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The development of summer drought reconstructions for 12 Piedmont and Coastal Plain climate divisions in the southeastern U.S. from existing and original tree-ring chronologies is described. The drought metric reconstructed is the Palmer Meteorological Drought Index (PMDI), a modification of the Palmer Drought Severity Index (PDSI). A composite chronology of average yearly growth index values from individual chronologies covers the common period 1690-1984. The reconstructions have been tested for validity using PMDI data not included in regression modeling.

The reconstructions included 6 periods of sustained (> 4 yr) summer drought in the study area during the period 1690-1900. The instrumental record (1900-2006) contains 5 such droughts. Two periods of multi-year summer drought more severe than any in the observed record were found in the reconstructions, the most recent of which ended around 1821. After 1900, prolonged summer droughts in the Piedmont exhibited similar severity to historic droughts, but were more frequent. The data indicate that interactions between the contemporary synoptic features which control drought climatology in the region (e.g., the El-Niño-Southern Oscillation, the Atlantic Multidecadal Oscillation, the north Atlantic subtropical anticyclone, and winter mid-latitude cyclone tracks) discourage the development of multi-decadal droughts of the type that periodically affect the interior American West. Long-term reconstructions suggest “megadroughts” are unlikely in the

southeastern U.S. in the absence of significant modification of dominant features of the general atmospheric circulation.

TREE-RING BASED RECONSTRUCTION OF MULTI-YEAR SUMMER DROUGHTS IN PIEDMONT AND COASTAL PLAIN CLIMATE DIVISIONS OF THE SOUTHEASTERN U.S., 1690-2006

by

Jason T. Ortegren

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Approved by

Paul A. Knapp
Committee Chair

This dissertation is dedicated, with profound love and gratitude, to my wife Tabatha, without whose personal and technical support this work would have been unimaginable. And to my daughter Shelby, who laughs when we sneeze, and who has opened unto us a rich new existence.

APPROVAL PAGE

This dissertation has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

Committee Chair _____
Paul A. Knapp

Committee Members _____
Michael Lewis

_____
Dan Royall

_____
Peter T. Soulé

_June 13, 2008_____
Date of Acceptance by Committee

_June 13, 2008_____
Date of Final Oral Examination

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Jason T. Ortegren
Greensboro, NC
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CHAPTER I

INTRODUCTION

[1.0] *Drought*

Worldwide, drought affects more people than any other natural hazard (Hayes *et al.* 2004). At any given time, some region of the U.S. is likely experiencing mild to severe drought conditions (Soulé 1992). Although droughts usually lack the visible direct impacts associated with hurricanes or tornadoes, the recent rise in economic and other losses due to drought implies that the U.S. may be increasingly vulnerable to climatic fluctuations (Hayes *et al.* 2004).

The year 2007 was among the driest on record in much of the southeastern U.S. (Maxwell & Soulé 2008). In April, the state of Georgia implemented "level 2 drought response," restricting outdoor water uses with potential fines and reconnection fees to violators. Local precipitation deficits ranged from 12.01 cm in Athens to over 30 cm in Lafayette (Hernandez, 2007). In October, concerns over inter-state water rights between Alabama, Florida, and Georgia led to a legal confrontation. Concurrently, South Carolina challenged North Carolina in the U.S. Supreme Court regarding a diversion of the Catawba River in North Carolina. Farmers from Virginia to Alabama sold livestock; pastures failed to produce, and the cost of hay became prohibitive in many cases. Also in October, it was estimated that 96% of Virginia farmland had insufficient topsoil moisture (Copeland & O'Driscoll 2007a). Sixteen counties in South Carolina had banned outdoor

uses, and North Carolina, suffering the driest year in the state's recorded history, reported that reservoirs in some communities—including Raleigh and Durham—had fallen below a four month municipal supply. Municipalities in the northern 1/3 of Georgia were down to an estimated 80-day supply (Copeland 2007b).

North Carolina farmers lost an estimated $382 million in 2007. Further, industries such as landscaping and nursery/garden supply have suffered, leading to increased unemployment and requests for charity assistance (Baker 2007; Copeland 2007b). Local governments were also impacted. Durham, North Carolina leaders considered spending $60 million on emergency water source alternatives and future storage; Siler City, North Carolina paid $1 million to buy water from the town of Sanford, North Carolina (Baker 2007).

In 2008, the U.S. Federal Emergency Management Agency (FEMA) estimated economic losses during the year 2007 due to drought at well over $5 billion (FEMA 2008). The National Climatic Data Center (NCDC) reported that of 50 weather-related disasters with losses greater than $1 billion each for the period 1980-2006, twelve were droughts, and an additional six were wildfires, which are often related to drought (NCDC 2007a). The 1980 summer drought cost the U.S. approximately $16 billion (Stahle & Cleaveland 1988). Widespread drought in 1999 resulted in agricultural losses estimated at $1.35 billion over a total of 1383 counties, home to approximately 109 million people and an estimated 919,000 farms comprising approximately 25% of U.S. cropland and 32% of pastureland (Morehart *et al.* 1999). Drought impacts are often spatially segregated, with core zones of intense drought (where droughts are longest and most

severe) and broad regions experiencing less severe conditions (Morehart *et al.* 1999). The spatial distribution of economic impacts of the 1999 drought follows the geography of drought intensity. Overall, 40% of the total financial losses were accounted for by a larger "standard intensity" drought region, while 60% were concentrated in smaller areas where drought intensity and duration were most severe (Morehart *et al.* 1999).

Economic loss data rarely reflect all crop losses nor do they account for the indirect effects of drought, such as increased energy for cooling (Hayes *et al.* 2004). Warm-season droughts often contribute to ambient temperature increases because of the relative lack of evaporative cooling near the surface. Beyond the impacts on agriculture and energy production, drought can also significantly increase demand on urban and rural water resources and quality (Cook *et al.* 1999). Other non-economic impacts include reductions in stream flow, ground water, and reservoir levels, which can have severe impacts on fish and wildlife (Morehart *et al.* 1999).

In spite of the number of measurable drought impacts, some (Hayes *et al.* 2004) believe that because of poor quantification, the importance of drought is commonly underestimated by officials, and that this results in reactive, rather than proactive, drought management strategies. Unfortunately, the limited time span covered by meteorological records includes insufficient realizations of possible long-term climatic forcing mechanisms for rigorous testing (Cook *et al.* 1999). This time limitation raises the question of whether patterns of drought frequency and intensity from the observed record fully represent the natural variability of regional moisture conditions during previous centuries. Drought forecasts and water resource management plans often rely on data

from only the instrumental period, which could be anomalous in the context of a longer record. The climatic record can be extended by the use of proxy climatic data, such as the annual growth rings of climate-sensitive trees (Fritts 1991). A longer record is more likely to capture fluctuations at lower frequencies (events with recurrence intervals greater than the length of the instrumental record).

An understanding of the patterns of single-year drought events is important because such events are often associated with regime shifts of regional-scale climatic controls (Knapp *et al.* 2004). Conversely, sustained droughts, aside from increased local impacts, may also affect a much broader region both ecologically and economically (Woodhouse *et al.* 2002). Multi-year droughts can be devastating to entire local economies and industries. This is especially true of sustained summer droughts, because of increased drought impacts associated with higher temperatures and because of increased water demand for agricultural uses during the middle of the growing season (Namias 1955; Karl & Young 1987; Soulé 1988; Soulé & Meentemeyer 1989). Prolonged summer droughts are the direct focus of this study. Additional information on the history of severe multi-year droughts may improve long-term forecasting and resource management. Also, investigators have confirmed the recurrence in the U.S. of historic "megadroughts," dry periods of greater longevity, severity, and spatial coverage than any in the instrumental record (Stahle *et al.* 1998; Gray *et al.* 2004c; Stahle *et al.* 2007; Herweijer *et al.* 2007). Especially in the western half of North America, these multi-decadal severe droughts recurred about once per century in the 14th, 15th, and 16th centuries. The 16th century megadrought affected much of the eastern U.S., as well as the

western half of North America (Stahle *et al.* 2007). Severe multi-year droughts have been implicated in the disappearance of the Lost Colony of Roanoke (1587-1589) and in extremely high death rates during the early years of the Jamestown settlement (1607-1625; [Stahle *et al.* 1998]). No comparably severe or persistent droughts occurred in Virginia, North Carolina, South Carolina, or Georgia during the instrumental record, but Virginia (at least) was prone to extended drought during previous centuries (Stahle *et al.* 1998). The impacts of a modern megadrought in the southeastern U.S., particularly in the rapidly urbanizing Piedmont region, could be catastrophic given the water resource and agricultural limitations imposed by only single-year severe droughts in the region (Baker 2007; Copeland 2007b).

Further, projections of global climate change indicate possible changes in drought frequency and intensity as well as increasing temperatures (Stahle & Cleaveland 1992; Cook *et al.* 1999; D'Arrigo *et al.* 2002; Gray *et al.* 2004b; Hayes *et al.* 2004; Le Quesne *et al.* 2006; Griggs *et al.* 2007; Li *et al.* 2007). The detection of potential anthropogenic climate change requires representative data on natural climatic fluctuations over a longer time period than is covered by instrumental records (Stahle & Cleaveland 1992; Cook *et al.* 1999; Le Quesne *et al.* 2006; Griggs *et al.* 2007). Historic climate patterns can help place observed patterns in a larger context. By extending climatic knowledge beyond the observed record, we may improve our ability to forecast, plan for, and mitigate the impacts of drought (Cook *et al.* 1988; Cleaveland & Duvick 1992; Soulé 1992; Stahle & Cleaveland 1992; Cook *et al.* 1999; D'Arrigo *et al.* 2002; Gray *et al.* 2004b; Hayes *et al.* 2004; Le Quesne *et al.* 2006; Griggs *et al.* 2007; Li *et al.* 2007).

The current dendroclimatic literature is replete with requests for the development of new chronologies and further analysis of paleoclimate using tree rings, epecially where surface water supplies are vulnerable to drought and other climatic fluctuations (Blasing *et al.* 1988; Cook *et al.* 1988; Stahle & Cleaveland 1988; Cleaveland & Duvick 1992; Stahle & Cleaveland 1992; Cook *et al.* 1999; Hayes *et al.* 2004; Knapp *et al.* 2004).

Because drought impacts vary between locations, and because the most profound water resource impacts are often felt in population centers, drought patterns in regions experiencing rapid population growth deserve specific attention. The population of the southeastern U.S. grew substantially during the period 1990-2005 (Fig. 1). In the four-state region including Virginia, North Carolina, South Carolina, and Georgia, growth was concentrated in the Piedmont physiographic province (Henderson 2006; U.S. Census Bureau 2008; Figs. 2, 3, & 4). Expansion of existing urban centers combined with rapid suburban development has increased demand on local water supplies.

The Piedmont region also generally lacks large rivers, situated as it is in the middle and upper reaches of the drainage basins of the Southeast. Thus, municipal water supplies in the region are particularly vulnerable to drought. Data on municipal water consumption are not as easily accessible as population and agricultural data, but the importance of drought for water resource management and planning cannot be overstated, particularly in an area with significant population growth. For example, the Winston-Salem, North Carolina, water utility reports an increase in water pumped for municipal consumption from 55,214,016.5 liters/day in 1990 to 60,131,266 liters/day in 2000 (Hargrove 2007).

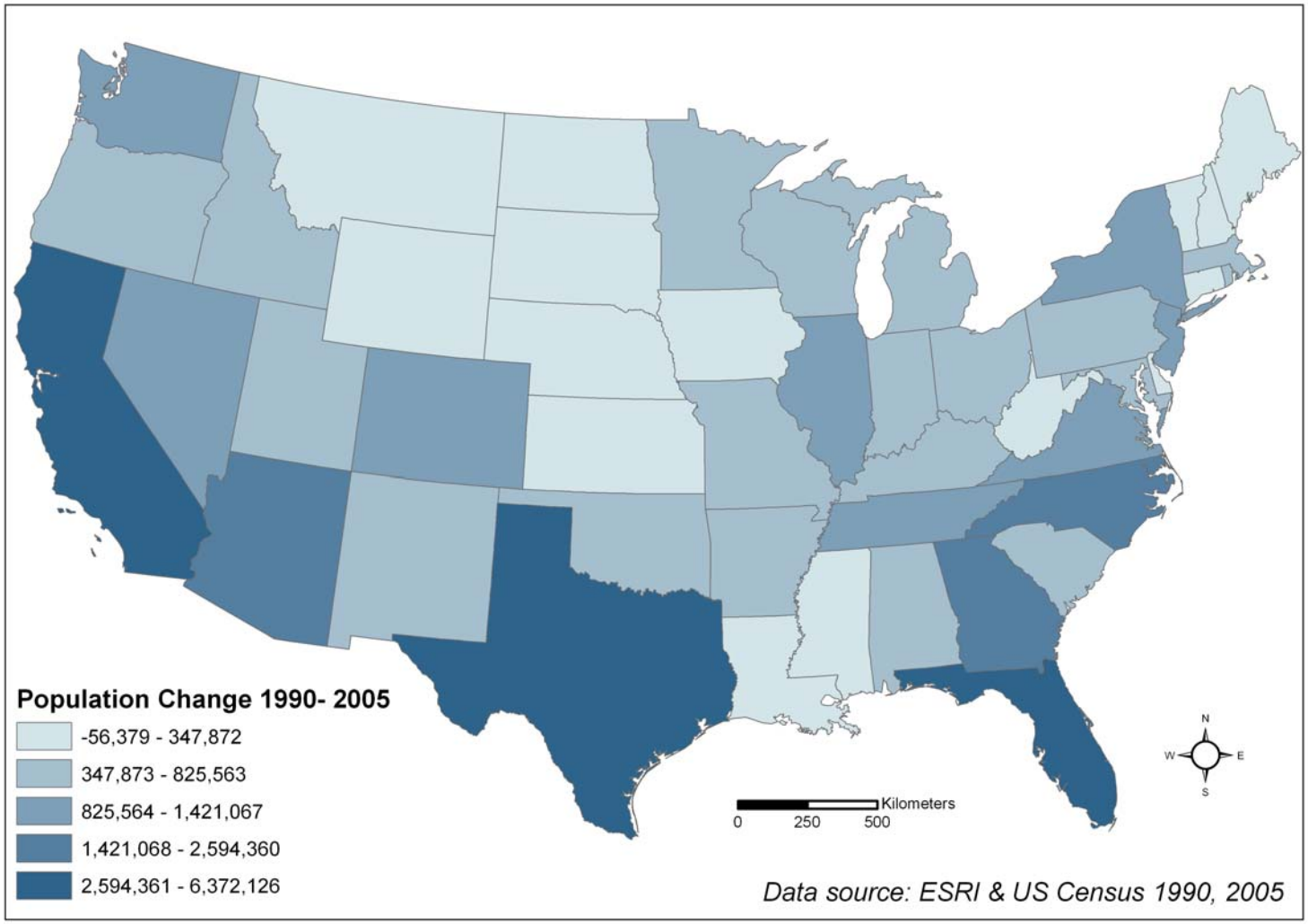

Figure 1. State population change (total) 1990-2005

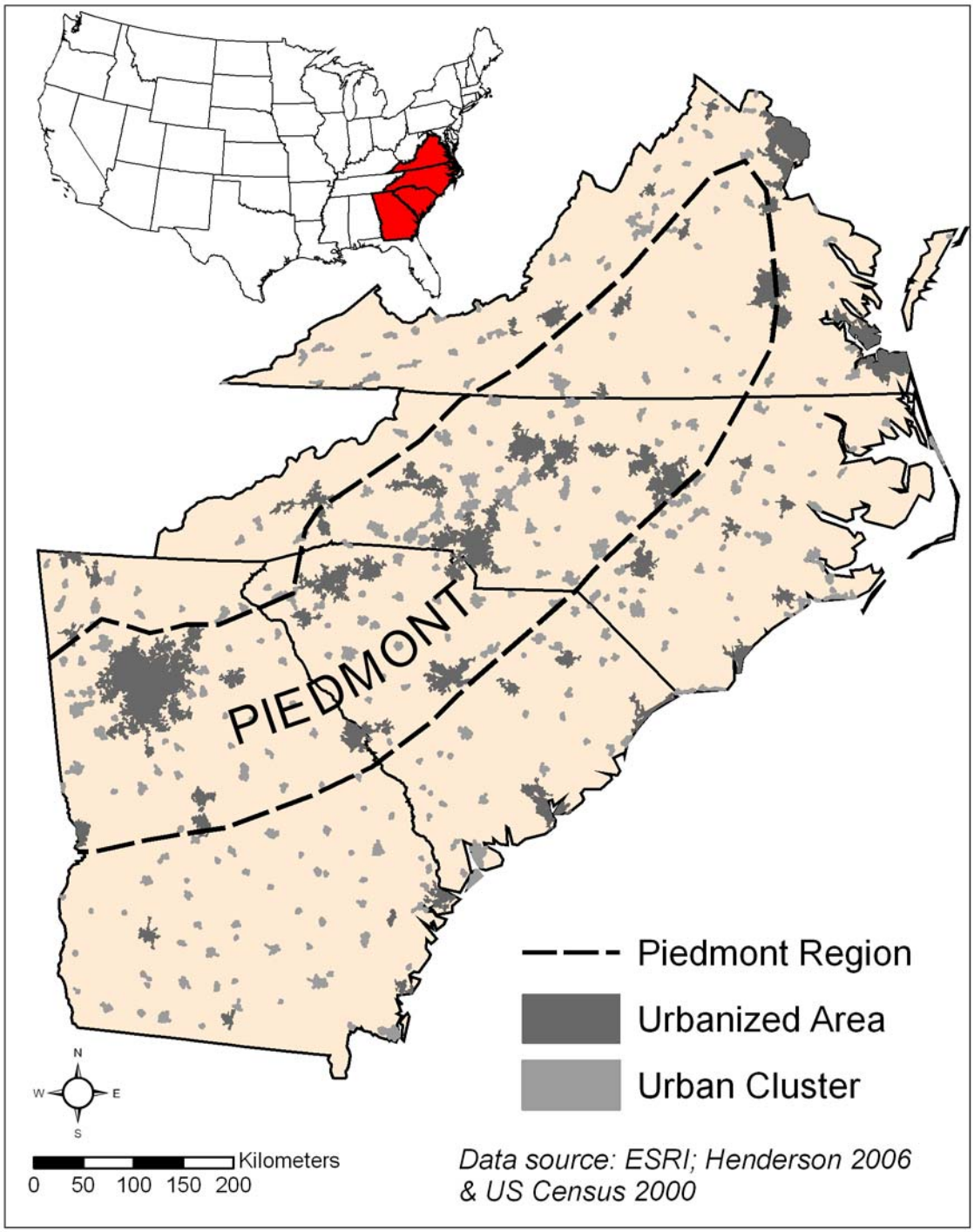

Figure 2. Study area with U.S. Census-designated Urbanized Areas and Urban Clusters (measures of population density; see Appendix A).

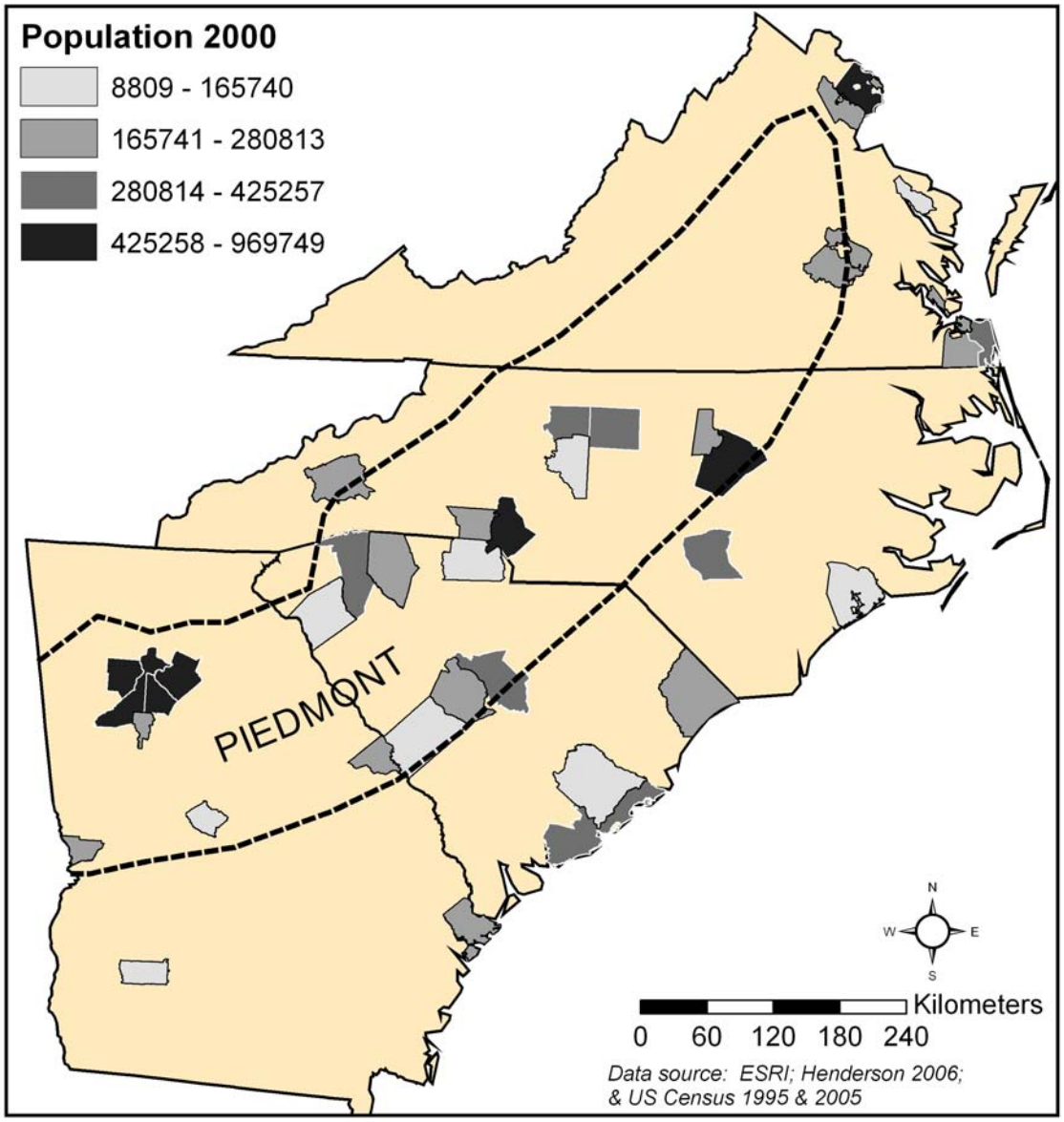

Figure 3. Ten most populous counties in each state of the study area, 1990 (U.S. Census 2008).

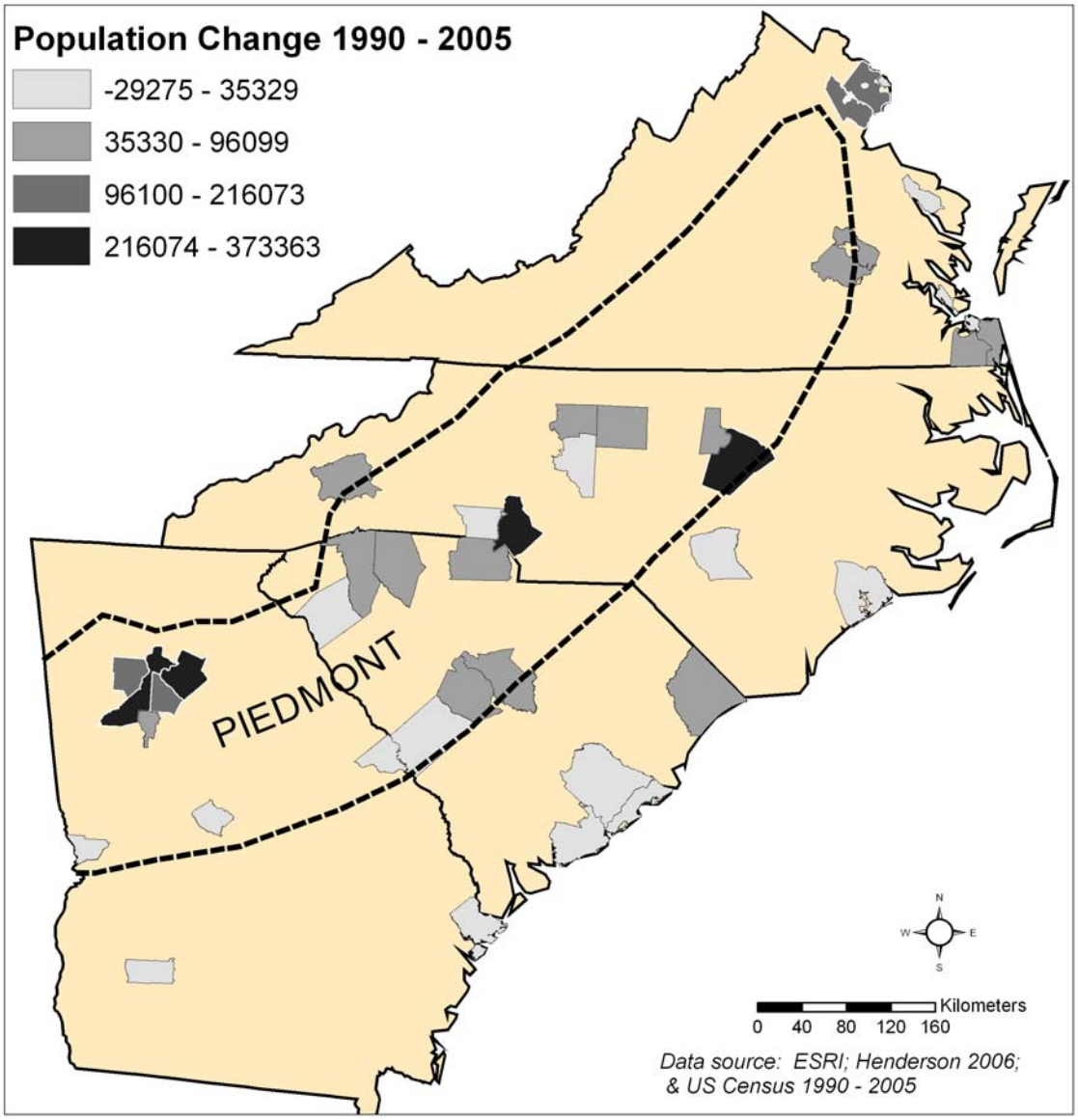

Figure 4. Total population change 1990-2005, in the ten most populous counties of each state in the study area (U.S. Census Bureau 2008).

[2.0] *Objectives*

In response to the documented need for a better understanding of historic climatic patterns, specifically patterns of drought in important agricultural areas and population centers, the specific objectives of this research are:

1) To reconstruct historic drought in the southeastern U.S., with a focus on the Piedmont region, and:
    a) identify climate divisions in and near the Piedmont with homogeneous summer drought characteristics;
    b) identify, analyze, and interpret temporal patterns of drought;
    c) interpret emergent drought patterns in the context of synoptic-scale controls; the ability to forecast drought depends on an understanding of the ocean/atmosphere interactions that cause drought in a given region.
2) To contribute to the existing body of tree-ring data and research in the Southeast, which currently lacks a dense network of tree-ring chronologies.

CHAPTER II

LITERATURE REVIEW

[1.0] *Climatic Regionalization*

A number of studies have identified homogeneous climatic zones within larger regions (e.g., Cattell 1966; Horel 1981; Walsh *et al.* 1982; White *et al.* 1991; Malmgren & Winter 1999; Knapp *et al.* 2002; Ali 2004). The most common method of identifying clusters of common climatic variability is eigenvector analysis (Richman 1986; White *et al.* 1991; Malmgren & Winter 1999). Although eigenvector analysis refers collectively to empirical orthogonal functions, principal components analysis (PCA), and common factor analysis, PCA may be more appropriate for the interpretation of modes of variation (White *et al.* 1991). A sample of eigenvector-based climatic regionalizations is reviewed below.

PCA was used to regionalize temporal patterns of snowfall in Pennsylvania from 1950 to 1990 (Acker & Soulé 1995). Four principal components (PCs) of snowfall variability accounted for a substantial portion of the variance of the original data. A varimax rotation aided spatial interpolation of the PCs (regions). The results of the PCA indicated four temporally distinct snowfall regions in Pennsylvania, including areas of cyclical patterns, areas of stable patterns, areas of long-term upward trend, and areas of long-term downward trend (Acker & Soulé 1995).

A rotated PCA (RPCA) allowed regionalization of snow water equivalents in the upper Colorado River Basin (Timilsena & Piechota 2007). Four significant PCs were identified and subjected to varimax rotation. The authors were able to combine the regionalization of snow water equivalents with a 480-year tree-ring record to extend the record of long-term drought patterns in the study area (Timilsena & Piechota 2007).

Seasonal precipitation variability in Hawaii was examined using RPCA (Kolivras & Comrie 2007). The PCA identified nine distinct regions of precipitation variability. The PCA-derived regions were consistent with observed precipitation patterns, including distinct separations between leeward and windward locations. The PCA also captured altitudinal zonation in precipitation patterns on Maui, where the grid of recording stations was most dense. The PCA regionalization facilitated synoptic analysis of long-term precipitation patterns in different parts of Hawaii (Kolivras & Comrie 2007).

Precipitation regions in the southern U.S. have been identified by the use of PCA (Henderson & Vega 1996). The regionalization exposed patterns that allowed correlation analyses with atmospheric teleconnection features. A varimax rotation was employed to best create physically based homogeneous precipitation regions, and the precipitation divisions with high loadings on a retained factor were grouped into subregions. The authors analyzed seasonal precipitation regions and the influences of several known teleconnection indexes. The Bermuda High index (BHI) was most strongly correlated with variability in spring precipitation in much of the study area (Henderson & Vega 1996).

Climatic regionalization is inherent to tree-ring reconstructions of climate. Tree-ring data from a given location were often strongly correlated with climate data in a larger surrounding region (Cook & Jacoby 1977; Duvick & Blasing 1981; Blasing *et al.* 1988; Cleaveland & Duvick 1992; D'Arrigo *et al.* 2002; Knapp *et al.* 2002; Griggs *et al.* 2007; Akkemik *et al.* 2008). Tree-ring data may have also correlated strongly with climate data in areas well removed (e.g., > 200 km) from the data sites (Duvick & Blasing 1981; Blasing *et al.* 1988; Stahle & Cleaveland 1988; Stahle & Cleaveland 1992; Griggs *et al.* 2007). Regions in which instrumental climate data were strongly correlated with tree-ring data have been considered homogeneous climatic regions, in spite of some observed variability within the identified region (Duvick & Blasing 1981; Blasing *et al.* 1988; Stahle & Cleaveland 1988; Stahle & Cleaveland 1992; Knapp *et al.* 2002; Griggs *et al.* 2007).

[2.0] *Defining Drought*

Drought is defined in a variety of ways, and a selected definition generally depends on the purpose of drought analysis. For example, droughts that affect stream and reservoir levels often display different spatial and temporal characteristics than droughts with severe local agricultural impacts (Soulé 1992). The response of agriculture to drought may be immediate; one extremely dry month during the growing season may devastate crops in an entire region. Conversely, hydrological responses to drought conditions (i.e., lower stream levels and reduced water table elevations) tend to operate at longer time scales (Soulé 1992). The slow movement of soil moisture and reduced rates of evapotranspiration associated with groundwater create a lag between the onset of drought

and hydrological impacts. Hydrological drought also exhibits a lagged response to drought recovery. Several months of average or above-average precipitation may be required to restore groundwater to normal levels, while agriculture may respond to only one or two significant precipitation events (Soulé 1992). The most common drought-related climatic variables reconstructed using tree rings are the drought indices developed by Palmer (1965). Four different drought indices have been created based on Palmer's model, each with the ability to detect different categoriesof moisture surplus or deficiency. The most commonly used index is the PDSI, which detects meteorological drought intensity by incorporating moisture balance variables over a time window before and after the time of reference. This incorporation of prior and subsequent moisture conditions means the PDSI has an intermediate response time to changes in the moisture balance, and is considered representative of "average" growing-season drought conditions (Stahle & Cleaveland 1988; Soulé 1992; Stahle & Cleaveland 1992). Despite its extensive use, the PDSI is retrospective (the calculation for a given month includes information from subsequent months), thus real-time (operational) use of the PDSI is ineffective, especially for the detection of the end of a wet or dry spell (Guttman 1991).

Water resource managers and planners needed operational means of assessing drought conditions. In response, the PDSI model was altered to allow real-time application. The resulting Palmer Meteorological Drought Index (PMDI) provides a reasonable operational alternative to the PDSI. The two indices are equal during any established wet or dry spell, but are slightly different during transition periods (Heddinghaus & Sabol 1991). While the PDSI is a well-known indicator of drought, the PMDI has gained

acceptance among both researchers and field technicians. As part of its National Drought Atlas, the National Climatic Data Center (NCDC) calculated historic PMDI values for a number of weather stations in the Historical Climatology Network (HCN) across the U.S. (NCDC 2008). The PMDI is the only drought index included in the National Drought Atlas.

The second modification to the original Palmer model led to the development of the monthly moisture anomaly (Z) index (ZINX). The ZINX has a short-term response to moisture balance flux and is thus considered a measure of agricultural drought intensity. The quick response allows the ZINX to detect average or above-average monthly moisture conditions embedded in a longer drought. Often, one wet month during the growing season can minimize agricultural losses even during a decade-scale dry regime. Conversely, one severely dry month during the growing season can cause irreparable agricultural damage in spite of a longer-term wet spell (Blasing *et al.* 1988; Soulé 1992).

The third index derived from Palmer's model is the Palmer Hydrological Drought Index (PHDI). The PHDI has the slowest response to moisture variation, and expresses anomalies related to stream flow, groundwater availability, and lake/reservoir levels, which generally exhibit a lagged response to moisture deficiency or surplus (Kangas & Brown 2007). Thus, the PHDI is useful for assessing long-term drought intensity, but tends to omit the first few months or years of longer droughts and to detect drought conditions for some time after normal or above-average precipitation returns to a region (Soulé 1992). For each of the (dimensionless) indices, drought severity is qualitatively described such that an index value of <= -2 indicates "moderate" drought, <= -3 is

"severe," and <= -4 is considered "extreme." Each of the three indices has value for analyzing patterns of drought and each was incorporated in preliminary analysis to determine if one or more could be related to tree growth to reliably reconstruct droughts of different spatial coverage and intensity. It has also been demonstrated that spatial patterns of drought frequency are significantly different when compared between the three indices (Soulé 1992). A liberal definition of drought would be based on all three indices, ensuring that the first few months of a longer drought are captured by the reconstruction (Rhee & Carbone 2007).

[3.0] *Causes of Drought in the Southeastern U.S.*

There is no consensus on the specific synoptic conditions that cause drought in the southeastern U.S., and the topic deserves further investigation. Droughts in much of North America are the result of various combinations of conditions in the tropical and sub-tropical Pacific and Atlantic Oceans and associated atmospheric circulations. However, these teleconnections are not uniform across space, and the interactions between the climatic forcing mechanisms are complex. For example, the two decadal-scale droughts of the 20th century in the American Great Plains and Southwest have been associated with a warm phase of the Atlantic Multidecadal Oscillation (AMO [McCabe *et al.* 2004; Knight *et al.* 2006]). The AMO is an index of detrended sea-surface temperature (SST) anomalies over the North Atlantic, identified as an important climatic control (McCabe *et al.* 2004). During the last ~150 years, phases of the AMO have lasted between 20 and 40 years with a SST range of 0.4°C between warm and cool (Enfield *et al.* 2001). Research indicates that droughts across most of North America are

longer and more frequent during warm phases of the AMO, with the exception of Florida and the Pacific Northwest, which tend to be wetter (McCabe *et al.* 2004). The 1930s Dust Bowl and the 1950s drought in the American Southwest fall within a positive (warm) AMO that lasted from 1925-1965 (McCabe *et al.* 2004).

Pacific Ocean conditions also influence drought in North America, and interact with the AMO in ways that remain poorly defined. The Pacific Decadal Oscillation (PDO) is defined as the leading principal component of North Pacific monthly sea surface temperature variability (Enfield *et al.* 2004). Like the AMO, the PDO is an index in which positive and negative values represent warm and cool phases, respectively. Warm and cool phases of the PDO lasted between 20 and 30 years during the 20th century (Enfield *et al.* 2004). Widespread droughts in North America in 1996 and 1999-2002 were associated with warming in the North Atlantic (positive AMO) and cooling in the North Pacific (negative PDO). During the period covered by the instrumental climatic record, North American droughts tend to be most severe under positive AMO and negative PDO conditions. However, the southeastern U.S. experienced drought most frequently when both indices were positive (McCabe *et al.* 2004). Regardless of the phase of the PDO, warm phases of the AMO are associated with increased drought frequency over much of the U.S. (McCabe *et al.* 2004). Evidence suggests that the AMO has a strong influence on precipitation in much of North America, and may also modulate the strength of El Niño / Southern Oscillation (ENSO) teleconnections with winter precipitation in the southern tier of the U.S. (McCabe *et al.* 2004).

The ENSO index describes SST anomalies in the eastern tropical Pacific Ocean. Positive values of the ENSO index indicate above-average SSTs off the coast of Peru (i.e., El Niño events) and negative values represent anomalously cool conditions in the same location (i.e., La Niña events). Tropical Pacific conditions have been demonstrated to strongly influence climate in North America and elsewhere (Cordery & McCall 2000; Rogers & Coleman 2003). For example, in the southeastern U.S., El Niño events are associated with wetter-than-average winters due to a northerly shift of the subtropical jet and frequent upper level troughing in the region. La Niña conditions generally cause drier winters in the Southeast because of persistent upper level ridging associated with an enhanced trough in the central U.S. and northerly displacement of the polar front jet (Cordery & McCall 2000; Rogers & Coleman 2003). The ENSO is integrally linked to oscillations of SST in the southern Pacific, the time series of which is termed the Southern Oscillation Index (SOI [Le Quesne *et al.* 2006]).

Another example of the types of interactions between the various indices of climatic forcing mechanisms is the apparent modulation of ENSO teleconnections by the PDO. During positive PDO phases, El Niño events exhibit a more robust pattern of wetter winters in the southern tier of the U.S. (Enfield *et al.* 2001). However, winter precipitation is further modulated by the AMO. During warm phases of the AMO, 500-millibar geopotential heights (hPa) tend to be low across the Southeast. This troughing is associated with an increased frequency of winter mid-latitude cyclones (MLCs) and precipitation in the region. Positive AMO tends to strengthen ENSO teleconnections in the southeastern U.S., but runs counter to ENSO teleconnections in the West, where the

ENSO pattern is weakened during AMO warm phases. Under negative AMO conditions, the 500-millibar ridge-trough pattern is enhanced, which accentuates ENSO response in the semi-arid Intermontane West and Great Plains, and weakens the response in the central and southeastern U.S. (Enfield *et al.* 2001). The slow variability in northern Oceans—and their complex interactions—render ENSO teleconnections non-stationary over the U.S. (Enfield *et al.* 2001).

While the influences of the PDO, AMO, and ENSO are principally linked to winter conditions, recent findings indicate that summer droughts in the Southeast may be associated with a weakening of the Bermuda (sub-tropical) high pressure system over the North Atlantic (Anchukaitis *et al.* 2006). Dry summers in the study area during the last ~25 years have been linked to anomalously low values of sea level air pressure (SLP) over the extra-tropical western North Atlantic (Anchukaitis *et al.* 2006). Reduced pressure at the center of the Bermuda High results in weaker circulation around the anticyclone and less moisture advection into the southeastern U.S. (Anchukaitis *et al.* 2006).

Stahle & Cleaveland (1992) examined the relationship between the Bermuda High and growing season precipitation in the Southeast. Their tree-ring reconstructions showed that extremes of spring rainfall and decade-scale regimes of moisture anomalies found in the instrumental record were regular features of climate in the Southeast for the past 1000 years. The authors noted that spring and summer rainfall extremes were frequently out-of-phase in the Southeast, with specific intraregional variability potentially undetected by the large-scale analysis. The inverse relationship between spring and summer

precipitation in the instrumental and reconstructed records was attributed to annual variations in the seasonal migration of the Bermuda High.

Typically, during the course of one year the center of the Bermuda anticyclone migrates on a roughly elliptical path with major axis at ~ 29° N, bounded by 25° N - 40° N and 20° W - 50° W (Sahsamanoglou 1990; Davis *et al.* 1997). The Bermuda High generally migrates west as it strengthens from winter through spring. From June through August, it usually migrates east/northeast, and during fall and winter it weakens and retreats to its mean position over the southeastern North Atlantic, centered at approximately 30° N, 35° W (Stahle & Cleaveland 1992; Davis *et al.* 1997). During droughts in the study area, the western flank of the anticyclone ridged in the interior southeastern U.S., strongly west of its mean position. During wet extremes, the western flank of the circulation ridged east of its mean position, generally offshore over the western North Atlantic (Stahle & Cleaveland 1992). While the anticyclone occupies preferential locations at different times of year, its position and strength vary significantly both intra- and interannually (Davis *et al.* 1997).

Examination of spring and summer precipitation in the Southeast from the instrumental record revealed that many of the driest springs were followed by wet summers, and vice versa (Stahle & Cleaveland 1992). When the Bermuda High expands strongly westward in spring, low-level moisture advection is often diverted around the periphery of the anticyclone, and along with general subsidence associated with the strong upper-level ridge, dry springs result (Namias 1955; Soulé 1988; Soulé & Meentemeyer 1989). However, the pattern often changes around midsummer as the

anticyclone drifts northeast, and moisture advection around the southern and western periphery results in increased summer precipitation in the region. The years 1925 and 1980 are examples of the seasonal migration pattern discussed above. Conversely, the years 1958 and 1974 demonstrate that wet springs and dry summers may result from the failure of the Bermuda High to expand west in spring, followed by strong westward expansion during summer (Namias 1955; Soulé 1988; Soulé & Meentemeyer 1988; Stahle & Cleaveland 1992). Strong relationships between anomalies in the migration of the Bermuda High and other oceanic/atmospheric circulation features have not been reported. Also, the Southeast has been historically prone to land-falling tropical cyclones, which often produce considerable precipitation before dissipating inland. The relationship between the location and strength of the Bermuda High during summer and fall and patterns of tropical cyclone tracks, frequency, and intensity requires further research to quantify long-term variations in the proportional contribution of tropical precipitation to drought climatology in the Southeast.

Fluctuations in the AMO, PDO, and SOI appear to interact and modulate one another's teleconnections to regional climate in different ways. It seems logical that a relationship exists between variations in the Bermuda High and variations in Atlantic and/or Pacific Ocean conditions. However, in the absence of confirmed relationships between the Bermuda High and other known climatic controls in the region, long-term forecasting of drought remains difficult in the southeastern U.S.

[4.0] *Tree-Ring Research*

[4.1] *Dendroclimatology*

Following the work of Fritts (1976), researchers have implemented standard dendroclimatological techniques to reconstruct a wide variety of climatic variables extending backward in time beyond the earliest instrumental records. For example, tree-ring data have been used to reconstruct drought indices, spatio-temporal patterns of precipitation and temperature, seasonal and annual atmospheric circulations, stream flow, lake levels, and other environmental phenomena (Duvick & Blasing 1981). A representative sample of these studies, many of which focused on large-scale (i.e. hemispheric to global scale) climatic patterns, is reviewed below.

Fritts (1991) conducted a comprehensive dendroclimatic reconstruction in a follow-up to his original reference work (Fritts 1976). The more recent publication provides a start-to-finish guide to completing dendroclimatic research, so in the context of a broad reconstruction of temperature, precipitation, and sea level air pressure across the western U.S. and most of the North Pacific (Fritts 1991). The tree-ring data used by Fritts represented most of the existing site chronologies at the time, which were limited to roughly the western half of the U.S. After thorough explanations of all methodological decisions along the way, the results of the analysis were presented and discussed extensively at the synoptic (regional) scale (Fritts 1991).

Concerns about climate change at different time scales and the potential for anthropogenic forcing of global climate have increased the demand for reliable information regarding climatic fluctuations long before observed records (Fritts 1976;

Duvick & Blasing 1981; Stahle *et al.* 1988; Cook *et al.* 1999; Le Quesne *et al.* 2006; Griggs *et al.* 2007; Li *et al.* 2007). Because of the human impacts associated with drought, many dendroclimatologists have specifically addressed historic drought patterns.

[4.2] *Drought Reconstructions*

[4.2.1] *Examples of Reconstructions of the Palmer Drought Indices*

North Carolina drought conditions have been reconstructed using tree rings (Stahle *et al.* 1988). Two chronologies were developed from bald cypress (*Taxodium distichum*) in the coastal plain to reconstruct June PDSI values for a 1600-year period (Stahle *et al.* 1988). The tree-ring data were analyzed with respect to specific climatic regimes including the Medieval Warm Period (~ a.d. 1000-1300) and the Little Ice Age (~ a.d. 1300-1600). The results indicated that during the last millennium, North Carolina has experienced persistent regimes of above- and below-average precipitation on the order of roughly 30 years each. However, the reconstruction model was calibrated to state average PDSI values, and thus little information on regional or local conditions was obtained. The authors expressed the need for new chronology development and data analysis in order to further assess growing season moisture variability (Stahle *et al.* 1988).

In an analysis of tree-ring—drought relationships in New York, Cook and Jacoby (1977) reconstructed July PDSI values from 1731 to 1970, primarily in order to demonstrate that tree-ring data could successfully reconstruct drought in the northeastern U.S. They concluded that drought reconstructions are feasible, but warn that their tree-ring indices were highly intercorrelated, which adversely influenced certain elements of

model creation. Their findings imply that episodes of more persistent, but less severe, drought were more common in the past than in the last century. This type of result indicates that the patterns of drought from observed records may not explain the full natural climatic variability of a region, nor its susceptibility to drought over the long term.

Drought history in Texas from 1698-1980 was reconstructed by Stahle & Cleaveland (1988). They reconstructed June PDSI for two different regions in the northern and southern parts of the state from nine tree-ring chronologies to evaluate interannual persistence of moisture extremes, recurrence probabilities for drought of different levels of severity, and frequency characteristics of the observed vs. reconstructed series in search of long-term periodicity. Data analysis revealed a probability of 90% for at least one moderate June drought each decade in Texas. Further, the risk of severe June drought differs along a spatial boundary between north and south Texas, where the 50% probability of recurrence is estimated at 15 years and 10 years, respectively (Stahle & Cleaveland 1988). The results also indicated an increased probability of summer drought during the year following a June drought.

The southeastern U.S. suffered a severe drought in 1986 (FEMA 2008). Cook *et al.* (1988) examined tree-ring data to assess the possible recurrence interval of such an event using reconstructions of June PDSI. According to instrumental records, the recurrence interval of drought similar to 1986 was estimated at approximately 100-110 years, meaning 1986 was the most severe drought on record (Karl & Young 1987). By extending the record to 1700 using tree rings, Cook *et al.* (1988) were able to assert that

the 1986 drought was unprecedented even in the proxy record, indicating a recurrence interval of approximately 300 years for a single-year event of equivalent severity. The reconstructions provide insight to historic patterns of drought, but the low spatial resolution of the tree-ring data and the decision to model averaged PDSI over a large region are likely to have obscured important sub-regional and local variability.

Regional drought patterns in China have been reconstructed using tree rings (Li *et al.* 2007). Chinese regional drought variability was more stable during the 19th century, and highly variable with persistent regimes of wetness and dryness in the 20th century. The drought of the late 1920s was the most severe in the last two centuries, followed by the wettest decade in the reconstructions in the 1930s. A long-term wetting trend was observed in northwestern China, with a concurrent drying trend in north-central China. The analysis suggests strong teleconnections between ENSO and drought in north-central China (Li *et al.* 2007).

[4.2.2] *Examples of Precipitation Reconstructions*

In addition to drought indices, researchers have examined drought history by reconstructing actual precipitation values. In some cases, spring precipitation in the year of growth had the greatest association with ring width (e.g. Stahle & Cleaveland 1994). However, others found that annual precipitation exhibited the strongest relationship to growth (e.g. Blasing *et al.* 1988). Often, the precipitation variables that exhibited the strongest correlations with tree-ring width were statewide averages (e.g., Duvick & Blasing 1981; Blasing *et al.* 1988). It is desirable to find a strong relationship between

growth and climatic variables over smaller areas in order to extract local and subregional variability.

Annual precipitation amounts in Iowa since 1680 were reconstructed by Duvick & Blasing (1981). Ring widths of white oak were found to be most closely coupled with precipitation from the prior August to July of the year of ring formation. Three chronologies were averaged to create a regional chronology index, which was then used to reconstruct statewide average precipitation.

In their 250-year reconstruction of annual precipitation in the south-central U.S., Blasing *et al.* (1988) found the strongest correlation between annual growth and total precipitation during the 12-month period from prior July to June of the year concurrent with ring growth. As in other studies, (e.g., Cook & Jacoby 1977), the authors noted that while drought years were reconstructed accurately, precipitation during wet years was often underestimated. This is not surprising, as the variation in tree-ring growth is indicative of climate as a limiting factor; moisture is not necessarily limiting to growth during wet years. This common finding could cause problems for the investigation of past periods of wetness, but should not hinder attempts to reliably reconstruct drought. Drought frequency and intensity during the reconstructed period were not significantly different from 20th-century observations. Thus, the authors concluded that droughts similar to the most severe on record may be expected to recur even without further warming due to anthropogenic or other causes (Cook & Jacoby 1977).

A 750-year tree-ring reconstruction of Wyoming precipitation indicated a shift in drought severity and duration around 1900 (Gray *et al.* 2004c). Single-year and decadal

droughts were generally more severe prior to the 20th century, and droughts in both the 13th and 16th centuries were longer and more severe than any on record in Wyoming. Precipitation exhibited variations at higher frequencies after ~1750, with more frequent single-year droughts, but fewer decadal scale droughts. Precipitation variability was strongly associated with ENSO conditions, and the Big Horn Basin exhibited a response similar to the southwestern U.S. (i.e. drier during La Niña events). Interestingly, the high country around the basin experienced the opposite response, with decreased precipitation during El Niño events (Gray *et al.* 2004c).

Precipitation in central Chile was reconstructed for ~800 years using a combination of tree-ring data, historical documentation, and proxy records of the terminus of a retreating glacier (Le Quesne *et al.* 2006). The authors report a dramatic increase in the risk of drought in the late 19th and early 20th centuries, the result of an increased envelope of variability after ~1850, with more frequent extremes of dry/wet conditions. Prior to the 20th century, decadal variability was higher, with more intense prolonged episodes of drought/wetness. Due to the pronounced regime-like behavior of drought in central Chile, the probability of occurrence has changed over time, and the last few decades contain the highest risk of drought recurrence in the reconstructions.

Using only oak species, a high-frequency regional precipitation reconstruction in the north Aegean region evaluated the optimal methods for oak chronology creation (Griggs *et al.* 2007). The ~1000-year reconstruction contains a distinct period of high-frequency extremes in precipitation from the 15th through the 17th centuries, a period often referred to as the Little Ice Age. Interestingly, the authors note an increase in relative tree-ring

widths after ~1950 that does not reflect increased precipitation in the region (Griggs *et al.* 2007) . The post-1950 relative growth increases could represent a biological response to rapid increases in atmospheric carbon dioxide (Voelker *et al.* 2006; Knapp & Soulé 2008).

A multi-species tree-ring reconstruction of spring/summer precipitation in the eastern Mediterranean covered ~250 years, and included discussion of connections to large-scale atmospheric circulation (Touchan *et al.* 2005). Similar main modes of atmospheric patterns and surface air temperature distribution were related to extreme wet and dry summers for the last 50 and the last 237 years. The precipitation reconstruction compared well with historical documentation of floods, droughts, famines and fires. The authors noted no visible trend in reconstructed precipitation, but a notable increase in the frequency of single dry years during the 19th and 20th centuries. The variability in precipitation for the instrumental period was closely linked to SLP and hPa patterns over the Atlantic Ocean and the Mediterranean Sea, but the authors advise caution when relating tree-ring indices to circulation features due to non-stationarity and generally insignificant relationships between eastern Mediterranean precipitation and large-scale circulation features.

Tree-ring data from two ecologically contrasting sites in the southern Colorado Plateau were used to reconstruct precipitation and temperature for the growing season over the last ~1425 years (Salzer & Kipfmueller 2005). The reconstructions exhibited roughly decadal scale variability in both precipitation and temperature. The independent reconstructions permitted analysis of extreme combinations of cool/dry, cool/wet,

warm/dry, and warm/wet conditions. The only indication of a direct link to a climatic forcing mechanism was an association between explosive volcanic eruptions and the onset of cool/dry regimes. The analysis indicated that the post-1976 warm/wet regime was unprecedented in the last 14 centuries.

[4.2.3] *Other Applications of Tree-Ring Research*

Atmospheric circulation features were the focus of a study by Cleaveland and Duvick (1992), who analyzed 350 years of climatic variation in Iowa based on tree ring reconstructions. The tree-ring data were found to be significantly associated with several climatic variables, including statewide average annual precipitation and two of Palmer's (1965) monthly drought indices for June and July. The resulting reconstruction of Iowa drought history was found to correlate strongly with certain circulation features, specifically the ENSO index. The results also indicated some climatic modulation associated with solar cycles centered on sunspot minima, and the authors suggested that incorporating solar and ENSO influences may help improve climate forecasting in Iowa.

Historic precipitation and stream flow reconstructions in northwestern Turkey demonstrated the multiple utility of tree-ring data (Akkemik *et al.* 2008). The reconstructions were calibrated to emphasize high-frequency (interannual) variations in precipitation and stream flow. A nested regression modeling procedure was employed, in which separate nests of tree-ring chronologies covered different time periods prior to the instrumental record (Akkemik *et al.* 2008). Droughts and floods from the reconstructions were compared to historical documents from the archives of the Ottoman Empire. The analysis indicated common climatic extremes across Turkey (Akkemik *et al.* 2008). The

authors designated positive and negative anomaly thresholds at 115% and 85%, respectively, of the long-term mean annual ring-width. By these criteria they identified 61 dry and 35 wet events in the pre-instrumental period covered by the tree-ring data (1650-1930), with a mean drought return period of ~5 years. No droughts of 3 or more years were indicated by the reconstructions (Akkemik *et al.* 2008).

Tree-ring evidence of climate and stream flow variability in the western U.S. has been linked to large-scale circulation indices (Redmond & Koch 1991). In particular, precipitation during the period October-March was strongly correlated with the ENSO Index averaged over July-November. The association was opposite for two separate regions of study. During an El Niño event, average precipitation was low in the Pacific Northwest and high in the Southwest U.S.; the reverse was true during times of high ENSO values (La Niña events). The authors demonstrated that stream flow shared similar statistical associations with the ENSO Index.

Stream flow levels were analyzed in terms of large-scale atmospheric and oceanic curculations for the Puelo River in Chile from a 400-year tree-ring record (Lara *et al.* 2008). Circulation features in high and low latitudes were correlated with variations in stream flow, with seasonal distinctions. Summer and fall stream flows exhibited negative correlations with the Antarctic Oscillation, and positive correlations with tropical Pacific SST variations in winter and spring (Lara *et al.* 2008). Variations in Puelo River stream flow operated in a dominant 84-year cycle that explained ~25% of the temporal variability in the data. The Puelo River has experienced a general decrease in stream

levels since 1943, while models indicate the potential for future reductions in precipitation and stream flow in the region.

Stream flows in the Upper Colorado and South Platte River basins have been reconstructed from tree-rings for the last 300-600 years (Woodhouse & Lukas 2006). The 20th century stream gage record did not represent the full range of stream-flow characteristics in the previous 2 to 5 centuries, and the distribution of extreme low flow years was markedly uneven during the past 3 centuries (Woodhouse & Lukas 2006). The authors also concluded that multi-year droughts worse than the 1950s have occurred in the region, with the greatest concentration during the 19th century (Woodhouse & Lukas 2006).

Tree-ring data may be combined with other information to assess various environmental phenomena that are indirectly related to climate. Approximately 1000 years of lake level changes at Kluane Lake in Yukon Territory, Canada, were reconstructed from tree-ring data, radiocarbon, alluvial stratigraphy, and sub-bottom acoustic data (Clague *et al.* 2006). The combination of data types permitted an explanation of the hydro-geomorphic history of lake changes, including episodes of increased (decreased) inflow and outflow, and increased (decreased) erosion/deposition.

Dendrochronology was also used to evaluate lake level changes at Jämtland, in the Central Scandinavian Mountains of Sweden (Gunnarson 2001). The study incorporated well-preserved sub-fossil pine from the (present-day) lake bed. Pine specimens from 5 different historic periods were used to create 5 floating chronologies from 498 BC to 1865 AD, with gaps of ~80 years separating each. The temporal gaps in the data and the

distributions of submerged trees suggested historic cycles involving periods of high mortality as lake levels rose and drowned trees near the shore, and subsequent periods of intense germination associated with lake level declines and increased exposure of the former lake bed. Interestingly, the author noted that both the existence and the preservation of the trees in the study area was likely due to lake level changes, as low lake levels allowed germination, and high lake levels preserved fallen trees.

Further demonstration of the diversity of applications for tree-ring data was provided by Yamaguchi (1985), who evaluated historical tephra eruptions of Mount St. Helens using patterns of narrow tree-ring growth correlated to known tephra eruptions. The data indicated that two major explosive tephra eruptions ~500 years ago were separated by about 2 years, with minor explosive activity in the interim. The results suggested that distinctive tree-ring patterns might have formed in trees across different tephra-layer thicknesses, that tephra coarseness interacted with tephra-layer thickness to determine the impacts of tephra fallout on forest trees, and that tree-rings may be a valuable data source for the reconstruction of past volcanic activity (Yamaguchi 1985). The value of such applications was reinforced by the use of tree-ring data to determine exact dates of 17 events during and after the Kalama eruptive period of Mount St. Helens (1479 to the mid-1700s [Yamaguchi and Hoblitt 1995]). Tree-ring dates were used to designate early, middle, and late phases of the Kalama eruptive period, and to assess the behavior of the volcano between historic eruptive periods (Yamaguchi & Hoblitt 1995).

Finally, a recent development in dendrochronology involved analysis of the isotopic components of individual tree rings, which may capture a variety of environmental

signals (Miller *et al.* 2006). Tree-ring isotopic analysis was used to reconstruct 220 years of tropical cyclone activity in the southeastern U.S. Oxygen isotope values of tree ring cellulose reflected the isotopic composition of source water (Miller *et al.* 2006). Large tropical cyclones often produce large amounts of precipitation in the Southeast, and the oxygen isotope concentrations of the rainfall are lower than those associated with low-latitude thunderstorms by as much as 10% (Miller *et al.* 2006). These reduced oxygen isotope levels are then captured by tree cellulose as the tree utilizes the water, and represent an isotopic record of tropical cyclone activity. Decadal periods of high and low tropical cyclone activity were identified in the reconstructions. The 1950s contained the highest levels of tropical cyclone activity in the 20th century, with significant activity in the 1770s, 1800-1820s, 1840-1850s, and 1865-1880 as well. Periods of low activity included 1781-1805 and the 1970s (Miller *et al.* 2006).

The potential of tree-ring research is well documented. This paper addresses historic multi-year summer droughts in the southeastern U.S. specifically where growing human populations may be vulnerable to severe water shortages. Instrumental records are of insufficient length to display natural climatic fluctuations at long time scales. Tree-ring data are ideally suited to extending our knowledge of climate prior to historical records, which in turn should improve our ability to forecast and plan for climatic extremes.

[5.0] *Carbon Dioxide Enrichment of Woody Plants*

The release of stored CO_2 from terrestrial reservoirs, especially the combustion of fossil fuels, has caused the atmospheric concentration of CO_2 to increase steadily during the last century (LaMarche *et al.* 1984; DeLucia *et al.* 1999; Knapp *et al.* 2001; Mohan *et*

al. 2007). Increases in atmospheric CO_2 have been discussed most often in the context of the potential role of greenhouse gases in global climate change (LaMarche *et al.* 1984; Ceulemans & Mousseau 1994; DeLucia *et al.* 1999; Mohan *et al.* 2007; Cao *et al.* 2008). However, the impacts of increased atmospheric CO_2 on vegetation have received recent attention.

Controlled studies in greenhouses and growth chambers have evaluated tree growth responses to increased CO_2 (Mohan *et al.* 2007). Growth responses to changing CO_2 concentrations have also been noted for trees in intact forests with artificially enhanced levels of CO_2, and for trees in forest stands with no artificial manipulation of CO_2 (DeLucia *et al.* 1999; Cao *et al.* 2008). Many studies concluded that temperate forest species experience a fertilization effect in response to increased atmospheric CO_2 (LaMarche *et al.* 1984; Graybill & Idso 1993; DeLucia *et al.* 1999; Huang *et al.* 2007; Mohan *et al.* 2007; Cao *et al.* 2008).

Plants respond in various ways to increases in atmospheric CO_2. A nearly universal response is the direct fertilization effect of increased photosynthesis, along with partial closure of leaf stomata, which leads to reduced water loss by evapotranspiration, and thus an increase in water-use efficiency (WUE), although responses to CO_2 vary between species (Ceulemans & Mousseau 1994; Beerling *et al.* 1996; LaDeau & Clark 2001; Huang *et al.* 2007; Cao *et al.* 2008). Enhanced WUE has been demonstrated in semi-arid tree species, with higher-than-expected growth during drought, especially at the driest sites (Knapp *et al.* 2001). However, indirect fertilization effects have been reported for temperate forest trees. Potential indirect growth impacts associated with increases in

atmospheric CO_2 include both above- and below-ground responses, such as increased leaf (photosynthetic) surface, enhanced fine root distribution, and changes in temperature or precipitation (LaMarche *et al.* 1984; Huang *et al.* 2007).

The overall result of CO_2 enrichment is that many tree species exhibited increased biomass production, especially stem biomass (Huang *et al.* 2007; Mohan *et al.* 2007). Most of the empirical literature regarding CO_2 fertilization involved controlled experimentation in greenhouses. However, many tree-ring studies reported increased radial growth rates that may be related to increases in ambient atmospheric CO_2 concentrations, especially in the 20th century (LaMarche *et al.* 1984; Payette *et al.* 1985; D'Arrigo *et al.* 1987; Hari & Arovaara 1988; Kienast & Luxmoore 1988; Payette *et al.* 1989; Archambault & Bergeron 1992; Graybill & Idso 1993; D'Arrigo & Jacoby 1993; Nicolussi *et al.* 1995; Knapp *et al.* 2001; Bunn *et al.* 2005; Wang *et al.* 2006; Huang & Zhang 2007; Knapp & Soulé 2008). The basis of dendroclimatology is the ability to remove non-climatic growth trends from long tree-ring records. Long-term growth enhancement caused by increasing atmospheric CO_2 may have important implications for tree-ring research, and should be considered when examining tree-ring data collected in the late 20th century (LaMarche 1984; Knapp and Soulé 2008).

CHAPTER III

METHODS

[1.0] *Study Area*

The geographic focus of this study was the Piedmont physiographic region between the Atlantic Coastal Plain and the Appalachian mountains, a region stretching roughly from Richmond, Virginia, through central North Carolina, South Carolina, and Georgia (Fig. 3). The climate of the region is classified by the Köppen system as humid mid-latitude warm summer (Cfa) meaning that the coldest month averages > 0° C, the warmest month averages > 22° C, and the driest month averages > 60 mm precipitation (Tarbuck & Lutgens 2006). The southeastern U.S. as a whole experiences no marked dry season, receiving primarily convective precipitation during the warm season and frontal precipitation associated with mid-latitude cyclones (MLCs) during winter. Thus, a single-year summer moisture deficiency may be offset by a subsequent active MLC season, or by the autumn incursion of (a) tropical cyclone(s). However, from a moisture-balance perspective, the occurrence of sustained (multi-year) droughts of varying magnitudes requires circumstances that hinder both summer convective storm formation and winter MLC precipitation in the region. In the case that the above circumstances coincided with a period of low Atlantic tropical storm activity, severe, prolonged droughts could have significant water-resource impacts on the southeastern U.S.

Because of municipal water supply considerations, this study was focused on summer droughts in the Piedmont region. However, the Piedmont is not climatically defined. I used the correlations between instrumental climate division data in the southeastern U.S. (all 30 climate divisions in the four-state region) and tree-ring data from the same area to identify a homogeneous summer drought region that included the population centers of the Piedmont. The data and the identification of the summer drought region are discussed below.

[2.0] *Data*

[2.1] *New Tree-Ring Data*

This study included an update of an existing chronology originally created in 1979 (Cook 1980). The chronology update (WLP) was conducted by sampling longleaf pine (*Pinus palustris*) at Weymouth Woods Sandhills Nature Preserve in North Carolina, during summer 2007 (Fig. 5**;** Table 1).

The WLP chronology was produced using accepted dendrochronological techniques (Stokes & Smiley 1968; Fritts 1991). The site was selected because of its relative lack of human disturbance during recorded history, and because of its potential to contain trees of extreme (greater than 300 years) age. Longleaf pine trees are climatically sensitive, and have been shown to respond to moisture limitations (Devall *et al.* 1991; Telewski & Lynch 1991; D'Arrigo *et al.* 2002).

At the field site, at least two increment core samples were taken from 35 living trees. For laboratory preparation and data analysis, the samples were mounted and progressively sanded to >400 grit, after which ring-growth increments were measured to

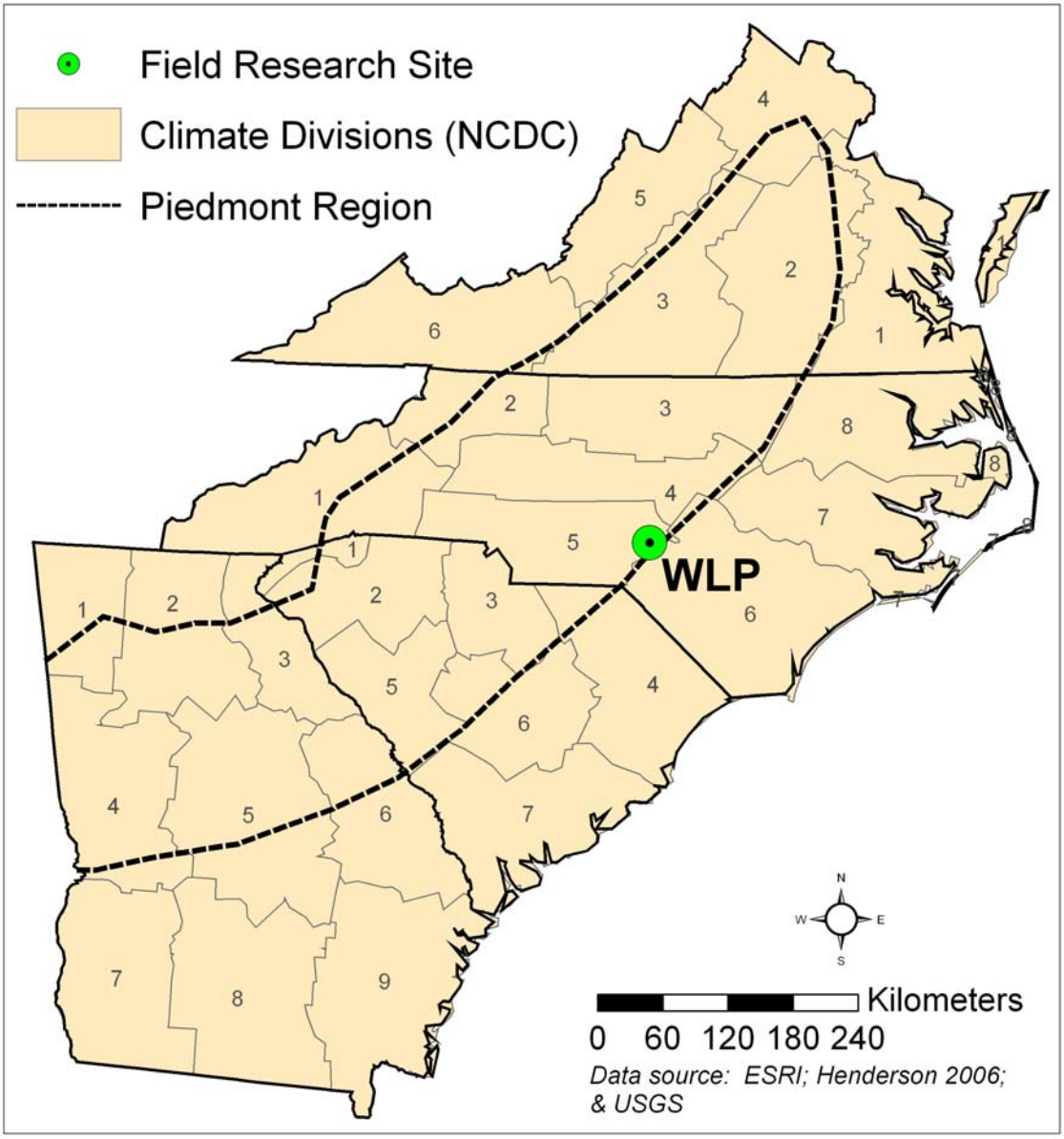

Figure 5. Data collection site for one updated tree-ring chronology (WLP). The site is Weymouth Woods Sandhills Nature Preserve.

Table 1. Tree-Ring Chronologies

Site Name (Site Code)	Species	Period (AD)	Lat. / Long.	Author(s)
Weymouth Woods (WLP)*	*Pinus palustris*	1690-2006	35N / 79W	Ortegren, J
Patty's Oaks (PED)**	*Quercus alba*	1520-2002	37N / 79W	Pederson, N
Blue Ridge Parkway (BRP)**	*Quercus prinus*	1673-2002	37N / 79W	Pederson,N
Pine Mountain (PMN)**	*Quercus prinus*	1794-2002	33N / 84W	Knight, T
Rambulett Creek (RCP)**	*Quercus stellata*	1762-2002	32N / 84W	Knight, T
Montpelier (MNP)	*Quercus alba*	1713-2000	38N / 78W	Druckenbrod, D *et al.*
Kilmer Memorial Forest 1 (KM1)	*Liriodendron tulipifer*	1672-1997	35N / 83W	Stahle, DW & Sierzchula, S
Kilmer Memorial Forest 2 (KM2)	*Tsuga canadensis*	1784-1997	35N / 83W	Stahle, DW & Sierzchula, S
Shot Beech Ridge (SBR)	*Quercus rubra*	1771-1997	35N / 83W	Stahle, DW & Therrell MD
Hampton Hills (HAM)	*Quercus alba*	1770-1992	35N / 78W	Barefoot, AC
Beidler Swamp (BDS)	*Quercus lyrata*	1640-1992	33N / 80W	Stahle, DW & Sierzchula, S
Four Holes Swamp (FHS)	*Taxodium distichum*	1001-1985	33N / 80W	Stahle, DW & Cleaveland, MK
Black River North Carolina (BRN)	*Taxodium distichum*	365-1985	34N / 78W	Stahle DW
Ocmulgee River (OCM)	*Taxodium distichum*	1202-1984	32N / 83W	Stahle, DW
Kilmer Memorial Forest 3 (KM3)	*Quercus alba*	1641-1983	35N / 83W	Cook, ER
Kelsey Tract (KEL)	*Tsuga canadensis*	1560-1983	35N / 83W	Cook, ER
Kelsey Tract 2 (KLS)	*Tsuga caroliniana*	1677-1983	35N / 83W	Cook, ER
Mountain Lake Virginia 2 (ML2)	*Quercus alba*	1552-1983	37N / 80W	Cook, ER
Hemlock Cove (HCO)	*Tsuga canadensis*	1531-1982	37N / 79W	Cook, ER
Mount Rogers (MRO)	*Tsuga canadensis*	1645-1982	36N / 81W	Cook, ER
Watch Dog (DOG)	*Quercus prinus*	1642-1981	38N / 78W	Cook, ER
Pinnacle Point / Hawksbill Gap (PCL)	*Quercus alba*	1612-1981	38N / 78W	Cook, ER
Ramseys Draft Recollection (RAM)	*Tsuga canadensis*	1595-1981	38N / 79W	Cook, ER
Dale City (DAL)	*Tsuga canadensis*	1780-1978	38N / 77W	Puckett, LJ & Chittenden W
Linville Gorge (LIN)	*Quercus alba*	1617-1977	35N / 81W	Cook, ER
Clemson Forest (CLF)	*Pinus echinata*	1684-1973	34N / 82W	Cleaveland, MK

***New chronology; **Unpublished chronologies used with permission of the respective authors.**

.001 mm resolution. Based on findings regarding the biological growth processes of trees outside the tropics (Tainter *et al.* 1984), three different measurements were taken for each annual ring, representing widths for earlywood, latewood, and total ring width. Earlywood and latewood are terms for two distinct phases of annual growth experienced by many tree species. Earlywood is composed of relatively large, thin-walled xylem cells formed early in the growing season, while latewood cells are smaller and thicker-walled, and form later in the growing season (Telewski & Lynch 1991). For longleaf pine, a close relationship has been documented between latewood width and July-to-October rainfall (Telewski & Lynch 1991). Each measurement series was treated independently, and three distinct chronologies were created for the site (WLP-earlywood, WLP-latewood, and WLP-total ring width). Each of the three entered subsequent processing and climatic correlation analyses in order to isolate the best possible growth response to moisture deficiency in the WLP data.

[2.2] *Existing Tree-Ring Data*

Approximately 35 tree-ring chronologies within or near (<100 km) the Piedmont were available from the International Tree Ring Data Bank (ITRDB 2007). All were initially considered for inclusion in the study. The ITRDB is a clearinghouse of tree-ring data submitted by scientists from around the world. Some available chronologies included analytical descriptions of the data, or pre-processed completed growth indexes, while others included only ring width measurements. I obtained total annual ring width measurements for 25 existing potential predictor tree-ring chronologies (Fig. 6; Table 1)

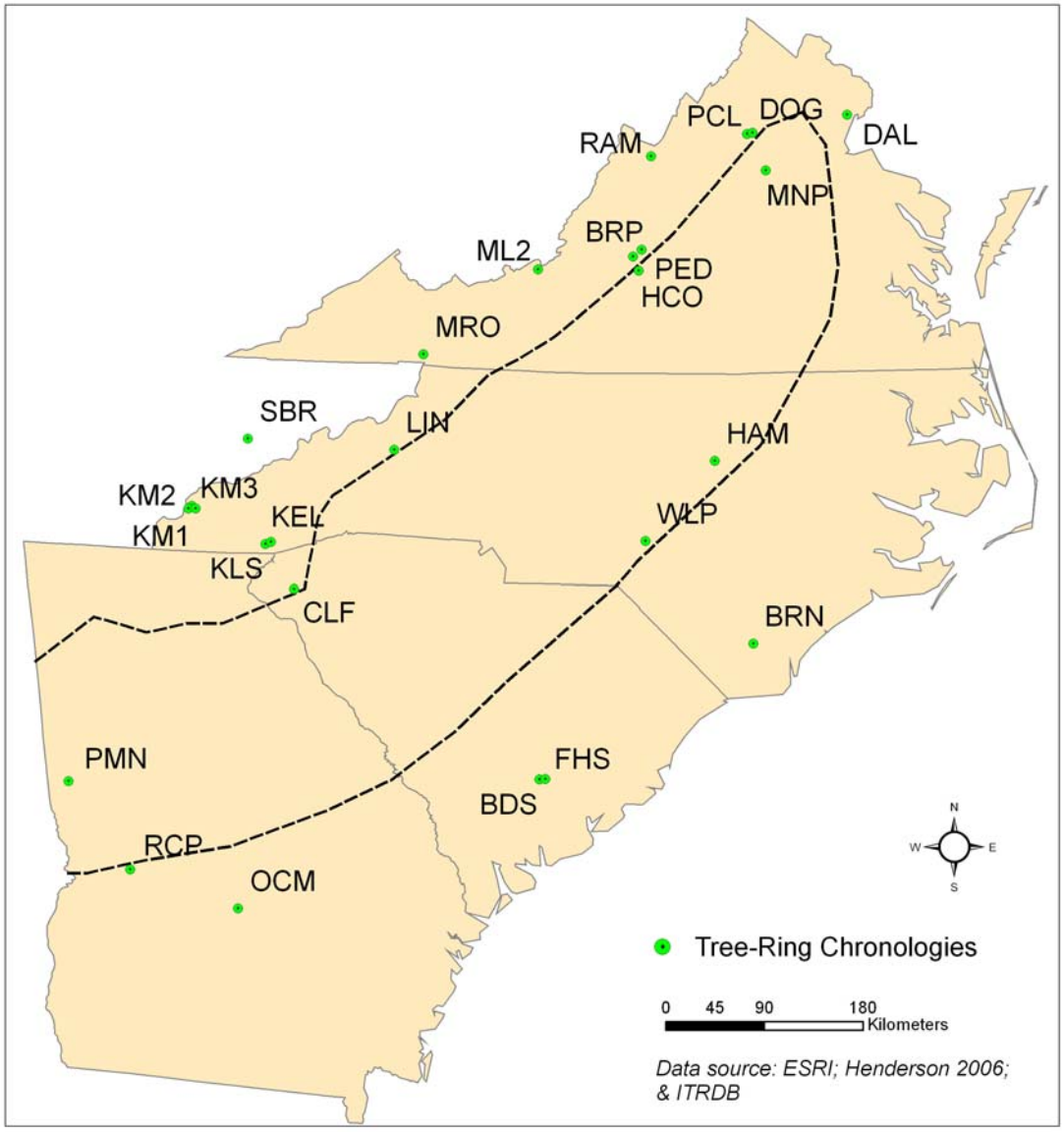

Figure 6. Locations of new (WLP) and existing tree-ring chronologies (n=26) included in this study. Three-letter codes refer to sites listed in Table 1.

with growth data extending backwards in time beyond 1750 AD. Not all of the selected data sites had earlywood and latewood measurements posted at the ITRDB, but total ring width series could be obtained from each. These data sets were treated individually, and I created a standardized annual growth index (chronology) for each site. The methods of chronology creation for the existing data sets and the new data set were identical, and are described below.

[2.3] *Chronology Development*

Each set of raw tree-ring measurements was evaluated using the computer program COFECHA (Holmes 1983) to ensure proper crossdating and assess series correlation and mean sensitivity of ring widths. The COFECHA program analyzed patterns in the ring-width measurement series of each individual sample from a data site and detected (flags) possible errors in crossdating. The assignment of flags by COFECHA to individual samples in a data set can guide a reconsideration of the crossdating of increment core samples. However, COFECHA allowed only a statistical analysis of the similarity between the individual time series at the site. Further examination of the physical samples may indicate that COFECHA, rather than the crossdating procedure, was in error (Fritts 1991). COFECHA provides two other critical measures of the quality of a tree-ring data set. First, the program assesses the inter-series correlation of each sample at a site; a mean inter-series correlation above 0.6 is desirable (Holmes 1983). Second, the program provides the mean interannual sensitivity of all samples. Higher mean sensitivity at a site indicates a greater likelihood of a strong growth-limiting signal, often climate-related (Stahle & Cleaveland 1992; Knapp & Soulé 2002).

I examined the quality measures of the 25 existing chronologies included in the study (Table 2). The number of flags at individual sites ranged from zero (SBR) to 56 (BRP). Inter-series correlations ranged from 0.478 (MRO) to 0.720 (BRN). Mean sensitivities ranged from 0.163 (DOG) to 0.659 (BRN). The numbers of flags and the low (e.g., < 0.200) mean sensitivities at some sights were not optimal. However, the available data were bound by these constraints, and the 25 existing chronologies were retained for analyses.

For the three new chronologies (WLP-earlywood, WLP-latewood, and WLP-total ring width), COFECHA helped determine the optimal data set (i.e., highest mean sensitivity and highest inter-series correlation). The greatest sensitivity and inter-series correlation for the WLP site were found in the latewood chronology. The WLP latewood chronology was retained for analysis.

After quality control of the crossdated measurements, an individual chronology was created for each data set (N=26; 25 existing chronologies and WLP-latewood) with the computer program ARSTAN (Cook & Holmes 1985). Each chronology was detrended using a negative exponential curve to account for biological radial growth trends associated with increasing tree age (Fritts 1976).

Table 2. Tree-Ring Metadata

Site Code	Elevation (m)	Samples	Flagged Segments	Interseries Correlation (r)	Mean Sensitivity
WLP	122	35	13	0.590	0.491
PED	375	31	46	0.492	0.228
BRP	373	26	56	0.482	0.167
PMN	220	59	3	0.657	0.215
RCP	181	62	8	0.576	0.245
MNP	200	24	22	0.502	0.211
KM1	250	30	10	0.563	0.288
KM2	250	14	3	0.522	0.242
SBR	1372	26	0	0.629	0.168
HAM	108	32	18	0.542	0.228
BDS	12	49	17	0.623	0.336
FHS	12	42	35	0.588	0.551
BRN	2	89	10	0.720	0.659
OCM	53	41	8	0.650	0.527
KM3	1200*	30	26	0.525	0.175
KEL	1200*	31	17	0.591	0.234
KLS	1200*	30	4	0.671	0.202
ML2	750*	26	13	0.609	0.205
HCO	500*	37	18	0.622	0.216
MRO	750*	26	44	0.478	0.217
DOG	900*	25	26	0.531	0.163
PCL	900*	25	23	0.544	0.175
RAM	810*	24	14	0.562	0.196
DAL	53	24	8	0.710	0.239
LIN	800*	40	36	0.505	0.202
CLF	250	33	21	0.482	0.245

*** Elevations not reported; the listed elevations are estimates.**

[2.4] *Tree-Ring Data Reduction*

The indexes of radial tree growth from each site were compiled and analyzed using eigenvector analysis. This study employed S-mode PCA, the most common approach in the climatic literature (Horel 1981; Walsh *et al.* 1982; Richman 1986; White *et al.* 1991; Acker & Soulé 1995; Henderson & Vega 1996; Kolivras & Comrie 2007; Timilsena & Piechota 2007).

The fundamental goal of PCA is to express a majority of the variance in the original data in a smaller number of variable dimensions, thereby reducing complex data sets to physically interpretable abstractions (White *et al.* 1991; Malmgren & Winter 1999). In practice, a small number of PCs can often account for as much variance as the original variables by discounting noise in the data. Regardless of the chosen procedure, the PCs are orthogonal (uncorrelated), and the first PC accounts for as much of the variance as possible, while each successive PC accounts for as much as possible of the remaining variance. The principal components that explain a substantial portion of the total variance can be extracted and treated in a number of ways, depending on the objectives of the analysis (Cattell 1966).

After an initial S-mode PCA retaining all factors, the investigator must select the number of PCs to retain for further analysis. There are several methods to select the number of factors to retain, such as Monte Carlo simulations, a target level of cumulative explained variance (e.g., 60% or 70%), and a minimum eigenvalue cutoff [(e.g. >1 or >2) Richman 1981; Ali 2004]. Retention of too few components may oversimplify spatial patterns. Retention of too many components often involves the inclusion of increased

noise in the data, which may distort spatial patterns and lead to splintering of spatial units (Richman 1981). A common approach to selecting PCs for retention is the scree plot (Cattell 1966). The scree plot shows the curve of explained variance associated with each successive PC. A leveling-off of the scree plot indicates a substantial reduction in explained variance by the addition of more PCs, and provides a valuable guide for selecting a range of factors to retain. However, no method insures that the correct number of PCs will be extracted. The results must come from PCs that display logically interpretable patterns (Cattell 1966).

The input matrix for the first-run, unrotated S-mode PCA consisted of 26 variables (columns), representing the individual tree-ring chronologies, and 171 observations (rows), representing annual growth index values for the common period 1803-1973. The results of the first-run, unrotated S-mode PCA retaining all factors (N=27) determined that the first six PCs of tree-ring data explained >70% of variance among tree-ring chronologies, and eigenvalues for *only* PCs 1-6 were >1. However, the scree plot indicated a leveling-off in explained variance after the fourth PC, and only the first four PCs had eigenvalues >2.

Therefore, I proceeded by retaining four, five, and six PCs in order to determine the number of subregions that were logically and physically interpretable (Cattell 1966; White 1991; Kolivras & Comrie 2007). The data were then submitted to PCA with four, five, and six PCs retained and a varimax rotation. In general, the results of unrotated PCA do not yield physically interpretable patterns of climate behavior (Richman 1981; Richman 1986). The varimax rotation technique is the dominant orthogonal rotation in

the climate literature (Horel 1981; Walsh *et al.* 1982; White *et al.* 1991; Acker & Soulé 1995; Henderson & Vega 1996; Malmgren & Winter 1999; Timilsena & Piechota 2007). After rotation, the subregions stabilized (i.e., showed no signs of splintering and were spatially contiguous) when four PCs were retained (White *et al.* 1991). The first four PCs of the selected tree-ring data account for ~60% of the variance in the data.

The chronologies were grouped according to loading scores on the four PCs, which reflected spatial patterns of variance in the selected tree-ring data across the southeastern U.S. (Table 3; Fig. 7). Having isolated subregions (PCs) in which the tree-ring data exhibited similar variations, one composite chronology was created for each of the four PCs by averaging the annual growth index values of each individual chronology within a given PC. Each of the 27 individual tree-ring chronologies (Table 1; Fig. 6), were tested alone for correlation against a suite of drought-related climatic variables. The (four) composite chronologies of average yearly index values from all sites in each PC were also tested for climatic relationships (Table 3; Fig. 7).

[2.5] *Climate Data*

Raw monthly and seasonal precipitation, PDSI, PHDI, and PMDI values, as well as 3-, 6-, and 9-month values of the Standardized Precipitation Index (SPI) from 1900-2006 for all climatic divisions in the four-state region (Fig. 5) were obtained digitally from the NCDC (2007). Each monthly variable was averaged over several overlapping 3-, 6-, and 9-month periods intended to capture the growing season during which moisture shortage was most limiting to tree growth. Monthly and seasonal (multi-month average) values, as

Table 3. Rotated factor loading scores on the first four principal components of variance in the tree-ring data, 1803-1973.

Site Code	PC1	PC2	PC3	PC4
PED	0.816	0.085	0.262	0.145
SBR	0.682	0.266	-0.066	-0.063
BRP	0.587	0.561	0.134	0.17
KM3	0.693	0.291	-0.013	0
LIN	0.667	0.137	0.272	0.212
ML2	0.819	-0.064	0.213	0.131
PCL	0.772	0.2	-0.286	-0.034
DAL	-0.072	0.657	0.014	-0.092
HCO	0.314	0.799	0.07	0.103
KEL	0.33	0.686	0.003	0.328
KLS	0.276	0.643	-0.42	0.263
MRO	0.225	0.773	0.332	0.02
RAM	0.454	0.68	0.227	0.165
DOG	0.255	0.657	0.503	0.053
HAM	0.014	-0.071	0.482	0.361
KM1	0.129	0.245	0.795	-0.048
KM2	0.188	0.198	0.707	0.19
MNP	0.074	-0.103	0.836	0.199
CLF	-0.118	0.342	0.468	-0.131
PMN	0.25	-0.021	-0.008	0.604
RCP	0.105	0.02	0.337	0.647
BDS	0.057	0.075	0.317	0.613
WLP	-0.017	-0.173	-0.027	0.451
BRN	-0.004	0.089	-0.03	0.695
FHS	0.122	0.287	-0.01	0.675
OCM	-0.045	0.25	0.084	0.594

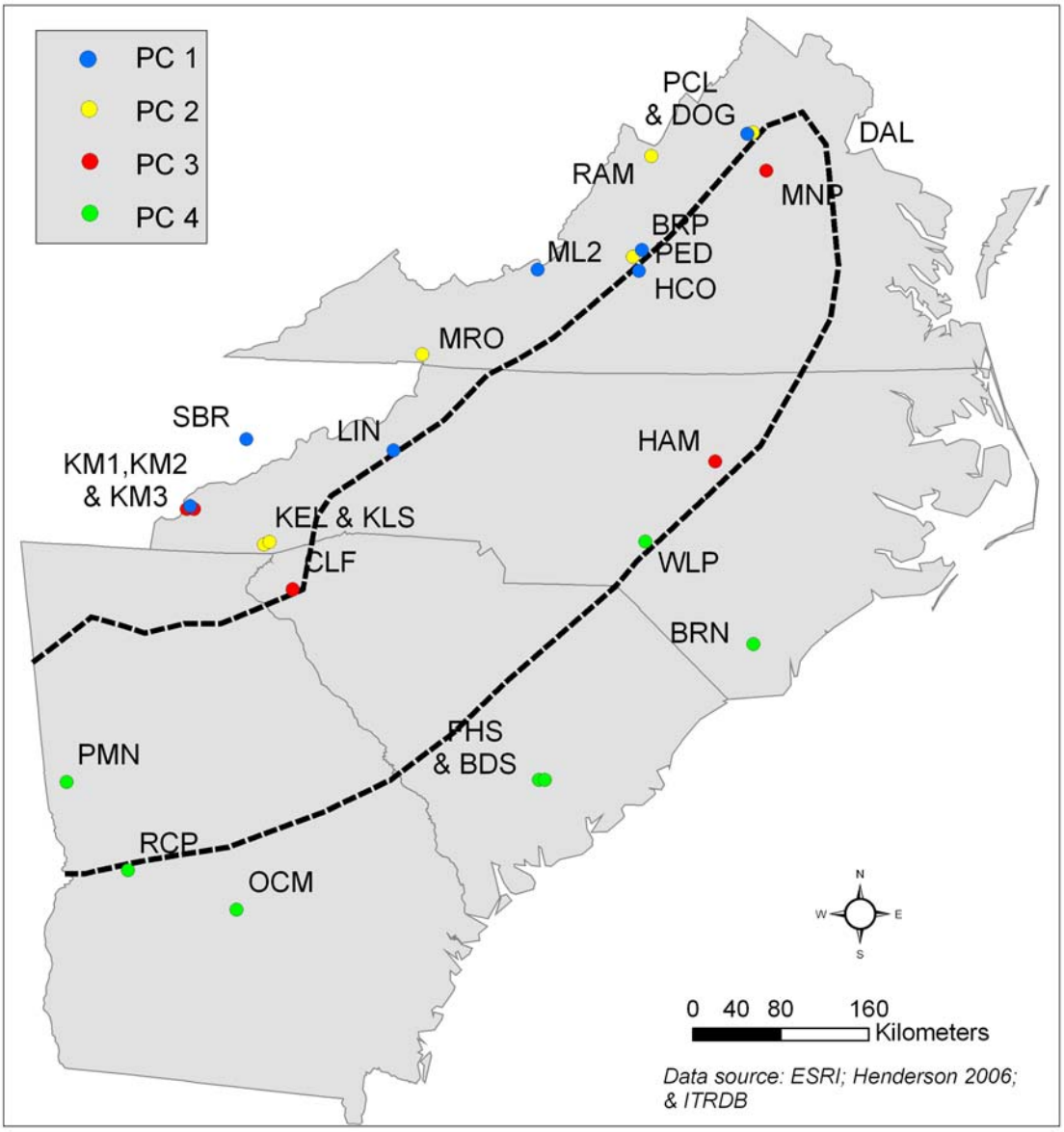

Figure 7. Subregional groupings based on PCA. Chronologies are shaded according to maximum loading scores on the first four principal components of tree-ring variance in the southeastern U.S.

well as lagged effects (e.g., autumn drought inhibiting growth in the following growing season) were included in tests for correlation with the tree-ring data described above.

Recent findings indicate that climate reconstructions using tree-ring data collected during the late 20th-early 21st centuries should be examined to determine if increases in atmospheric CO_2 have affected growth (Knapp & Soulé 2008). It has been demonstrated that certain species experienced increased water-use efficiency (WUE) in response to rising CO_2, with radial growth rates exceeding those expected under given climatic conditions (Voelker *et al.* 2006). A time series of reconstructed annual values of atmospheric CO_2 concentrations (in ppm) was included in preliminary regression analysis to assess its effect on model strength (Knapp & Soulé 2008).

[3.0] *The Growth-Climate Relationship*

Bivariate correlation analyses between all individual tree-ring chronologies as well as the PC composite (average) chronologies revealed that in all cases, the PC composite chronologies were more strongly correlated with state climate division drought variables than were the individual tree-ring chronologies. Additionally, in all cases, seasonal average climate division drought variables exhibited higher correlations than monthly average variables with tree-ring chronologies.

The PC1 chronology was not strongly correlated with any climate division drought variable in the study area. The PC2 chronology was significantly ($p < .01$) but weakly ($r < 0.45$) correlated with spring (March-April-May) average drought conditions in Coastal Plain climate divisions in South Carolina and Georgia. The PC3 chronology was weakly correlated with summer (June-July-August) average drought conditions in

Virginia and the Piedmont of North Carolina, South Carolina, and Georgia. In three Virginia climate divisions (VA2, VA4, and VA5), the PC3 composite chronology had the highest correlation with summer drought conditions (PMDI and PDSI). However, the PC4 composite chronology was strongly and significantly associated with summer average drought conditions (PMDI) in parts of the Carolinas and Georgia. The 12 climate divisions in which summer average PMDI was strongly ($r > 0.65$) correlated with the PC4 composite chronology were considered a homogeneous summer drought region (Fig. 8). Because of the strength of the association between the PC4 composite chronology and summer drought conditions in contiguous Piedmont and Coastal Plain climate divisions, and because of the weakness of the drought signal captured by the remaining tree-ring data, the PC4 composite chronology was the only tree-ring data set retained for regression modeling. None of the tree-ring data exhibited strong correlations (e.g., $r > 0.5$) with Virginia climate division drought data.

The sample depth of individual tree-ring chronologies in PC4 decreased after 1984 (the end date of several chronologies in that PC). After 1984, the explanatory power of the PC4 composite index decreased. However, because the instrumental climate record covers the period 1900-present, tree-ring reconstructions of climate for that period are unnecessary. I therefore used only data from the period 1900-1984, a period common to all PC4 tree-ring chronologies, for calibration and verification of regression models for the reconstructions.

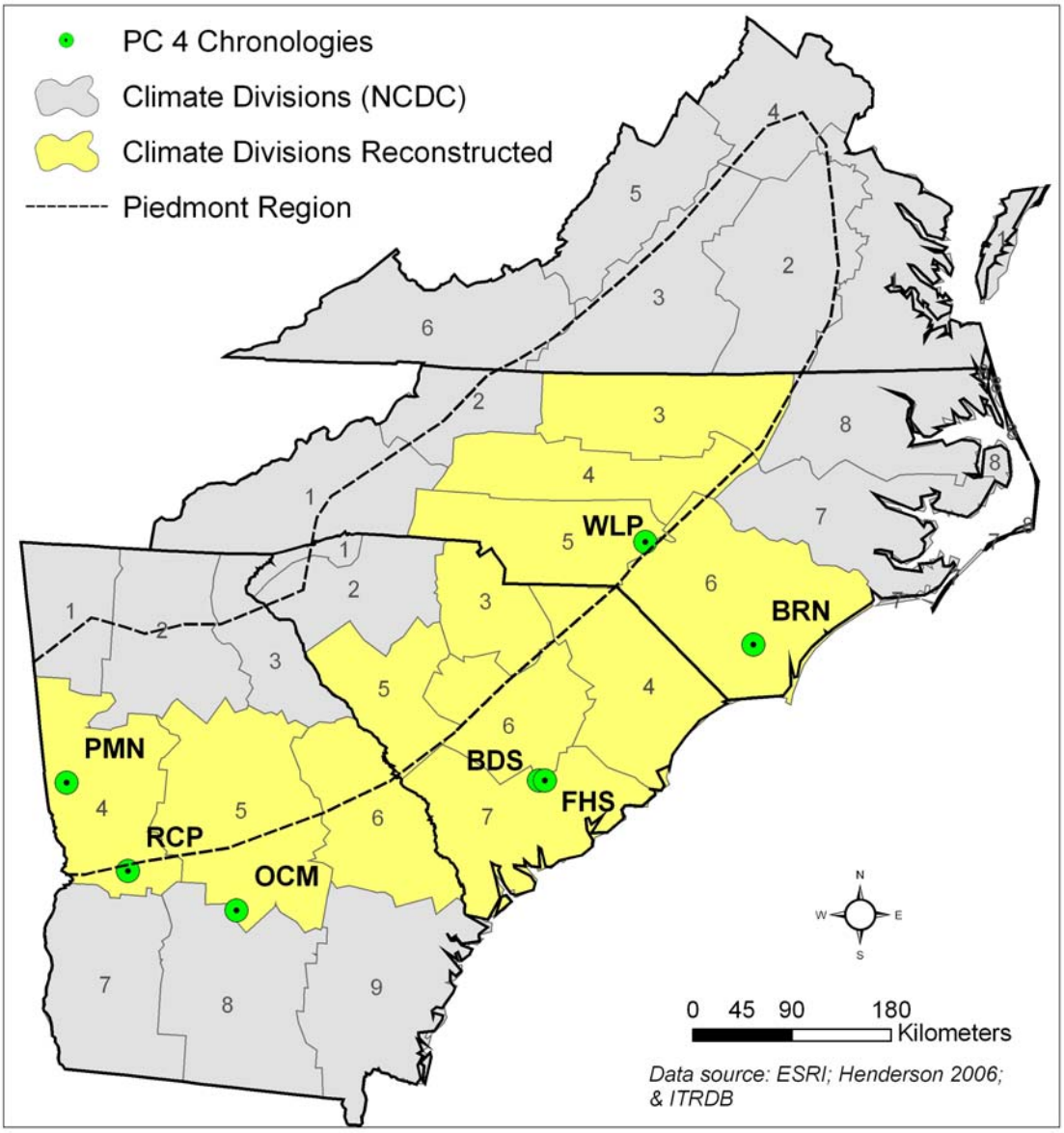

Figure 8. The twelve climate divisions reconstructed from the PC4 composite chronology, and the locations of the seven individual chronologies included in the PC4 composite.

The optimal modeling strategy for reconstruction included the composite (average) annual growth index values calculated from seven individual chronologies (Fig. 8**;** Table 3), covering the common period 1794 to 1984. Each of the seven chronologies loaded most heavily on PC4. However, the period of coverage (beginning in 1794 & 1762 AD) for the two shortest chronologies (PMN and RCP; Knight 2004) in this group of seven placed limitations on the length of reconstruction. I excluded PMN and RCP, calculated the composite growth index for the five remaining chronologies in PC4, and calibrated and verified regression models based on that index as well.

Comparison of the models based on five-chronology versus seven-chronology input indicated that model strength was reduced by the removal of PMN and RCP, but not substantially. Without the shorter chronologies, reliable models could be created that extended back to 1690 with full sample depth.

While both options produced reasonably accurate reconstructions of independent observed data, the differences in model explanatory power and verification results indicate that the two excluded chronologies affected the relationship between the composite chronology and PMDI in the study area. Model coefficients were slightly different between the five-chronology and seven-chronology models. I selected a nested modeling procedure: 1) for the period 1794-1984, the reconstructions were based on the composite (average) chronology from the seven individual chronologies in PC4; and 2) for the years 1690-1794, the reconstructions were based on the same composite chronology, but with input from only the five PC4 chronologies with start dates prior to 1691 (Gunnarson 2001).

Having isolated the strongest relationship between tree-ring growth and drought climatology in the Piedmont region, climate division calibration models for the period 1943-1984 (the first half of the instrumental record) were developed with the seven-chronology composite growth index as the dependent variable, and summer average PMDI from a given climate division and annual atmospheric CO_2 concentrations (ppm; [Knapp & Soulé 2008]) as independent variables. Calibration models for each climate division were also derived without the input of CO_2, in order to determine whether CO_2-related growth effects observed elsewhere (e.g., Voelker *et al.* 2006; Knapp & Soulé 2008) were operative during the study period in the southeastern U.S. In most cases, inclusion of annual CO_2 concentrations in the split-period calibration models improved explanatory power, but was often not statistically significant at the 0.05 level. The 12 climate division calibration models without CO_2 had an average explained variance of 0.581.

The resulting linear regression models—without CO_2—were verified against observed summer average PMDI by climate division for the independent period 1900-1942 (Fritts 1976; Appendix B). The models accurately replicated observed droughts. However, the cutoff between the calibration and verification periods (1942-43) is roughly the time period in which atmospheric CO_2 began to increase most rapidly (Knapp & Soulé 2008). It is possible that tree growth exhibited little response to gradual increases in atmospheric CO_2 in the first half of the 20th century, and that in the second half of the century, as CO_2 concentrations increased more rapidly, tree growth exhibited a similar increase (LaMarche 1984; Knapp *et al.* 2001).

Because of this possibility I created multivariate calibration models for each climate division over the entire common period (1900-1984) with the annual PC4 growth index and CO_2 as predictors, and evaluated the results against models that did not include CO_2. In all cases, the optimal models for reconstruction included CO_2 (average R^2 for the 12 climate divisions = 0.55). When modeled based on the full common period, CO_2 was significant at the 0.05 level for all but one climate division (South Carolina Division 6; $p = 0.06$). All reconstructions in this study were based on the full-sample (1900-1984) multivariate regression models including annual tree-ring growth and annual CO_2 (Appendix B).

[4.0] *Definition of a Prolonged Summer Drought*

In order to identify periods of multi-year summer drought, I examined the instrumental record of summer average PMDI in the study area. The homogeneous drought region identified above experienced five occurrences of multi-year summer drought during the 20th century, in the 1920s, 1950s, 1970s, 1980s, and late 1990s (Stahle & Cleaveland 1992; O'Driscoll & Copeland 2007). In some cases, one year of average or above-average moisture was embedded in a longer-term (> 4 yr) drought, but the cumulative impacts of multi-year summer drought may not be alleviated by one wet summer (Soulé 1992). The five-year moving average (average of the current summer and the previous four summers) provides a smoothed representation of summer PMDI variability in the reconstruction. Moving averages of different periods (e.g., 7-year, 30-year) have been used in climatological research in order to capture long-term (low-frequency) variation and to avoid discontinuities with changes in climatic normals of consecutive periods

(Walsh *et al.* 1982; Timilsena & Piechota 2007). Calculation of the moving average using only the current and previous values in the data series is appropriate for evaluating cumulative impacts up to and including the point of interest (Timilsena & Piechota 2007). This calculation also allows the earliest as well as the most recent periods of the data (i.e., to present) to be calculated with an identical formula.

I computed the five-year moving average of the instrumental summer PMDI record and ranked each overlapping five-year period (pentad). Each pentad represented a five-year window, the average value of which was associated with the final (most recent) year in the window. The data indicated that during the instrumental period, a five-year moving average value < -1.3 was a threshold reached by droughts >4 years in length, and was indicative of the cumulative effects of multi-year droughts in the study area. Each of the confirmed multi-year summer droughts of the instrumental period exhibited 5-year moving averages that reached the -1.3 threshold. All pentads that reached the 5-year moving average threshold contained at least four out of five years with dryer-than-average moisture (i.e., three severe dry years in a five-year period were not sufficient to achieve the threshold).

Droughts of the 1950s and the late 1990s lasted more than five years, and contained multiple pentads that reached the threshold. To isolate individual occurrences of prolonged summer drought, I ranked the non-overlapping pentads. The five driest (most negative) non-overlapping pentads were the five documented multi-year droughts. Because of the success of the threshold 5-year moving average value at identifying known droughts in the instrumental data, I defined a prolonged summer drought as any

five-year period with summer average PMDI < -1.3. I examined overlapping pentad averages to identify prolonged summer droughts greater than five years in length.

CHAPTER IV

RESULTS

[1.0] *Drought Reconstruction*

The first three principal components of tree-ring variability in the southeastern U.S. did not correlate well with climate division drought variables in the four-state study area. PC1 included tree-ring data from the mountainous western portion of the study area, and was not significantly correlated with any drought variable in the region. PC2 also consisted of tree-ring data from upland regions, but slightly east of the PC1 sites. No strong ($r > 0.5$) correlations existed between PC2 tree-ring data and drought variables in the Southeast. PC3 tree-ring data sites were in the western and northern Piedmont, and exhibited significant but weak ($r < 0.5$) association with summer drought conditions in portions of Virginia. The weakness of the relationships between the first three PCs and drought variables in the study area precluded drought reconstructions in the areas not correlated with PC4 tree-ring data. The explained variance in climate division drought conditions by any of the first three PCs is < 20%. Further investigation may reveal the climatic or other environmental signal captured by those data.

Twelve contiguous climatic divisions in the Piedmont and Coastal Plain exhibited significant relationships with the PC4 composite chronology used to reconstruct historic summer droughts (Fig. 8). Multivariate linear regression models (Appendix B) for each division calibrated with observed summer average PMDI and atmospheric CO_2 during

the period 1900-1984 indicated that the PC4 composite chronology explained 43-60% of the variance in summer drought conditions for all twelve climatic divisions (Appendix I). However, because the independent variables (tree-ring growth index and CO_2) were identical in each model, spatial variability within the twelve climate division reconstructions is the result of slightly different model coefficients, and should not be interpreted as spatial variability of the PMDI within the reconstructed region. Rather, the consistent relationship between the PC4 composite chronology and drought conditions in the twelve climate divisions indicates a region of homogenous summer drought climatology.

The summer drought reconstruction is highly correlated ($r = 0.72$, $p < .01$) with the observed record during the common period 1900-1984 (Figure 9). For the observed period 1900-1984, all reconstructions overestimated positive values of the PMDI (wet conditions), but reproduced droughts quite accurately. Overestimation of wetness is common in tree-ring reconstructions, as there is no theoretical upper limit to annual growth (Cook & Jacoby 1977).

The reconstruction for Georgia climate division 5 (Fig. 10), which displayed the highest explanatory power and produced the most accurate estimates of magnitudes of dryness/wetness during the instrumental period, was considered the "regional" drought reconstruction. The Georgia division 5 reconstruction will be displayed and discussed henceforth as the representative reconstruction of summer drought conditions in the

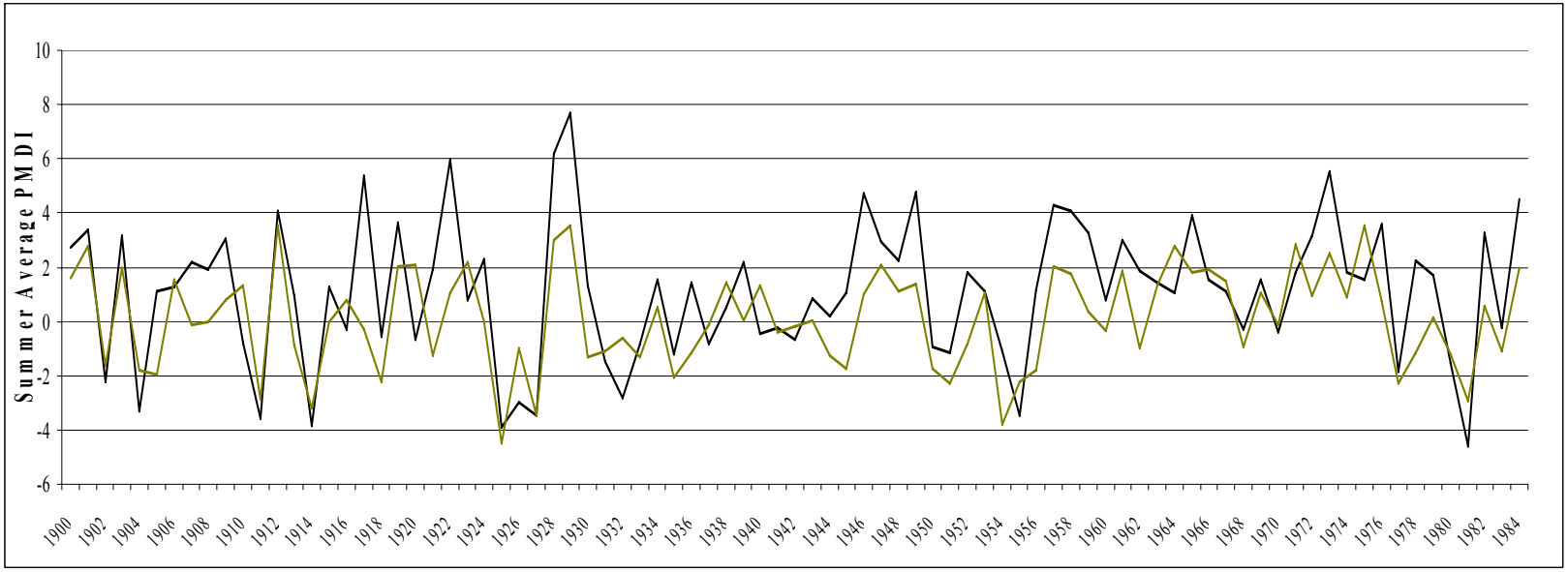

Figure 9. Comparison of the tree-ring reconstruction (black line) and the instrumental record (red line) for the common period 1900-1984. The two time series have a Pearson correlation coefficient (r) of 0.72 ($p < .01$). The reconstruction replicates drought much more accurately than wetness.

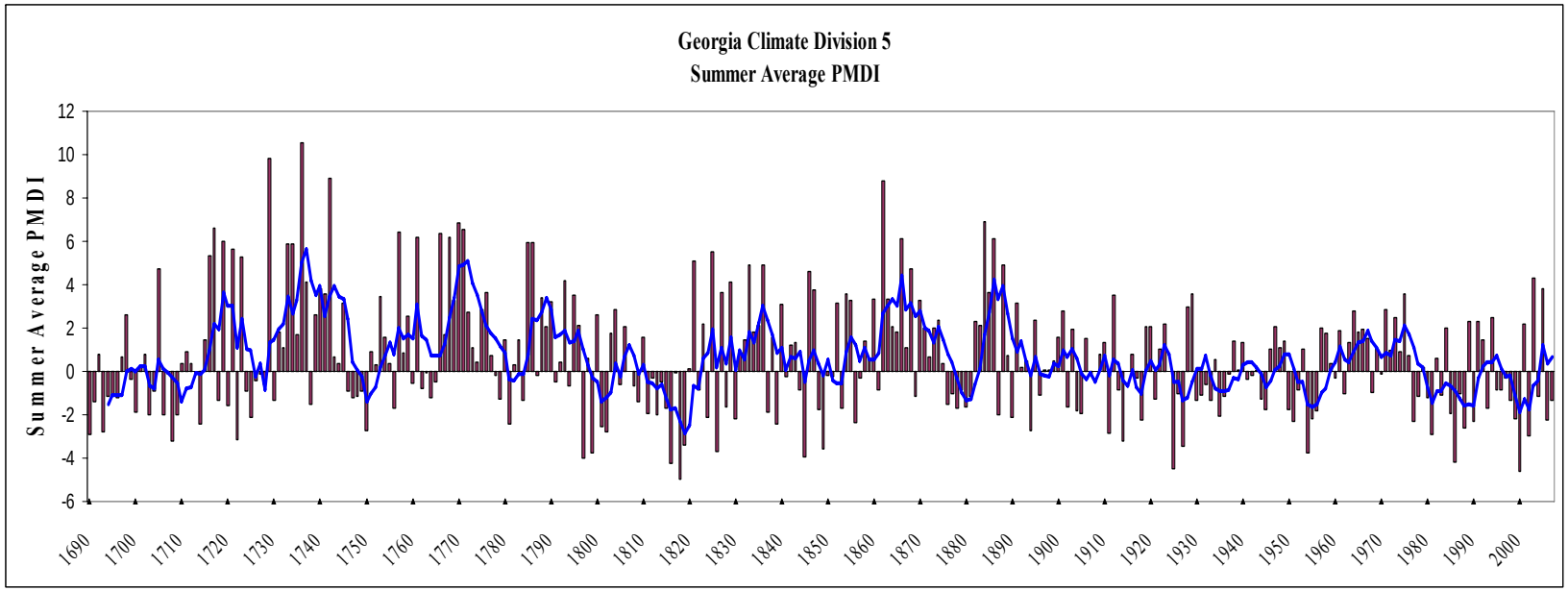

Figure 10. Reconstruction of Georgia climate division 5 summer average PMDI, 1690-1899 (1900-2007 are observed values). Columns represent annual values; the blue line shows the five-year moving average.

central and eastern North Carolina, South Carolina, and Georgia during the period 1690-1900 A.D. The period 1900-2007 is covered by the instrumental record, so reconstructed values for 1900-1984 provide no new climatic information, but are useful for comparison with the pre-instrumental period. The faithful estimation of observed droughts by the reconstruction allows comparisons of drought frequency and intensity between the reconstructed and observed records. However, incorporation of many (e.g., 30) overestimated wet summers in the calculation of a moving average may reduce the effectiveness of comparison between long-term fluctuations in the tree-ring reconstruction and the instrumental record. I therefore examined regime-like summer drought behavior using only the reconstructed record 1690-1984, rather than including the observed record for the 20th century.

[2.0] *Sustained Droughts, 1690-2006*

During the period of study, the Piedmont of North Carolina, South Carolina, and Georgia experienced eleven episodes of sustained (> 4 yr) summer drought. The longest and most severe drought in the region during the last 300 years occurred during the period 1811-1820 (Fig. 10). The beginning of the study period, 1690-1712, was a time of persistent drought with at least three wet summers embedded. The early period may have consisted of two or more distinct multi-year summer droughts, although the five-year moving average indicates below-average summer soil moisture conditions in 20 of the 23 years (Fig. 10).

Several droughts in the reconstruction spanned more than 5 summers, and multiple pentads during those droughts were ranked among the driest, even though summer

drought conditions were continuous. For example, the three driest overlapping pentads ended in the years 1819, 1820, and 1818, and the sixth and seventh driest ended in 1816 and 1817, respectively (Table 4). The non-overlapping pentads with 5-year moving average summer PMDI values <-1.3 represent the 11 distinct occurrences of sustained summer drought in the Piedmont during the last ~300 years (Fig. 11).

Five of the 11 periods of sustained drought were between 1900 and 2006; six such periods occurred between 1690 and 1899. The data indicated a 34.7% probability of a prolonged summer drought in a given decade for the 317-year study. That probability changed through time, rising to 46.7% for the period 1900-2006. During the last 5.6 decades (1950-2007), the probability increased to 71.4%. Also, the droughts from 1950 – present were the second, third, fourth, and sixth most severe (most negative 5-year average) multi-year droughts in the period of analysis.

For the entire period of study, seven of the 11 sustained droughts exhibited a rapid return to above-normal moisture conditions (Fig. 12). The seven abrupt transitions from dry to wet involved increases in annual summer PMDI of > 3.5 units (1.25 standard deviations) from the final negative summer to the first positive summer. Because of the lag between moisture input and hydrological drought response, the sharp increase in PMDI at the end of certain multi-year summer droughts is intriguing.

Table 4. The 20 driest overlapping pentads, 1699-2007. No other five-year periods in the 317-year combined tree-ring and instrumental record reached the threshold average of -1.3.

Pentad end	5-yr moving average (summer PMDI)
1819	-2.8711
1820	-2.5102
1818	-2.2840
2000	-1.8560
2002	-1.7847
1816	-1.7397
1817	-1.6867
1955	-1.6180
1990	-1.5627
1988	-1.5567
1954	-1.5247
1956	-1.5213
1989	-1.4947
1694	-1.4854
1981	-1.4847
1801	-1.4194
1710	-1.3946
1750	-1.3823
1927	-1.3593
1880	-1.3486

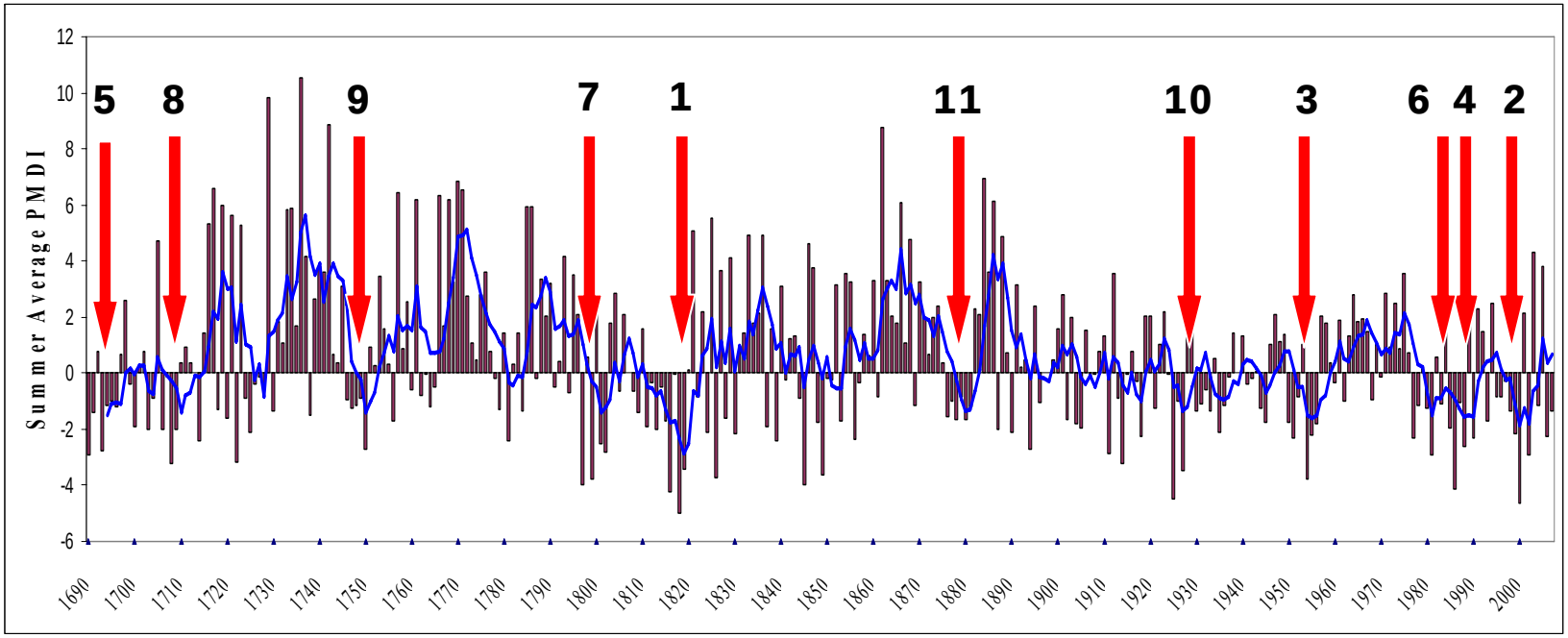

Figure 11. The eleven driest (ranked) non-overlapping pentads in the study period, representing eleven occurrences of sustained drought in the study area: (1) 1815-1819, (2) 1996-2000, (3) 1951-1955, (4) 1986-1990, (5) 1690-1694, (6) 1977-1981, (7) 1797-1801, (8) 1706-1710, (9) 1746-1750, (10) 1923-1927, (11) 1876-1880.

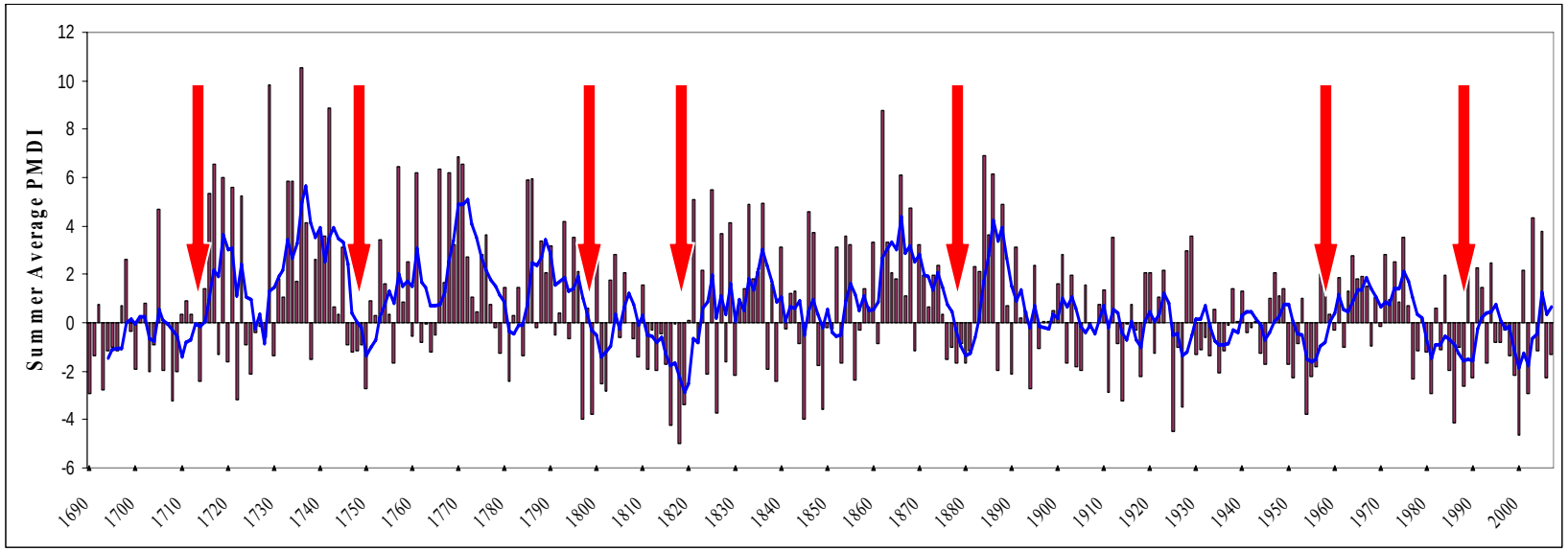

Figure 12. Red arrows indicate seven periods of sustained drought with rapid recovery to above-average moisture conditions.

[2.1] *Multi-decadal Moisture Regimes*

Previous investigators have noted that the instrumental climatic record for North Carolina contains marked regimes of wetness and dryness approximately 30 years in length (Stahle & Cleaveland 1988). Tree-ring evidence of historic state-average June drought conditions indicated that similar cycles have been part of North Carolina climate throughout the last 15 centuries (Stahle & Cleaveland 1988). The instrumental record for Georgia climate division 5 and the present Piedmont drought reconstruction both contain multi-decadal variation at time scales similar to those identified in North Carolina.

Comparison of the 30-year averages of the instrumental record and the reconstruction during the common period (1900-1984) indicated that the reconstruction accurately replicated multi-decadal variation in summer drought conditions in the study area (Fig. 13). The mid-1920s through the mid-1960s was a period of drier-than-average summers including the severe 1950s drought, followed by a wetter-summer regime from the mid-1960s to the mid- or late-1990s, then a return to below-average summer moisture (Figs. 13 & 14). The full reconstruction identifies multi-decadal wet and dry regimes throughout the period 1690-1984 as well (Fig. 15). Drier summers dominated between 1690 and 1715, and the mid-1700s to the early-1800s was a prolonged regime of wetter summers. The early 1800s to mid 1800s were drier, including severe uninterrupted drought from 1811-1820. The mid-1800s to the early 1900s was a period of wetter summers, leading into the drier regime in the early half of the instrumental record. It is noteworthy that interannual variability was high during both

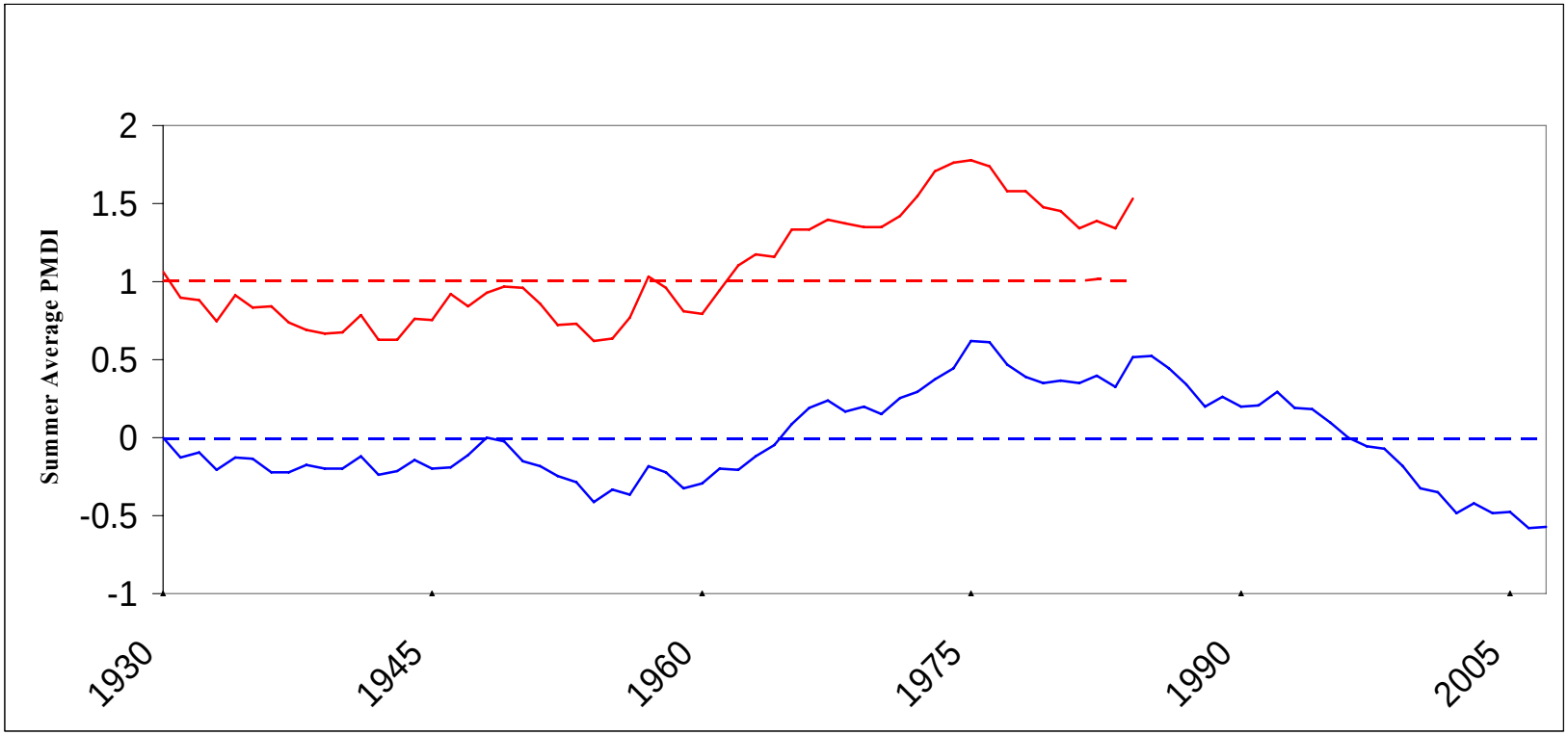

Figure 13. 30-year moving average series of the summer drought reconstruction (top) and observed Piedmont summer drought conditions (bottom). The dashed lines represent the means of the respective series. The reconstruction has a higher mean PMDI value because of the overestimation of wetness, and because of the observed decrease after the end date of the reconstruction. The series have a Pearson correlation coefficient (r) = 0.952.

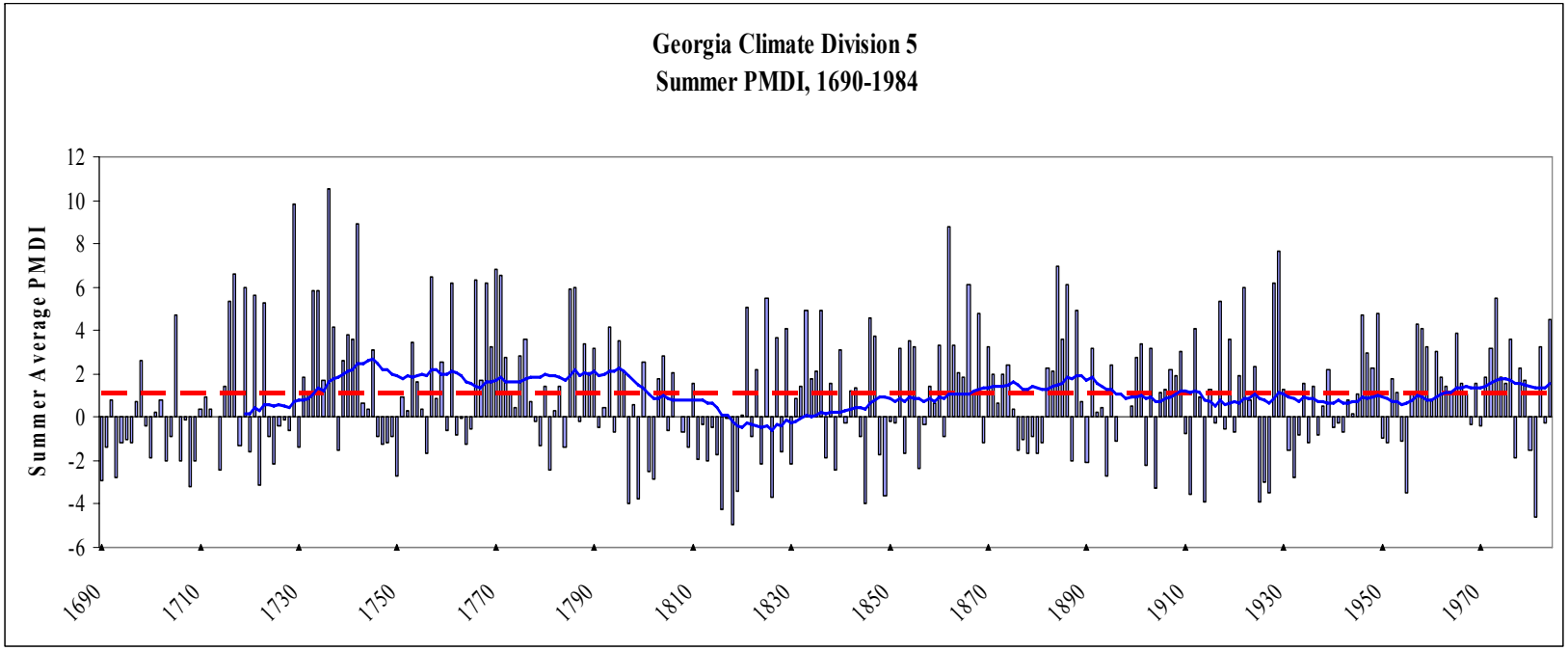

Figure 14. Interannual (columns) and multi-decadal (smoothed series) variations in reconstructed summer moisture. No observed values are displayed. The smoothed series is the 30-year moving average of annual values. The dashed line is the mean of the full reconstruction.

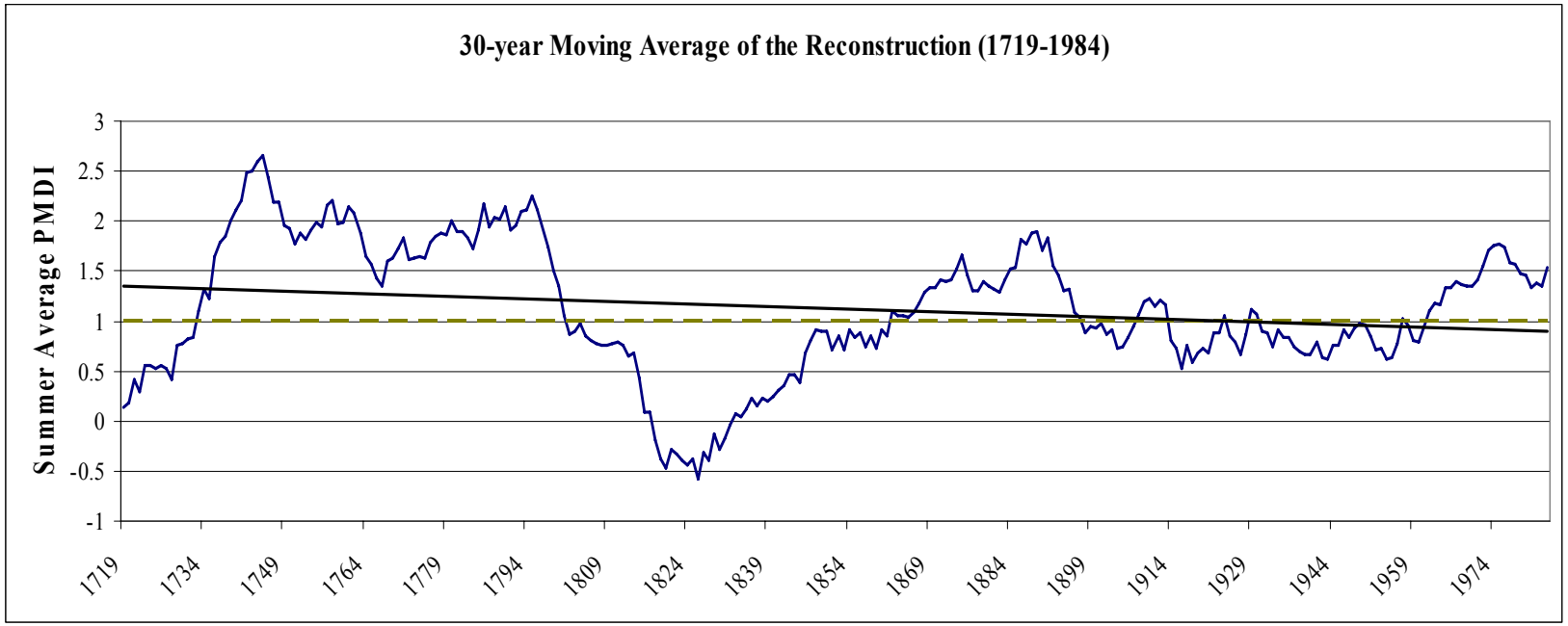

Figure 15. The smoothed time series of summer PMDI emphasizes multi-decadal variability, with distinct wet and dry regimes between 30 and 60 years in length. The horizontal dashed line represents the mean of the full reconstruction. The solid black line shows the long-term linear trend of the reconstructed data.

wet and dry regimes, and that droughts and wet spells may occur during wet and dry regimes, respectively (Fig. 14).

The reconstruction contains nine non-overlapping thirty-year periods, spanning 1714-1984, as well as the 24-year period from 1690-1713 (Fig. 16). These periods demonstrate the regime-like nature of summer moisture conditions in the study area. Early in the study period, certain 30-year segments exhibited means substantially above and below the long-term mean, with magnitudes of wetness and dryness unequaled in later segments of the reconstructed record. The magnitude of multi-decadal variation declined after around 1850. The higher variance early in the reconstruction may be due to the smaller sample size at each individual tree-ring data site. In general, tree-ring chronologies include decreasing numbers of samples in the earliest years because few of the trees in a given stand are extremely old, and greater proportions of forest stands consist of younger trees (Fritts 1976).

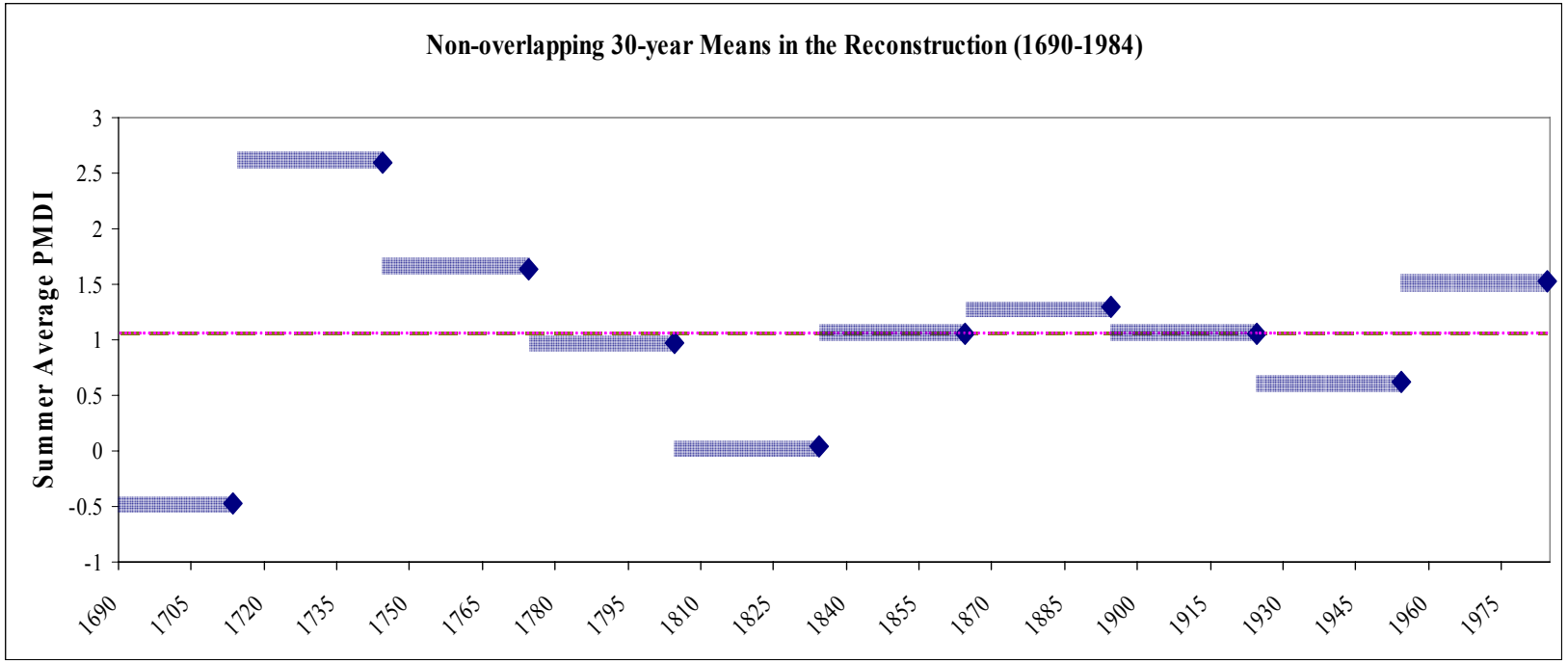

Figure 16. Mean summer PMDI for the ten non-overlapping 30-year periods in the reconstructions. The horizontal dashed line is the mean of the full reconstruction. The most recent period ends in 1984; the earliest period is only 24 years (1690-1713).

CHAPTER V

DISCUSSION

[1.0] *Tree-Ring Drought Relationships in the Southeastern U.S.*

The 27 individual tree-ring chronologies included in this study represent a majority of the tree-ring data in the southeastern U.S. as of June 2008. Principal components analysis revealed four dominant modes of variation in the tree-ring data. The fourth PC of tree-ring variability contained the only strong drought signal based on correlation analysis with instrumental drought variables in the study area. The first three PCs of tree-ring data did not correlate well with any climate division drought variable from Virginia to Georgia.

The lack of correlation with drought variables—even in the climate divisions in which the tree-ring data were collected—indicated that some other climatic and/or environmental factor (or factors) was responsible for the variations in tree growth at the sites in the first three PCs. The differences between the locations of the tree-ring sites deserve discussion. However, the metadata characteristics of the chronologies may also illuminate some of the differences in drought signal strength between PC4 and the other tree-ring data in the region.

First, the four PCs of tree-ring variability defined spatial regions with varying topoedaphic conditions. The tree-ring data in PC1 were from mountainous locations, which often produce diverse microclimates (Fig. 7; Table 3). Tree growth at highland

sites could be limited by a variety of non-drought factors including temperature (i.e., variations in growing season length) and soil depth/richness, especially on steep slopes. The complex interactions between topography, soils, climate, and tree growth may make extraction of a climate signal of any type difficult from the PC1 tree-ring chronologies. Additionally, each individual chronology in PC1 was from oak trees. The cluster of variance identified as PC1 may therefore be the result of differential species response to growth-limiting factors. Overall, the mean sensitivity of the chronologies in PC1 was the lowest of the four PCs (0.191; Table 3). Low mean sensitivities indicate low variance in the data, and thus are not often associated with strong climate signals in tree-ring data.

PC2 included tree-ring data from primarily mountainous locations in the north and west of the study area, adjacent to and east/southeast of the PC1 sites (Fig. 7; Table 3). Like the PC1 chronologies, the PC2 data may be impacted by the complex microclimates and topoedaphic settings associated with substantial local relief. Also like PC1, PC2 was dominated by one tree genus. Six of the seven PC2 chronologies were from hemlock trees, and one is from chestnut oaks. The mean sensitivity of the PC2 chronologies was the second-lowest of the four PCs (0.21; Table 3). Thus, the PC1 data were dominated by oak response at higher elevations, and the PC2 data were dominated by hemlock response at intermediate elevations. The lower mean sensitivity of PC1 and PC2 may be a reflection of regional growth conditions that are constantly limited by a complex assortment of conditions, and therefore do not exhibit a strong growth response to a single variable (i.e., seasonal drought variables).

The PC3 chronologies included upland sites in the western portion of the study area and Piedmont sites in the central and northern portions (Fig. 7; Table 3). The tree-ring response to seasonal drought conditions in the Southeast was better in PC3 than in the first two PCs, but in only a few climate divisions, and at a level of explained variance below those commonly reported in tree-ring reconstructions (e.g., $R^2 < 0.5$). The PC3 data were multi-species, with chronologies from white oak, tulip poplar, and shortleaf pine. The topoedaphic conditions of the individual chronologies in PC3 are also diverse. Three of the five sites (KM1, KM2, and KM3) are from upland locations in the southern Appalachians, and two (HAM & MNP) are in the eastern Piedmont of North Carolina and Virginia, respectively. However, even the Piedmont tree-ring sites in PC3 were not closely associated with drought conditions in Piedmont climate divisions. The mean sensitivity of the PC3 chronologies was 0.243 (Table 2), which is significantly larger than the same measure for PC1 (two-tailed t-test, $\alpha = 0.005$), but not significantly larger than PC2.

By contrast, the PC4 tree-ring data were strongly correlated with summer drought conditions in a broad region of the Southeast, including much of the Piedmont south of Virginia as well as Coastal Plain climate divisions in North Carolina and South Carolina. PC4 was also a mixed-species group, including three species of oak, bald cypress, and longleaf pine. Five of the seven PC4 data sites were in the Coastal Plain, and two sites (WLP & PMN) were near the Piedmont / Coastal Plain transition. Thus, topoedaphic conditions are reasonably homogeneous between the individual PC4 sites. Lower elevations and the relative proximity to major water sources (the Atlantic and Gulf

Coasts) may be responsible for the greater mean sensitivity among PC4 chronologies, which was 0.432 (significantly different from PCs 1, 2, and 3; $\alpha = 0.001$, 0.007, and 0.048, respectively). The strength of the climate signal captured by the PC4 data was unmatched by any other tree-ring data in this study, and at present may be considered the best combination of tree-ring data for drought research in the Carolinas and Georgia.

[2.0] *Piedmont Drought History, 1690-2006*

The results of the Piedmont tree-ring drought reconstruction indicated that multi-year summer droughts were part of the climate history of the southeastern U.S. for the past three centuries. Eleven occurrences of summer drought > 4 years in length appeared in the combined instrumental and proxy climatic records from 12 individual state climate divisions in North Carolina, South Carolina, and Georgia. Prolonged droughts were more frequent during the 20th century than during the preceding two centuries, and the maximum cumulative severities (represented by five-year average conditions) of four of the 20th century droughts ranked in the top six of the 11 total occurrences. Several investigators have noted changes in frequency and/or intensity of various environmental phenomena, including drought, around 1900 (Gray *et al.* 2004c; Le Quesne *et al.* 2006; Li *et al.* 2007; Lara *et al.* 2008). Whether the turn of the 20th century was a period in which many of Earth's systems experienced natural shifts, or whether such shifts were related to anthropogenic impacts on the environment is beyond the scope of this study. However, an apparent inflection point in the findings of a number of independent studies indicates that the topic deserves further attention.

The timing of reconstructed multi-year droughts in the Piedmont agrees with findings regarding historic droughts in the southeastern U.S. and North Carolina (Stahle & Cleaveland 1988; Stahle & Cleaveland 1992). However, the specific synoptic causes of drought in the region remain elusive. No relationship could be identified between ENSO conditions and the onset of summer drought in the study area during the observed period. Onsets of the sustained droughts of the 20th century in the study area were associated with warming of both the North Atlantic and North Pacific. No significant correlations existed between the AMO, PDO, and drought in the Piedmont, but the droughts of the instrumental period occurred during warm phases of the AMO, including the 1920s, 1950s, 1970s, and the late 1990s – early 2000s. The drought of the late 1970s began during a phase shift from cool to warm in both the AMO and PDO (Fig. 17). Between the droughts of the mid-1950s and the late 1970s, both the AMO and PDO were negative (cool phase). This was the only period > 10 years since 1950 in which no sustained droughts occurred in the study area, and also the only period in which both the North Atlantic and North Pacific were cooler than average.

The long-term variability noted in summer drought climatology in the study area may also be linked to shifting AMO conditions. The dry regimes from 1925 – 1955 and from the late-1980s to the present were concurrent with warm phases of the AMO. Conversely, wet regimes from 1891-1924 (see also Stahle & Cleaveland 1988) and from 1956-1984 were synchronous with cool AMO phases. Because of the observed influence on growing season precipitation in the region exerted by the Bermuda High, the synchronicity of long-term variability in the AMO and summer droughts in the

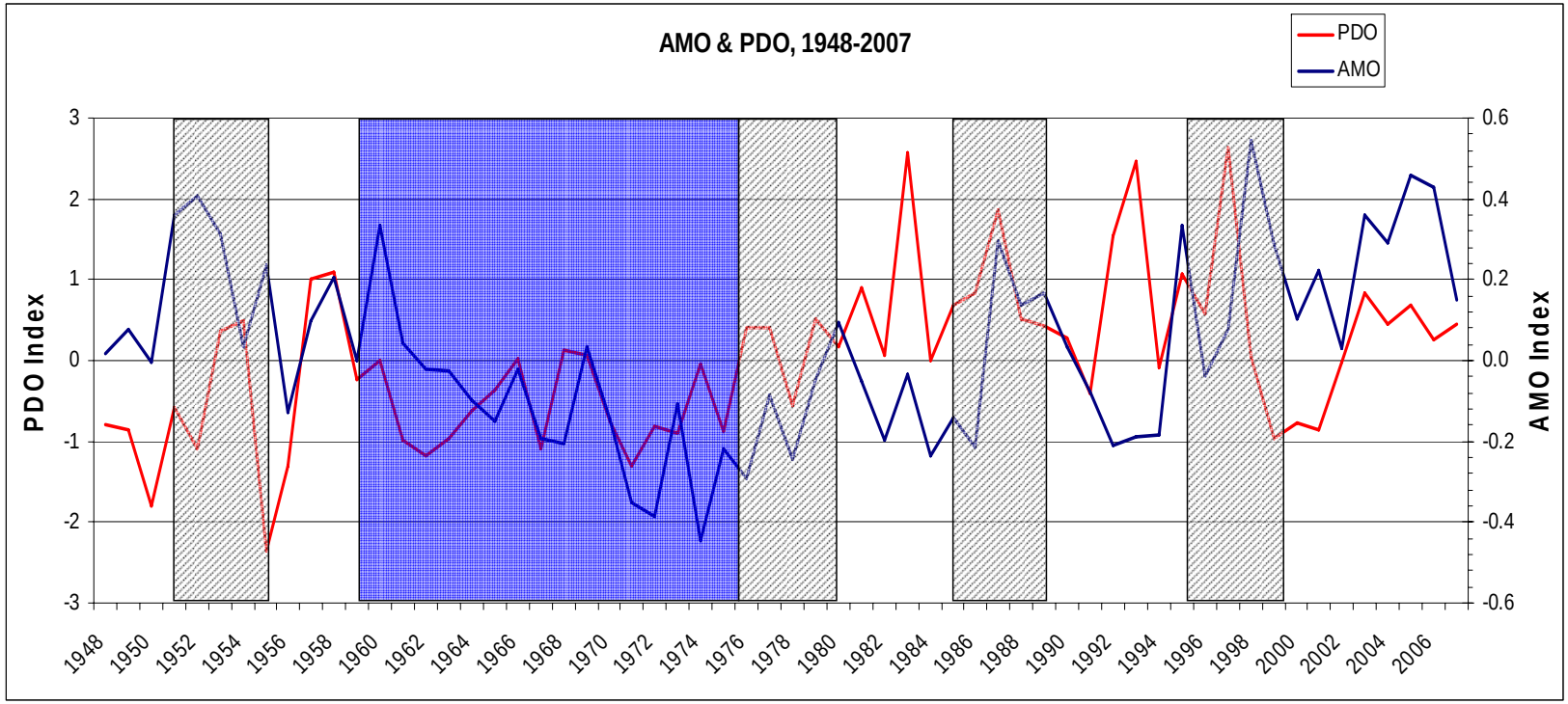

Figure 17. AMO and PDO indices 1949-2007. The blue shaded box approximates a concurrent cold phase in the two indices. The textured boxes enclose the four pentads representing multi-year droughts in the displayed period.

Piedmont is likely also related to the seasonal migration and strength of the Bermuda anticyclone. Anomalous westward expansion of the Bermuda High into the interior southeastern U.S. has been associated with dry regimes from 1925-55 and 1985-present (Stahle & Cleaveland 1992). From 1903 to 1980, three distinct "epochs" of mean central pressure in the Bermuda High have been identified (Sahsamanoglou 1990). During the period 1903-1930, central pressure was extremely high, from 1931-1967 central pressure was generally below normal, and from 1968-1980 central pressure was above normal (Sahsamanoglou 1990). This is further evidence of a relationship between the AMO and the North Atlantic subtropical anticyclone. Periods of above-average central pressure in the Bermuda High were concurrent with cool phases of the AMO, and the recorded period of below-average pressure was concurrent with warm-phase AMO, which itself appears conducive to summer drought in the study area. This is in agreement with the findings of Stahle & Cleaveland (1992), who attributed dry summers in the Southeast to weakened southeasterly (onshore) airflow and moisture advection in the southwestern quadrant of the Bermuda High.

The short-term (~30 yr) regime-like behavior of mean central pressure in the Bermuda High occurs within a long-term trend of decreasing intensity and spatial extent of the anticyclone (Sahsamanoglou 1992; Davis *et al.* 1997). In addition, during the last 90 years, the Bermuda High has exhibited a long-term eastward shift in mean position (Davis *et al.* 1997). The combination of eastward migration and decreasing intensity of the Bermuda High may explain the observed trend of decreasing summer precipitation in the Southeast. Reduced central pressure and weaker anticyclonic airflow around the high

are associated with reduced summer moisture advection in the study area. Strong ridging over the southeastern U.S. has been linked to the expansion and westward migration of the Bermuda High, whether during spring or summer. In the long term, reduced spatial expansion (weaker high pressure) and general eastward migration of the mean center of the high should lead to later arrival of maximum ridging in the southeastern U.S., during summer rather than spring. This also agrees with the findings of Stahle & Cleaveland (1992), who reported a long-term increase in spring precipitation concurrent to a long-term decrease in summer precipitation in the Southeast. If temporal variations in the summer position(s) of the Bermuda High can be statistically associated with shifts in the AMO and related circulation features, the ability to forecast long-term changes in summer drought conditions in the study area may be substantially improved.

The AMO has also been strongly linked to hurricane activity in the western subtropical Atlantic (Knight *et al.* 2006; Miller *et al.* 2006; Keim *et al.* 2007). The statistical relationship between wet and dry regimes of southeastern U.S. climate, warm and cool phases of the AMO, variations in the strength and position of the Bermuda High, and the spatio-temporal variability of precipitation from tropical cyclones may illuminate both the long-term and short-term mechanisms responsible for multi-year summer drought in the Southeast.

[2.1] *Drought recovery*

In the Piedmont drought reconstruction, seven (64%) of the 11 driest pentads exhibited a rapid recovery to above-average summer moisture conditions (one-year increase > 3.5 PMDI units from negative to positive). The abrupt change from drought conditions to

above-average moisture indicates substantial precipitation following the final summer of the prolonged droughts. One possibility is that landfalling tropical cyclones in the autumn and winter following the drought contributed large quantities of rainfall and helped to alleviate water shortage, although a detailed analysis of winter and spring precipitation in the study area with reference to the ends of droughts in the instrumental period could identify winter drought recovery unrelated to tropical precipitation. Some multi-year droughts in the region during the last 300 years exhibited rapid recovery indicative of substantial precipitation in the autumn, winter, and spring following the final summer of the droughts, which captures the Atlantic hurricane season in the southeastern U.S. and most of the MLC season. Discussion of these two possible mechanisms for regional drought recovery follows.

Typical autumn and winter precipitation in the region would generally be insufficient to eliminate cumulative moisture deficiencies resulting from multi-year summer droughts. However, winter moisture recharge to end a prolonged summer drought is plausible due to the enhanced winter ENSO teleconnections associated with warm PDO and warm AMO conditions, which are associated with observed summer droughts in the study area.

The short-term ENSO teleconnections to Piedmont climate appear to reduce the risk of multi-decadal droughts in the study area. It is well understood that strong El Niño conditions (above-average sea surface temperatures off the coast of northwest South America, and below-average sea surface temperatures in the western Pacific near Indonesia and northern Australia) generally lead to wetter-than-average winters in the

southeastern U.S. (Tarbuck & Lutgens 2006). However, modifications to the position of the subtropical jet caused by El Niño often result in the reduced incidence of Atlantic hurricane landfall in the southeastern U.S., as the subtropical jet serves to shear the tops off of hurricanes over the western Atlantic. Conversely, La Niña conditions (cooler-than-average sea surface temperatures off the coast of northwest South America and warmer-than-average sea surface temperatures in the western Pacific near Indonesia and northern Australia) tend to enhance the likelihood of Atlantic hurricane landfall in the southeastern U.S., but are generally associated with dry winters in the region. El Niño teleconnections to winter climate (wetter winters) in the Piedmont tend to be strengthened during warm-phase AMO, and further strengthened during warm-phase PDO.

Examination of monthly PMDI values in the study area during the instrumental period revealed that multi-year summer droughts in the Piedmont often ended during the winter or spring following the final year of a prolonged summer drought. For this evaluation, the end of a drought was defined as the month in which PMDI values became positive and continued to be positive for the succeeding two months. For example, the drought of the 1920s ended after March of 1928. April, May, and June of 1928 exhibited positive PMDI values, indicating a relatively wet spring, which is probably the result of precipitation associated with an active MLC season. Spring drought recovery also characterized the Piedmont droughts of the 1950s and the late-1990s – early-2000s. The 1950s drought ended after April, 1957, and the late 1990s drought ended after May, 2001. Two sustained droughts in the instrumental period ended during winter. The late-1970s drought ended after November, 1981, and the late 1980s drought ended after February,

1990. The evidence suggests that during the 20th century, multi-year summer droughts in the Piedmont ended because of substantial precipitation during the winter and spring following the last summer of drought. However, because of the nature of the PMDI, the calculation of which for a given month includes moisture conditions in prior months, winter drought recovery could potentially include the input of tropical moisture during the autumn or early winter after the final summer of a drought.

Landfalling tropical cyclones are common features of long-term climatology in the study area (Miller *et al.* 2006). Storms of tropical origin can produce large precipitation totals over land, even as storm classification (based on wind speed) drops with the storm's inland progress. Precipitation from tropical cyclones is therefore part of the background hydroclimatology of the southeastern U.S., including the Piedmont. During the instrumental period, the AMO has exerted strong influence over the number of tropical cyclones in the Atlantic Ocean that develop into strong (category 3 or higher) hurricanes (Knight *et al.* 2006; Miller *et al.* 2006). Under positive (warm) AMO conditions, more than twice as many tropical cyclones per season develop into major hurricanes than during cool AMO phases (McCabe *et al.* 2004). The AMO has not been found to modulate the number of tropical cyclones that develop, only the number that strengthen into major hurricanes.

Periods of high Atlantic hurricane activity and periods of prolonged drought in the Southeast coincide during the instrumental period, and are concurrent with periods of warm-phase AMO (Miller *et al.* 2006; Keim & Muller 2007). Comparison with a 220-year reconstruction of hurricane activity in the southeastern U.S. indicated that

reconstructed periods of drought also coincided with periods of high hurricane activity prior to the instrumental record (Miller *et al.* 2006).

Given the relationship between the AMO, observed droughts in the Southeast, and hurricane activity, historic active hurricane periods may represent historic warm phases of the AMO, and should co-occur with historic multi-year droughts in the study area. The reported periods of high hurricane activity prior to the instrumental record were coincident with prolonged droughts ending in 1801, 1820, 1880, 1957 and the droughts of the 1980s-present (Miller *et al.* 2006). The 1950s was the most active decade for tropical cyclones in the instrumental record, also concurrent with a severe prolonged drought in the study area. The return to warm-phase AMO around the late-1980s or early 1990s was associated with the substantial increase in hurricane activity and the return of multi-year summer drought from the late-1980s to present. Conversely, the reconstructed periods of low hurricane activity coincided with regimes of wetter summers, including 1781 – late-1790s, and the 1970s.

Warm-phase AMO conditions may also modulate tropical cyclone storm tracks. The 1950s and 1990s (warm AMO) were extremely active tropical cyclone decades along the Outer Banks of North Carolina, while the intervening period of cool AMO included very little tropical cyclone activity in the same location. Conversely, the 1950s and 1990s were hurricane seasons with anomalously low activity in southern Florida, and active hurricane seasons dominated the interim (Keim *et al.* 2007).

While the temporal variability in major Atlantic hurricane formation is partially explained by the AMO, some of the spatial variability could be attributable to the

location and strength of the Bermuda High. The periods of warm AMO in which the North Carolina coast saw extremely high tropical cyclone activity (1950s and 1990s) were also periods in which the region experienced multi-year summer droughts. Periods of cool AMO, associated with more southerly tropical cyclone tracks impacting Florida and the Gulf Coast, are associated with wetter summer regimes in the Piedmont. This could be explained by the relationship between the AMO and the Bermuda High, in which cool AMO is related to strong anticyclonic flow well west of the Atlantic coast during summer and enhanced moisture advection into the Piedmont. Conversely, AMO warming leads to reduced summer SLPs over the Atlantic, weaker anticyclonic flow, and less moisture advection during summer, with the southwest flank of the Bermuda High located off the North Carolina, South Carolina, and Georgia coasts guiding tropical cyclone tracks along the Atlantic coast north of Florida.

Of the seven droughts with rapid recovery to above-average moisture, hurricane records exist for three, represented by the pentads 1876-1880, 1951-1955, and 1986-1990 (Weather Underground 2008). In each case, long-term soil moisture deficits appear to have been alleviated in part by autumn incursions of tropical moisture. The 1876-1880 pentad represents a period of consecutive negative (dry) reconstructed values that ends after summer 1881. Reconstructed summer average PMDI values increased from -1.18 to 2.29 between 1881 and 1882. Two tropical systems impacting the study area made landfall in late August and early September 1881.

The first storm tracked through the southern Piedmont of Georgia during late August. The second storm made landfall in early September and would have produced

precipitation in the study area primarily in the Piedmont of North Carolina and South Carolina. Rainfall associated with these two systems could have significantly increased soil moisture in the Piedmont through the winter and into spring 1882. Autumn 1882 was also an active tropical storm season in which three tropical systems potentially impacted the study area and effectively ended any lingering moisture deficiency in the region.

Similar tropical cyclone seasons characterize the recovery from droughts in the 1950s and early 1990s. The 1950s drought, represented by the 1951-1955 pentad, actually ended after the summer of 1956. The PMDI value for summer 1956 was -1.8, while the summer PMDI of 1957 was 2.03. Hurricane Flossy made landfall in September, 1956 in southern Alabama and tracked northeast through the eastern Piedmont, returning to the open ocean around Cape Hatteras, North Carolina (Weather Underground 2008). While the official end (as defined above) of the 1950s drought was in April of 1957, the input of tropical precipitation in autumn of 1956 would presumably have had a significant impact on soil moisture, and may have begun the process of recovery which was completed in the following spring. Similarly, at the end of the 1986-1990 drought, tropical storm Marco made landfall in October of 1990, and Hurricane Bob arrived in August of 1991. The August 1991 precipitation from Hurricane Bob was included in the calculation of the 1991 summer PMDI, which was 2.3, up from -2.3 in summer of 1990. The final consecutive negative monthly PMDI value associated with this drought was in December 1990, with subsequent increases through spring and summer of 1991. Again, tropical precipitation in autumn 1990 probably contributed to soil moisture recharge that was captured by the PMDI calculation in the following months. A detailed analysis of

short-term drought recovery characteristics in the region is needed to test these hypotheses.

The identification of certain tropical systems in the instrumental record as droughtbusters—and the subsequent inference that similar phenomena may have occurred at points in the past—does not imply the absence of tropical storm activity during multi-year droughts. Nor does it imply that above-average soil moisture conditions in the Piedmont would necessarily be associated with precipitation from tropical cyclones. Rather, the data suggest that the climatic forcing mechanisms impacting the study area are aligned such that periods of high hurricane activity along the Atlantic coast are often simultaneous with periods of high winter MLC activity in the study area.

Thus, the development of multi-decadal sustained droughts in the study area would apparently require the long-term (> 20 yr) suppression of winter MLC activity and of well-developed tropical cyclones making landfall in the southeastern U.S. There is no evidence for long-term MLC suppression in the region, and long-term reductions in hurricane landfalls are associated with cool-phase AMO conditions, which are in turn associated with multi-decadal regimes of summer wetness in the study area.

The apparent inverse relationship between the probability of summer drought in the Piedmont and the probabilities of both wet winters and major hurricane landfall along the Atlantic coast raises the question whether combinations of synoptic features could ever combine to produce multi-decadal "megadroughts" in the southeastern U.S. The incursion of tropical moisture in the study area is more likely during periods in which

regional summer droughts and enhanced winter wetness are also most common (warm-phase AMO). Both long-term and short-term climatic controls over the Piedmont seem to shield the region from the development of multi-decadal megadroughts, either because of synoptic conditions conducive to wet summers, because of synoptics leading to wet winters, or because of tropical precipitation during times of summer drought.

The evident synoptic "safety net" protecting the southeastern U.S. from severe decadal-scale (or longer) droughts during the last three centuries failed to break up the longest drought in the present reconstruction, during the period 1811-1820. This exception to the short-lived (< 8 yr) nature of typical Piedmont droughts requires further discussion. In the context of the current knowledge of climatic controls in the Southeast, a possible explanation for the persistence of the 1810s drought emerges. The observed relationship between the AMO, PDO, and summer drought in the study area indicates that the 1810s were probably a period of above-average SSTs in both the North Pacific and the North Atlantic, with an associated weakening of the North Atlantic subtropical anticyclone, and thus reduced moisture advection into the Southeast during the growing season. Given the above conditions, a westerly displacement of the center of the (weakened) Bermuda High might have led to spring and summer ridging in the study area, and thus reduced precipitation. A westerly "epoch" of the Bermuda High during the 1810s could also have resulted in a decade of southerly tropical cyclone tracks, impacting south Florida and the Gulf of Mexico rather than the study area. No explanation for a westward shift of the Bermuda High during a regime of weakened anticyclonic airflow has been identified. However, one plausible explanation for these coincident anomalies

could involve the major volcanic eruptions of the era, including a major explosive eruption at an unknown location in 1810, and the eruption of Mt. Tambora in modern-day Indonesia in 1815 (Dai & Thompson 1991). The year 1816 has been labeled "the year without a summer," in reference to the global climatic impacts of the Tambora eruption and consequent dust veil (Dai & Thompson 1991). Reduced summer temperatures in the northern hemisphere are conceptually consistent with the notion of a weakened Bermuda High, as the contrast in summer warming between the continents and the North Atlantic would decline with a decrease in surface receipt of solar energy. The climatic impacts of major volcanic eruptions are yet poorly understood, but the co-occurrence of the only uninterrupted decadal-scale drought in the last 300 years in the study area and the last major decadal episode of explosive volcanic eruptions is probably not the result of chance.

[2.2] *Drought Regionalization—Virginia vs. the Southeastern U.S.*

This study focused on the four-state region of Virginia, North Carolina, South Carolina, and Georgia. However, the tree-ring data correlated well with drought conditions in the Piedmont of North Carolina, South Carolina, and Georgia, but showed little association with drought variability in Virginia. This "break" in drought climatology roughly along the North Carolina / Virginia border is of interest because the synoptic controls of climate in Virginia are fundamentally similar to those in North Carolina. The role of tropical systems as droughtbusters could explain the disparity in temporal patterns of multi-year droughts between Virginia and the other three states included in this study.

Tropical cyclones rarely make landfall north of North Carolina in the eastern U.S. (Keim & Muller 2007). During the period 1851-2005, the National Oceanic and Atmospheric Administration (NOAA) reported that a total of 281 tropical systems affected the eastern U.S. from Texas to Maine (NOAA 2006). Of those, Virginia was affected by a total of 10 tropical systems (3.56% of the total), North Carolina by 45 (16.01%), South Carolina by 29 (10.32%), and Georgia by 20 (7.12%). In general, the need for warm water reduces the likelihood of tropical cyclones making landfall in the northeastern U.S. Also, upper-level mid-latitude westerlies and the shape of the North Carolina coastline near Cape Hatteras often steer tropical storms eastward over the North Atlantic, further reducing the probability of landfall in the Mid-Atlantic states and New England (Fig. 18). Storms arriving at the U.S. east coast north of the Virginia / North Carolina boundary have been observed, but are rare (NOAA 2006). Additionally, the remnants of storms that make landfall in North Carolina, South Carolina, and/or Georgia may track northward into Virginia, but are often weakened *en route* to the degree that precipitation receipt in Virginia is not comparable to that in the other three states, and may not be sufficient to end embedded droughts from Virginia northward. This may help explain the prolonged droughts associated with the Lost Colony of Roanoke and the early years of the Jamestown settlement. Decadal-scale droughts in Virginia and points northward appear less likely to be ended by tropical systems.

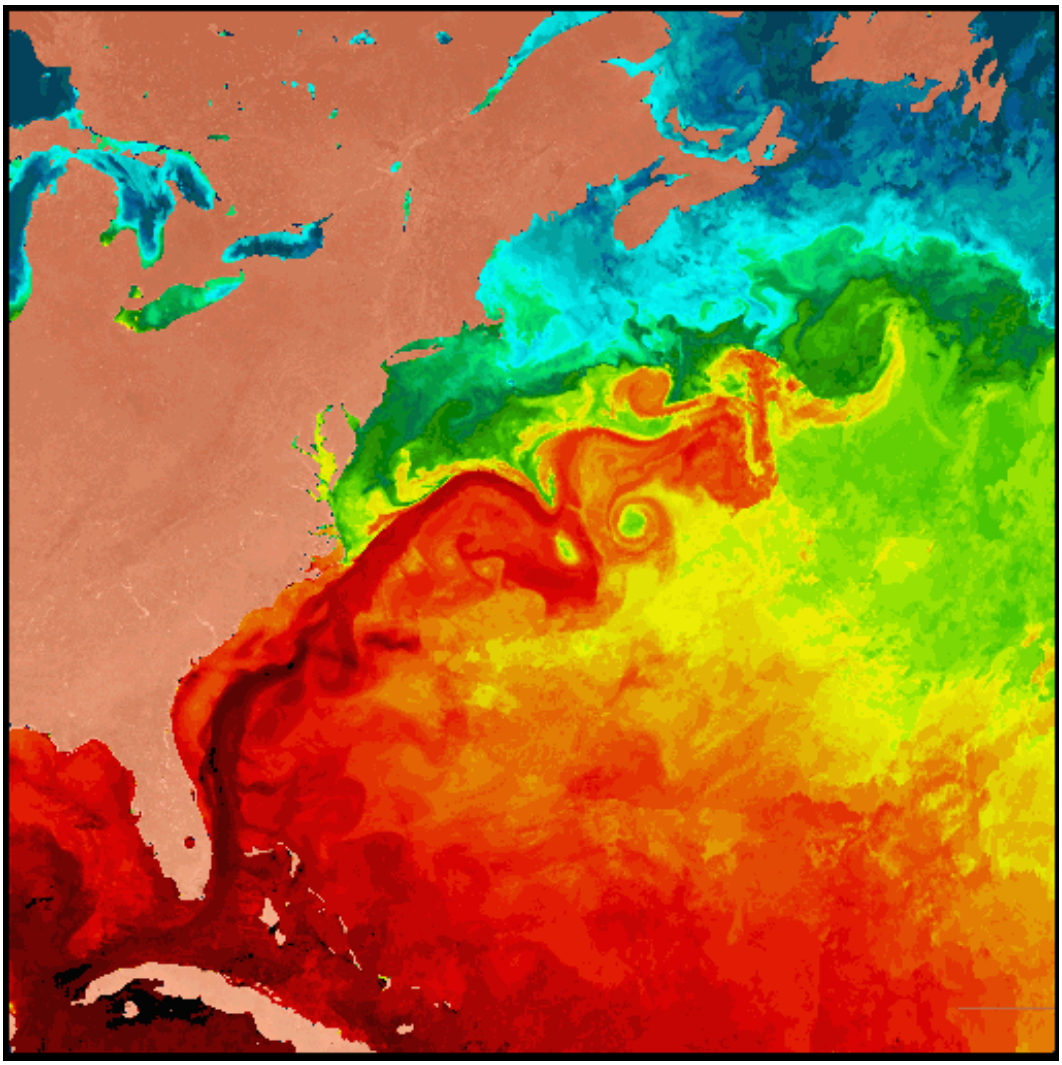

Figure 18. Satellite infrared image of sea-surface temperatures in the western Atlantic Ocean. The warm (red) Gulf Stream is deflected eastward near Cape Hatteras, North Carolina. Hurricanes rarely make landfall north of that point. Image retrieved 07/03/2008 from: http://www.k12science.org/curriculum/gulfstream/teachercurrentnow.shtml

CHAPTER VI

CONCLUSIONS

Water resource managers, municipal water suppliers, and the agricultural industries of the southeastern U.S. should acknowledge the recurrence of multi-year summer droughts in the Piedmont of North Carolina, South Carolina, and Georgia during the last three centuries. Severe impacts from droughts in the late-20th century illuminate the potential consequences of longer, more intense events. The recent and ongoing population growth of the southeastern U.S., particularly the Piedmont physiographic province, further emphasizes the need for better drought forecasting and management based on more complete historical climate records for the region.

The drought reconstruction faithfully replicated droughts from the observed record, and overestimated the magnitude of wet conditions. Inclusion of annual atmospheric CO_2 as a predictor in multiple regression models significantly improved the explanatory power of the models. Also, the multi-species regional predictor chronology explained summer drought variability at a level uncommon to tree-ring research. These findings may be valuable to future dendrochronological studies in the Southeast and elsewhere.

This study has contributed a new tree-ring based drought reconstruction for Piedmont and Coastal Plain climate divisions in the southeastern U.S., and has demonstrated that multi-year summer droughts of greater duration and severity than any on record have occurred in the region during the last 300 years. The probability of a multi-year drought

in a decade increased after about 1900, and increased substantially in the period 1950-2007. This shift in drought frequency may be related to documented shifts in other environmental phenomena during the 20th century. The recent drastic increase in the probability of sustained drought in the study area raises serious questions about the ability of the growing population centers in the region to cope with the types of extreme water resource limitations imposed by more frequent severe, multi-year summer droughts. Higher summer temperatures and increased potential evapotranspiration tend to exacerbate drought impacts relative to cooler-season droughts. Thus, increasing drought frequency combined with the documented out of phase relationship between spring and summer moisture conditions (Stahle & Cleaveland 1992), with long-term decreases (increases) in summer (spring) precipitation, may have serious implications for future drought climatology in the study area.

Piedmont and Coastal Plain summer drought climatology also exhibited multi-decadal regime-like behavior between wet periods and dry periods roughly 30 years in length. Interannual variability was high during these regimes, but the smoothed reconstruction confirms their recurrence during the last three centuries. These wet and dry regimes appear strongly related to the AMO index, but are also apparently linked to the behavior of the Bermuda High and to long-term variability in hurricane activity in the western Atlantic. The study area exhibits complex hydroclimatology in which mutli-decadal regimes of drier-than-average summers and multi-year summer droughts are often concurrent with regimes of high hurricane activity and generally wetter-than-average winters. These counteractive teleconnections imply that, unlike most of the the western

half of North America, the southeastern U.S. may have the benefit of a synoptic safety-net from multi-decadal megadroughts. However, it is noteworthy that while the Piedmont rarely experiences 15- or 20-year sustained droughts, the frequency of multi-year (5 – 7) summer droughts has increased substantially during the last 50-100 years.

The consistent relationship between both observed and reconstructed moisture conditions and the AMO implies that the present study may also represent a reliable reconstruction of the AMO itself during the pre-instrumental period 1690-1899. A better understanding of the relationships between conditions in the northern Atlantic and Pacific Oceans, the spatio-temporal variability of Atlantic tropical cyclone activity, and the North Atlantic supbtropical anticyclone should improve long-term forecasting of drought in the study area. Additionally, future research is needed on the proportional roles of MLC activity and tropical precipitation in "busting" sustained droughts in the Piedmont. Changes in winter precipitation patterns and/or changes in Atlantic tropical cyclone frequency, intensity, and storm tracks may result in a shift in overall drought climatology in the southeastern U.S. Such a shift would further emphasize the water resource limitations implied by the long-term trend of increasing summer drought in the Piedmont.

The distinction in warm-season drought climatology between Virginia and the other three states in the study area deserves more attention. The role of tropical cyclones in southeastern hydroclimatology may partially explain the discontinuity, as tropical systems rarely make landfall on the Atlantic coast north of North Carolina. Also, tropical cyclones tracking from the south into Virginia and points northward are usually

substantially weakened in the process. However, more information is needed regarding seasonal synoptic climatology that might help account for the lack of correlation between summer drought conditions in Virginia and North Carolina, South Carolina, and Georgia.

Results from this study are useful for planning purposes and for agricultural industries, as well as those involved in tree-ring research in the Southeast. The synthesis of the literature regarding synoptic causes of drought in the southeastern U.S. included in this study may contribute to future research on the complex interactions between teleconnective features and climatology in the region. Further paleoclimatic data analyses and testing will be needed to verify the specific patterns identified in this study, and to better inform long-term drought forecasting.

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APPENDIX A

Definitions: Urban Clusters and Urbanized Areas (U.S. Census Bureau 2000)

Urban Cluster (UC) – A densely settled area that has a census population of 2,500 to 49,999. A UC generall consists of a geographic core of block groups or blocks that have a population density of at least 1,000 people per square mile, and adjacent block groups and blocks with at least 500 people per square mile. A UC consists of all or part of one or more incorporated places and/or census designated places; such a place(s) together with adjacent territory; or territory outside of any place.

Urbanized Area (UA) – A densely settled area that has a census population of at least 50,000. A UA generally consists of a geographic core of block groups or blocks that have a population density of at least 1,000 people per square mile, and adjacent block groups and blocks with at least 500 people per square mile. A UA consists of all or part of one or more incorporated places and/or census designated places, and may include additional territory outside of any place.

APPENDIX B

Model Calibration and Verification

Model Calibration: 1943-1984

Climate Division	**Linear Regression Model**	
NC 3	D* = (G* - 1.146) / 0.058	$R^2 = .326$, $p < .001$
NC 4	D = (G – 1.137) / 0.073	$R^2 = .435$, $p < .001$
NC 5	D = (G – 1.132) / 0.072	$R^2 = .473$, $p < .001$
NC 6	D = (G – 1.127) / 0.067	$R^2 = .415$, $p < .001$
SC 3	D = (G – 1.15) / 0.064	$R^2 = .494$, $p < .001$
SC 4	D = (G – 1.128) / 0.058	$R^2 = .416$, $p < .001$
SC 5	D = (G – 1.147) / 0.052	$R^2 = .372$, $p < .001$
SC 6	D = (G – 1.14) / 0.051	$R^2 = .400$, $p < .001$
SC 7	D = (G – 1.132) / 0.058	$R^2 = .451$, $p < .001$
GA 4	D = (G – 1.135) / 0.069	$R^2 = .468$, $p < .001$
GA 5	D = (G – 1.139) / 0.067	$R^2 = .553$, $p < .001$
GA 6	D = (G – 1.14) / 0.052	$R^2 = .350$, $p < .001$

*** D is summer (June-August) average PMDI; G is the annual growth index value of the PC4 composite chronology.**

Model Verification: 1900-1942

Climate Division	**Pearson (two-tailed) correlation coefficient (r) between reconstructed and observed PMDI***
NC 3	0.674
NC 4	0.72
NC 5	0.762
NC 6	0.706
SC 3	0.759
SC 4	0.722
SC 5	0.805
SC 6	0.705
SC 7	0.724
GA 4	0.669
GA 5	0.719
GA 6	0.78

*** All correlations significant at p < .001.**

Final Model Calibration: 1900-1984 (common period) including atmospheric CO_2

Climate Division	**Multivariate Linear Regression Model^**	
NC 3	D* = (G* - 0.069 – (0.003)C*) / 0.071	r^2 = .431, p = .013
NC 4	D = (G + 0.149 – (0.004)C) / 0.079	r^2 = .538, p = .001
NC 5	D = (G – 0.12 – (0.003)C) / 0.082	r^2 = .602, p = .005
NC 6	D = (G – 0.279 – (0.003)C) / 0.073	r^2 = .521, p = .031
SC 3	D = (G – 0.166 – (0.003)C) / 0.078	r^2 = .586, p = .008
SC 4	D = (G – 0.359 – (0.002)C) / 0.071	r^2 = .535, p = .049
SC 5	D = (G – 0.19 – (0.003)C) / 0.073	r^2 = .568, p = .011
SC 6	D = (G – 0.399 – (0.002)C) / 0.065	r^2 = .534, p = .060#
SC 7	D = (G – 0.329 – (0.002)C) / 0.071	r^2 = .543, p = .038
GA 4	D = (G – 0.28 – (0.003)C) / 0.073	r^2 = .558, p = .023
GA 5	D = (G – 0.01 – (0.003)C) / 0.075	r^2 = .604, p = .002
GA 6	D = (G – 0.282 – (0.003)C) / 0.073	r^2 = .576, p = .022

*** D is summer (June-August) average PMDI; G is the annual growth index value of the PC4 composite chronology; C is the annual value (in ppm) of atmospheric CO_2.**

^ In all models, the PC4 composite growth index was significant at p < .001; the p values listed are for CO_2.

 # The SC 6 regression model was not a candidate to be the master regional reconstruction.