, absent rings, outliers
    Part 7:  Descriptive statistics

 RUN CONTROL OPTIONS SELECTED                             VALUE

         1  Cubic smoothing spline 50% wavelength cutoff for filtering
                                                            32 years
         2  Segments examined are                           50 years lagged successively by  25 years
         3  Autoregressive model applied                     A  Residuals are used in master dating series and testing
         4  Series transformed to logarithms                 Y  Each series log-transformed for master dating series and testing
         5  CORRELATION is Pearson (parametric, quantitative)
            Critical correlation, 99% confidence level   .3281
         6  Master dating series saved                       N
         7  Ring measurements listed                         N
         8  Parts printed                              1234567
         9  Absent rings are omitted from master series and segment correlations  (Y)

 Time span of Master dating series is  1862 to  2007   146 years
 Continuous time span is               1862 to  2007   146 years
 Portion with two or more series is    1863 to  2007   145 years


                                        ****************************************
                                        *C* Number of dated series        17 *C*
                                        *O* Master series 1862 2007  146 yrs *O*
                                        *F* Total rings in all series   2190 *F*
                                        *E* Total dated rings checked   2189 *E*
                                        *C* Series intercorrelation     .687 *C*
                                        *H* Average mean sensitivity    .426 *H*
                                        *A* Segments, possible problems    0 *A*
                                        *** Mean length of series      128.8 ***
                                        ****************************************
```

```
ABSENT RINGS listed by SERIES:            (See Master Dating Series for absent rings listed by year)

BSC003B     1 absent rings:   1910

            1 absent rings    .046%
```

```
PART 2:  TIME PLOT OF TREE-RING SERIES: BSCLW                                                      14:21  Thu 19 Nov 2009  Page   2
-----------------------------------------------------------------------------------------------------------------------------------
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050 Ident   Seq Time-span  Yrs
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    : -------- --- ---- ---- ----
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <============>    . BSC001A    1 1870 2007  138
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=========>    . BSC001B    2 1906 2007  102
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=============>    . BSC002A    3 1863 2007  145
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <===========>    . BSC002B    4 1884 2007  124
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <============>    . BSC002C    5 1874 2007  134
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <===========>    . BSC003A    6 1880 2007  128
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=============>    . BSC003B    7 1863 2007  145
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <===========>    . BSC003C    8 1882 2007  126
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<========>    . BSC005A    9 1916 2007   92
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<========>    . BSC005B   10 1915 2007   93
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <============>    . BSC007B   11 1878 2007  130
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=============>    . BSC007C   12 1868 2007  140
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <============>    . BSC010A   13 1877 2007  131
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=============>    . BSC010C   14 1862 2007  146
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=============>    . BSC015A   15 1866 2007  142
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<=============>    . BSC015C   16 1864 2007  144
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <============>    . BSC017A   17 1878 2007  130
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050
```

Year	Value	No	Ab
1862	-1.696	1	
1863	-2.567	3	
1864	-.533	4	
1865	.783	4	
1866	-.009	5	
1867	.648	5	
1868	.691	6	
1869	.586	6	
1870	-.810	7	
1871	.129	7	
1872	.023	7	
1873	-1.468	7	
1874	.188	8	
1875	.941	8	
1876	1.372	8	
1877	-.117	9	
1878	.533	11	
1879	-.753	11	
1880	.999	12	
1881	-1.407	12	
1882	.989	13	
1883	-.281	13	
1884	-.362	14	
1885	1.762	14	
1886	-.661	14	
1887	.759	14	
1888	.329	14	
1889	.311	14	
1890	1.154	14	
1891	-.495	14	

Year	Value	No	Ab
1900	1.820	14	
1901	.213	14	
1902	.458	14	
1903	.538	14	
1904	.053	14	
1905	-.389	14	
1906	.198	15	
1907	.557	15	
1908	.928	15	
1909	-1.399	15	
1910	-1.704	15	1
1911	-2.023	15	
1912	-1.682	15	
1913	-.232	15	
1914	.314	15	
1915	1.687	16	
1916	.980	17	
1917	-1.348	17	
1918	-.163	17	
1919	.844	17	
1920	.590	17	
1921	.574	17	
1922	.674	17	
1923	1.025	17	
1924	-.672	17	
1925	-.937	17	
1926	1.807	17	
1927	.847	17	
1928	-1.388	17	
1929	.597	17	
1930	-.442	17	
1931	-1.191	17	
1932	-.302	17	
1933	.980	17	
1934	-.380	17	
1935	-.405	17	
1936	-.113	17	
1937	-1.074	17	
1938	1.208	17	
1939	-1.295	17	
1940	-.594	17	
1941	1.168	17	

Year	Value	No	Ab
1950	.417	17	
1951	-1.799	17	
1952	-1.168	17	
1953	.623	17	
1954	-.570	17	
1955	.706	17	
1956	-1.691	17	
1957	.984	17	
1958	.221	17	
1959	1.455	17	
1960	.193	17	
1961	1.366	17	
1962	-.662	17	
1963	-.134	17	
1964	-.271	17	
1965	-.009	17	
1966	.896	17	
1967	-.317	17	
1968	.925	17	
1969	-1.427	17	
1970	-1.564	17	
1971	.127	17	
1972	.662	17	
1973	-1.506	17	
1974	.444	17	
1975	1.525	17	
1976	.378	17	
1977	.234	17	
1978	-.468	17	
1979	.947	17	
1980	-1.598	17	
1981	.987	17	
1982	-.344	17	
1983	.817	17	
1984	.317	17	
1985	-.133	17	
1986	-.037	17	
1987	.185	17	
1988	-1.108	17	
1989	.163	17	
1990	-.240	17	
1991	1.284	17	

Year	Value	No	Ab
2000	-2.930	17	
2001	.425	17	
2002	.650	17	
2003	1.218	17	
2004	-.624	17	
2005	-.037	17	
2006	-.005	17	
2007	-.264	17	

Year	Value	No	Ab	Year	Value	No	Ab

1892	.595	14	1942	1.742	17	1992	-.253	17
1893	-2.254	14	1943	.651	17	1993	-1.722	17
1894	.874	14	1944	.147	17	1994	.636	17
1895	-.385	14	1945	.745	17	1995	1.541	17
1896	-.495	14	1946	.990	17	1996	.082	17
1897	-.963	14	1947	-1.158	17	1997	-.508	17
1898	.945	14	1948	-1.832	17	1998	-.097	17
1899	-1.889	14	1949	1.048	17	1999	.949	17

```
PART 4:  Master Bar Plot: BSCLW                                                                      14:21  Thu 19 Nov 2009  Page   4
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   Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value
                   1900----------G 1950------B     2000l
                   1901-----A      1951g           2001------B
                   1902------B     1952-e          2002-------C
                   1903-------B    1953-------B    2003---------E
                   1904-----@      1954--b         2004--b
                   1905---b        1955-------C    2005----@
                   1906-----A      1956g           2006----@
                   1907-------B    1957---------D  2007---a
                   1908---------D  1958-----A
                   1909-f          1959----------F
                   1910g           1960-----A
                   1911h           1961----------E
   1862g           1912g           1962--c
   1863j           1913----a       1963----a
   1864--b         1914------A     1964---a
   1865--------C   1915----------G 1965----@
   1866----@       1916---------D  1966--------D
   1867-------C    1917-e          1967---a
   1868-------C    1918----a       1968---------D
   1869-------B    1919--------C   1969-f
   1870--c         1920-------B    1970f
   1871-----A      1921-------B    1971-----A
   1872-----@      1922-------C    1972-------C
   1873-f          1923---------D  1973-f
   1874-----A      1924--c         1974------B
   1875---------D  1925--d         1975----------F
   1876----------E 1926----------G 1976------B
   1877----@       1927--------C   1977-----A
   1878-------B    1928-f          1978---b
   1879--c         1929-------B    1979---------D
   1880---------D  1930---b        1980f
   1881-f          1931-e          1981---------D
   1882---------D  1932---a        1982---a
   1883---a        1933---------D  1983--------C
   1884---a        1934---b        1984------A
   1885----------G 1935---b        1985----a
   1886--c         1936----@       1986----@
   1887--------C   1937-d          1987-----A
   1888------A     1938---------E  1988-d
   1889------A     1939-e          1989-----A
   1890---------E  1940--b         1990----a
   1891---b        1941---------E  1991----------E
   1892-------B    1942----------G 1992---a
   1893i           1943-------C    1993g
   1894--------C   1944-----A      1994-------C
   1895---b        1945--------C   1995----------F
   1896---b        1946---------D  1996-----@
```

```
1897--d         1947-e          1997---b
1898---------D  1948g           1998----@
1899h           1949---------D  1999---------D
```

Correlations of 50-year dated segments, lagged 25 years
Flags: A = correlation under .3281 but highest as dated; B = correlation higher at other than dated position

Seq	Series	Time_span	1850 1899	1875 1924	1900 1949	1925 1974	1950 1999	1975 2024
1	BSC001A	1870 2007	.77	.76	.81	.76	.60	.64
2	BSC001B	1906 2007			.75	.75	.64	.64
3	BSC002A	1863 2007	.67	.72	.81	.77	.53	.50
4	BSC002B	1884 2007		.77	.75	.68	.65	.61
5	BSC002C	1874 2007	.64	.64	.83	.79	.67	.64
6	BSC003A	1880 2007		.81	.77	.78	.55	.56
7	BSC003B	1863 2007	.76	.83	.82	.80	.61	.62
8	BSC003C	1882 2007		.76	.75	.68	.63	.51
9	BSC005A	1916 2007			.76	.69	.68	.74
10	BSC005B	1915 2007			.73	.69	.60	.67
11	BSC007B	1878 2007		.70	.76	.70	.53	.60
12	BSC007C	1868 2007	.68	.68	.73	.72	.66	.63
13	BSC010A	1877 2007		.86	.67	.66	.71	.58
14	BSC010C	1862 2007	.64	.85	.73	.70	.74	.63
15	BSC015A	1866 2007	.61	.73	.74	.73	.67	.73
16	BSC015C	1864 2007	.58	.67	.68	.76	.63	.66
17	BSC017A	1878 2007		.65	.78	.75	.71	.61
Av segment correlation			.67	.75	.76	.73	.64	.62

```
------------------------------------------------------------------------------------------------------------------------------------

 For each series with potential problems the following diagnostics may appear:

 [A] Correlations with master dating series of flagged  50-year segments of series filtered with  32-year spline,
     at every point from ten years earlier (-10) to ten years later (+10) than dated

 [B] Effect of those data values which most lower or raise correlation with master series
     Symbol following year indicates value in series is greater (>) or lesser (<) than master series value

 [C] Year-to-year changes very different from the mean change in other series

 [D] Absent rings (zero values)

 [E] Values which are statistical outliers from mean for the year
====================================================================================================================================

 BSC001A   1870 to  2007     138 years                                                                                  Series   1

 [B] Entire series, effect on correlation (  .732) is:
       Lower   1980> -.013   1964> -.011   1982< -.010   1986> -.009   1963> -.007   1912> -.006  Higher   2000  .020   1911  .009

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1964 +3.0 SD
====================================================================================================================================

 BSC001B   1906 to  2007     102 years                                                                                  Series   2

 [B] Entire series, effect on correlation (  .689) is:
       Lower   2005< -.026   1978< -.017   1993> -.012   1998> -.010   1927< -.010   1935> -.008  Higher   2000  .034   1951  .009

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       2005 -5.0 SD
====================================================================================================================================

 BSC002A   1863 to  2007     145 years                                                                                  Series   3

 [B] Entire series, effect on correlation (  .639) is:
       Lower   1986< -.036   1882< -.012   1984< -.009   1988> -.008   1868< -.008   1879> -.008  Higher   1893  .013   1951  .009

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1986 -5.1 SD
====================================================================================================================================

 BSC002B   1884 to  2007     124 years                                                                                  Series   4

 [B] Entire series, effect on correlation (  .703) is:
       Lower   1973< -.018   1933< -.011   1889< -.009   1997> -.007   1988> -.007   1961< -.005  Higher   1911  .010   1912  .009
```

```
====================================================================================================================

 BSC002C   1874 to  2007     134 years                                                                    Series   5

 [B] Entire series, effect on correlation (  .684) is:
      Lower   1886< -.015   1993< -.012   1880< -.011   1899> -.010   1897> -.009   1917> -.006  Higher   1912  .009   1911  .008

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1993 -4.9 SD
====================================================================================================================

 BSC003A   1880 to  2007     128 years                                                                    Series   6

 [B] Entire series, effect on correlation (  .709) is:
      Lower   1983< -.025   1986< -.020   1980> -.011   1988> -.011   1920< -.011   1925> -.010  Higher   2000  .013   1893  .010

====================================================================================================================

 BSC003B   1863 to  2007     145 years                                                                    Series   7

 [B] Entire series, effect on correlation (  .737) is:
      Lower   1980> -.014   1863> -.012   1988> -.011   1983< -.010   1939> -.008   1947> -.006  Higher   2000  .012   1910  .006

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1910   -1.704      15      1

====================================================================================================================

 BSC003C   1882 to  2007     126 years                                                                    Series   8

 [B] Entire series, effect on correlation (  .692) is:
      Lower   1974< -.017   1917> -.013   1967> -.008   2000> -.008   2007> -.008   1960< -.005  Higher   1911  .011   1951  .009

====================================================================================================================

 BSC005A   1916 to  2007      92 years                                                                    Series   9

 [B] Entire series, effect on correlation (  .738) is:
      Lower   1973> -.034   1993> -.014   1968< -.008   1935> -.008   1934> -.007   1930> -.006  Higher   2000  .036   1926  .008

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1973 +3.1 SD
====================================================================================================================

 BSC005B   1915 to  2007      93 years                                                                    Series  10

 [B] Entire series, effect on correlation (  .683) is:
      Lower   1915< -.028   1973> -.026   1928> -.011   1935> -.011   1966< -.010   2005> -.008  Higher   2000  .044   1926  .010

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 BSC007B   1878 to  2007     130 years                                                                                    Series  11

 [B] Entire series, effect on correlation (  .647) is:
       Lower   1988< -.038   1973> -.017   1923< -.011   1940> -.010   1886> -.008   1878< -.006  Higher   2000  .026   1911  .012

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1988 -6.6 SD
==================================================================================================================================

 BSC007C   1868 to  2007     140 years                                                                                    Series  12

 [B] Entire series, effect on correlation (  .677) is:
       Lower   2000> -.019   1991< -.013   1890< -.010   1940> -.008   1901< -.006   1897> -.006  Higher   1899  .008   1926  .008

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1911 -5.2 SD;    2000 +3.1 SD
==================================================================================================================================

 BSC010A   1877 to  2007     131 years                                                                                    Series  13

 [B] Entire series, effect on correlation (  .668) is:
       Lower   1932< -.040   1998< -.030   2000> -.024   1930< -.017   1928> -.015   1965< -.006  Higher   1911  .009   1948  .008

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1932 -5.8 SD;    2000 +3.1 SD
==================================================================================================================================

 BSC010C   1862 to  2007     146 years                                                                                    Series  14

 [*] Early part of series cannot be checked from 1862 to 1862 -- not matched by another series

 [B] Entire series, effect on correlation (  .661) is:
       Lower   1873> -.025   2000> -.020   1928> -.019   1870> -.013   1863< -.008   1932< -.007  Higher   1911  .010   1915  .007

 [E] Outliers     4   3.0 SD above or -4.5 SD below mean for year
       1863 -4.6 SD;    1873 +3.8 SD;    1928 +3.4 SD;    2000 +3.2 SD
==================================================================================================================================

 BSC015A   1866 to  2007     142 years                                                                                    Series  15

 [B] Entire series, effect on correlation (  .696) is:
       Lower   1867< -.016   1911> -.016   1870> -.010   1957< -.007   1993> -.007   1886> -.007  Higher   2000  .025   1893  .010

==================================================================================================================================

 BSC015C   1864 to  2007     144 years                                                                                    Series  16

 [B] Entire series, effect on correlation (  .659) is:
       Lower   1911> -.014   1909> -.013   1999< -.013   1872< -.010   1871< -.010   1970> -.010  Higher   2000  .028   1893  .015
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==================================================================================================================================

 BSC017A   1878 to  2007     130 years                                                                                    Series  17

 [B] Entire series, effect on correlation (  .681) is:
       Lower   1879< -.032   1973> -.016   2007> -.012   2000> -.009   1911> -.008   1965< -.007  Higher   1948  .007   1942  .007

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1879 -5.5 SD
==================================================================================================================================

 [*] All segments correlate highest as dated with correlation with master series over   .3281
```

						Corr	//-------- Unfiltered --------\\					//---- Filtered -----\\			
Seq	Series	Interval	No. Years	No. Segmt	No. Flags	with Master	Mean msmt	Max msmt	Std dev	Auto corr	Mean sens	Max value	Std dev	Auto corr	AR ()
1	BSC001A	1870 2007	138	6	0	.732	1.07	2.52	.520	.577	.384	2.57	.407	.009	1
2	BSC001B	1906 2007	102	4	0	.689	1.13	2.40	.565	.447	.411	2.64	.518	.003	1
3	BSC002A	1863 2007	145	6	0	.639	.88	2.95	.445	.394	.426	2.80	.518	-.006	1
4	BSC002B	1884 2007	124	5	0	.703	.86	2.34	.451	.328	.464	2.66	.408	.061	5
5	BSC002C	1874 2007	134	6	0	.684	1.07	3.66	.716	.713	.392	2.59	.426	.026	1
6	BSC003A	1880 2007	128	5	0	.709	.96	3.68	.503	.433	.402	2.75	.472	-.053	1
7	BSC003B	1863 2007	145	6	0	.737	1.00	3.40	.471	.344	.417	2.72	.453	.026	1
8	BSC003C	1882 2007	126	5	0	.692	.96	3.85	.798	.789	.419	2.69	.480	.110	1
9	BSC005A	1916 2007	92	4	0	.738	1.23	2.78	.510	.059	.446	2.59	.479	-.018	1
10	BSC005B	1915 2007	93	4	0	.683	1.23	2.90	.541	.299	.399	2.60	.455	.019	1
11	BSC007B	1878 2007	130	5	0	.647	1.43	3.33	.675	.503	.389	2.61	.388	-.025	1
12	BSC007C	1868 2007	140	6	0	.677	.87	2.62	.473	.494	.495	2.62	.401	.045	1
13	BSC010A	1877 2007	131	5	0	.668	1.29	3.55	.669	.184	.548	2.85	.500	.006	1
14	BSC010C	1862 2007	146	6	0	.661	.98	3.59	.572	.291	.518	2.68	.453	.010	1
15	BSC015A	1866 2007	142	6	0	.696	1.21	2.83	.472	.487	.315	2.58	.422	-.015	1
16	BSC015C	1864 2007	144	6	0	.659	1.14	2.66	.484	.537	.331	2.62	.400	.058	1
17	BSC017A	1878 2007	130	5	0	.681	1.19	3.69	.815	.617	.488	2.69	.482	-.017	1
Total or mean:			2190	90	0	.687	1.08	3.85	.568	.449	.426	2.85	.449	.015	

- = [COFECHA BSCLWCOF] = -

Vita

Daniel Bruce Lewis was born November 6, 1974, in Knoxville, Tennessee to Larry and Linda Lewis (both former Marines). After getting "asked to not return" to an unnamed private school in Knoxville, he attended Norwood Elementary School. Daniel went to Northwest Middle School in Knoxville, then was transplanted to Union County for high school. After graduating high school in 1993, he enlisted in the Air Force as a Strategic Aircraft Maintenance Specialist and worked on B-1B bombers until 1996. When he was discharged, he figured he should do something relatively responsible with his life because he had a family, and began an undergraduate degree at the University of Tennessee. Daniel ended up choosing Geography as a major, predominantly because he actually made good grades in it. Daniel graduated in 2000 from the Geography department at UT and enrolled in the M.S. program in Geography in 2000. Daniel graduated with a M.S. degree in Geography in 2003, focusing on biogeography, climate, and environmental history. He worked as a research technician in the Laboratory of Tree-Ring Science at the University of Tennessee until January 2005, when he enrolled in the PhD program in Geology. After finally learning what an isotope was, he focused on using tree-ring chemistry to evaluate climate variability at Big Thicket National Preserve, Texas, with Dr. David Finkelstein, and graduated with a PhD in December 2009. Daniel subsequently sold his soul to the devil, and accepted a position with ExxonMobil as the resident charity case and circus act (the guy who dates trees).