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DENDROCLIMATIC ANALYSIS OF CLIMATE OSCILLATIONS FOR THE SOUTHEASTERN UNITED STATES FROM TREE-RING NETWORK DATA

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To the Graduate Council:

I am submitting herewith a thesis written by Yanan Li entitled "DENDROCLIMATIC ANALYSIS OF CLIMATE OSCILLATIONS FOR THE SOUTHEASTERN UNITED STATES FROM TREE-RING NETWORK DATA." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Henri D. Grissino-Mayer, Major Professor

We have read this thesis and recommend its acceptance:

Sally P. Horn, Carol P. Harden

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Thesis Presented
for the Master of Science Degree
The University of Tennessee, Knoxville

Yanan Li

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ABSTRACT

Dendroclimatological research along a geographical gradient is important to understanding both spatial and temporal characteristics of climate influences on tree growth. In this study, three tree-ring width chronologies, obtained from field collection and previous research, were used to represent tree growth along a longitudinal transect from coast to inland in the southeastern U.S: Hope Mills, located at the Atlantic Coastal Plain; Linville Mountain, located on the eastern side of the Appalachian Mountains; and Gold Mine Trail, located on the western side of the Appalachians. The variations of ring width indices in chronologies reflect extreme climatic events such as severe droughts or cold periods. Correlation and response function analyses were used to examine the climate-tree growth relationship at three sites. The temporal stationarity of climate signals was tested using moving interval analysis in DENDROCLIM2002.

Winter temperature was the limiting climate factor for the western mountain site, while moisture was more important for tree growth in the eastern mountain and coastal area sites. However, all significant climate signals found in the trees were not stable over time. The tendency of a shift from precipitation signal to temperature signal is notable around the mid-20th century. Winter North Atlantic Oscillation (NAO) had positive correlations with radial growth at the two mountain sites, which might explain the winter temperature response by trees. The Atlantic Multidecadal Oscillation (AMO) showed an annual feature of associations with growth, and the multidecadal duration of significant correlations was also apparent. The Pacific-related Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO) also tended to influence tree growth. Along the coastal-inland transect,

gradient features of climate oscillation signals did exist. Relationships changed with phase changes of the oscillations. Land-sea boundaries and high mountains may determine the climate response patterns in the Southeast. Other factors such as microenvironment, human disturbance, and biological reaction of trees to climate change also have influence. It is not reliable to use the composite chronology to study the effect of climate oscillations for the Southeast region. In the future, a large number of sample sites will be necessary to more extensively study the regional climate-tree growth relationship.

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CHAPTER 1

INTRODUCTION

1.1 Background

Climate change at any time scale results in feedbacks among the oceans, atmosphere, cyrosphere, and biosphere. Elements existing in these systems of the Earth, such as air masses, vegetation, and human, respond to or further trigger climate change over time with numerous interactions among themselves (Alverson *et al.* 2003). One of the manifestations of global climate change is the strong fluctuation of oceanic-atmospheric oscillations over large spatial scales, discovered in recent centuries. Impacts from either local climate variation or such large-scale climate oscillations can be imprinted on ecosystems. To understand long-term effects of climate change both in the past and in the future, it is necessary first to go beyond the time limit of instrumental records of climate. Exploration of the past is the key to understanding the future. Functioning as a linkage between the climate system and biosystem, environmental proxies are valuable for long-term and broad spatial scale studies of paleoclimate. Proxies of the past climate are natural archives that have, in some way, incorporated strong climatic information into their structure, such as coral, lake sediment, and tree rings (Bradley 1999).

Tree rings are an exceptionally valuable proxy for paleoenvironmental study because they provide continuous records with annual to seasonal resolution (Fritts 1976). Sources of tree rings for climate analysis vary, including living trees, historical structures or cabins, or even dead trees such as stumps, logs, and snags. Trees periodically start growth with photosynthesis during the growing season and shut down the mechanism whenever the environment is harsh enough to close its growth. The temperate climate causes annual formation of tree rings, which is the basis for tree-ring studies. Tree-ring variability, in terms of width, density, or other properties, is an essential anatomical characteristic of trees. It provides the possibility for absolute dating of each ring, and the variation found in tree-ring patterns records climate variation. The association between climate and tree-ring growth can be expressed and measured quantitatively. For example, dendrochronological studies revealed that up to 70% of the variance in indices of treeline ring-width variation is related to summer temperature changes (LaMarche *et al.* 1974, Hughes *et al.* 1987, Briffa *et al.* 1990, Jacoby *et al.* 2000, Briffa *et al.* 2008). However, unexpected or multiple environmental information could also be included in tree growth trends, such as competition, frost, insect outbreaks, landslides, and volcanic eruptions (Banks 1991).

Under most circumstances, tree growth is a function of climate variables such as temperature and precipitation. When it comes to long-term warming or cooling trends and low-frequency climate oscillations, tree rings may be a particularly good source. Because high-quality instrumental climate records are limited to less than 200 years, tree-ring chronologies extended back hundreds to thousands of years have distinct advantages. Reconstruction of climate over centennial to millennial time scales becomes possible with proxy data. The climatic variables most commonly reconstructed with tree-ring records are temperature, precipitation, Palmer Drought Severity Index (PDSI), sea surface temperature, El Nino/Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (PDO) (Stahle and Cleaveland 1992, Grissino-Mayer 1996, Stahle *et al.* 1998, Biondi *et al.* 2001, Bard 2002, Cook *et al.* 2004). Long-term climate reconstructed for the past is typically helpful to understanding the dynamics of climatic circulations. The reconstruction of spring rainfall for the past 1000 years from bald cypress (*Taxodium distichum* (L.) Rich.) by Stahle and Cleaveland (1992) showed its association with a large-scale circulatory control of the North Atlantic subtropical high pressure. The millennia-long tree-ring chronologies from samples collected in undisturbed forests in North Carolina, South Carolina, and Georgia were most responsive to spring and early summer rainfall (Stahle and Cleaveland 1992). The reconstruction illustrated a high interannual variability as well as decadal or multidecadal fluctuations of spring drought and wetness, and such phenomena may be caused by the change of the average position of the Bermuda High during the spring. Stahle and Cleaveland found that the western periphery of the Bermuda High moved westward into the southeastern U.S. during dry springs, but was located well offshore during wet springs.

Tree-ring networks use tree-ring data within a geographical range to study spatial characteristics of climate responses by trees or large-scale (regional, continental, or global) climate variations. For example, Speer *et al.* (2009) used samples from 664 trees in 17 sites broadly distributed in northern Georgia, eastern Tennessee, and western North Carolina to study the climate response of five oak species in the region of the southern Appalachian Mountains. Their results showed that, despite different species, regional chronologies had similar significant correlations with climatic variables including growing-season PDSI, summer and current September temperature, and growing-season and previous August precipitation. Carefully selected long tree-ring chronologies distributed over larger areas (continental or global) can provide a means to study low-frequency climate variability over time. Esper *et al*. (2002) used 1,205 radial tree-ring series from 14 high-elevation and middle-to-high latitude sites in the Northern Hemisphere extratropics to analyze the multicentennial temperature variability over the past 1000 years. The reconstructed temperature showed that the Medieval Warm Period was a large-scale occurrence in the Northern Hemisphere and appeared to have approached the magnitude of 20th-century warming (Esper *et al*. 2002). Previous research using tree-ring networks also revealed that global changes in temperature have large-scale spatial coherence, while precipitation changes are more local or regional, but often reflect circulation changes (Alverson *et al.* 2003).

1.2 Climate Change Studies from Tree-ring Data

Dendrochronology, the study of tree rings, is the highly specialized science of assigning calendar dates to the growth rings of trees (Stokes and Smiley 1996). Developed by A.E. Douglass in the early 20th century, this discipline uses terrestrial, long-term, tree-ring proxy data, and was initially used for finding evidence of sunspot cycles. Later, it opened up a broad array of applications in climatology, forest ecology, geomorphology, and archaeology (Nash 1999).

Although the issue of climate change has only been highlighted in recent decades, dendroclimatology, which studies the climate-tree growth relationship and past climate change using tree-ring data, has been widely and successfully applied. Dendroclimatic analysis is built upon related principles and assumptions and explores how trees respond to climate changes (Cook 1997). In general, a wide ring indicates that the year's climate was moist and cool, while a narrow ring indicates that it was dry and warm. A ring-width chronology contains the common characteristics of rings' variation from sufficient samples, and it may reflect climate change for that particular region. For example, Fritts (1965) statistically evaluated the relationships between climatic factors and fluctuations abstracted from dated tree-ring widths in locations in semiarid western North America. Multiple correlation results showed that ring-width variation was generally more related to precipitation than temperature, but that the two factors together strengthened the results markedly in the western U.S. (Fritts 1965).

The spatial consistency of climate patterns or extremes can be examined by investigating sensitive tree-ring patterns at different locations. Similar ring variations may occur over large geographic regions, but growth patterns in different locations may also reflect local environmental conditions. Fritts (1965) found that trees from low elevations or the lower forest border were controlled largely by moisture during the autumn, winter, and spring, while trees in high elevation or arid sites may be more influenced by precipitation during spring, summer, and autumn. And he concluded that the limiting factors for trees vary among different ecotones.

Fritts *et al.* (1965) then introduced the idea of investigating tree growth along ecological gradients, which was further studied by LaMarche (1974a, 1974b), Norton (1983), Kienast (1987), and additional researchers. Effects of climate on tree growth along an altitudinal gradient have been studied worldwide. It is commonly found that the upper forest limit is controlled primarily by air temperatures, whereas the lower forest limit is controlled primarily by precipitation (Fritts *et al.* 1965, LaMarche 1974a, Fritts 1976, Kienast *et al.* 1987, Block and Treter 2001, Wang *et al.* 2005). Focusing on a geographical gradient in the region of northern Arizona, Fritts *et al.* (1965) observed different strengths of the climate-tree growth relationship along the gradient. Samples of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson var. *scopulorum* Engelm.), and pinyon pine (*Pinus edulis* Engelm.) were collected along a gradient ranging from forest interior to semiarid lower forest border. The results showed that tree rings from three chronologies near the lower forest borders had low mean ring-width, a high percentage of locally absent rings, and the highest year-to-year width variation compared to rings from interior stands. Multiple correlation and correlation analyses revealed that the limiting power of winter and spring precipitation on trees increased from the forest interior to the lower forest border sites. Fritts *et al.* also graphically depicted such tree-ring characteristics in association with site differences along a vegetational and precipitation gradient (Figure 1). In addition, Fritts *et al.* suggested the importance of site selection in producing reliable tree-ring records of climatic fluctuations. In northern Arizona, the best chronologies are from marginal semiarid sites near the lower forest border. But, the quality of tree-ring chronologies can also be affected by different species, different regions, and other factors.

Since then, investigating tree growth along geographical gradients has been well applied around the world, including in the southeastern U.S. Kienast *et al.* (1987) analyzed the relationship between climate and maximum latewood density and total ring width of conifer species along altitudinal gradients in the Rhone Valley and Jura of Switzerland, Troodos Mountain of Cyprus, and the Front Range of Colorado. Response to summer temperature was significant at upper treelines and showed an altitudinal gradient trend which traded-off with the precipitation signal as elevation decreased. In the southeastern U.S, Jacobi and Tainter (1988) studied the effect of climate on radial growth of white oak along a gradient from xeric upland flats and upper slopes to mesic lower slopes in the South Carolina Piedmont. In general, the more xeric the community type, the greater the mean sensitivity and the interseries correlation, as well as the lower the first-order autocorrelation. They also statistically tested the difference in the length of the recovery period after drought events along the gradient. The hypothesis was rejected and no significant difference existed (Jacobi

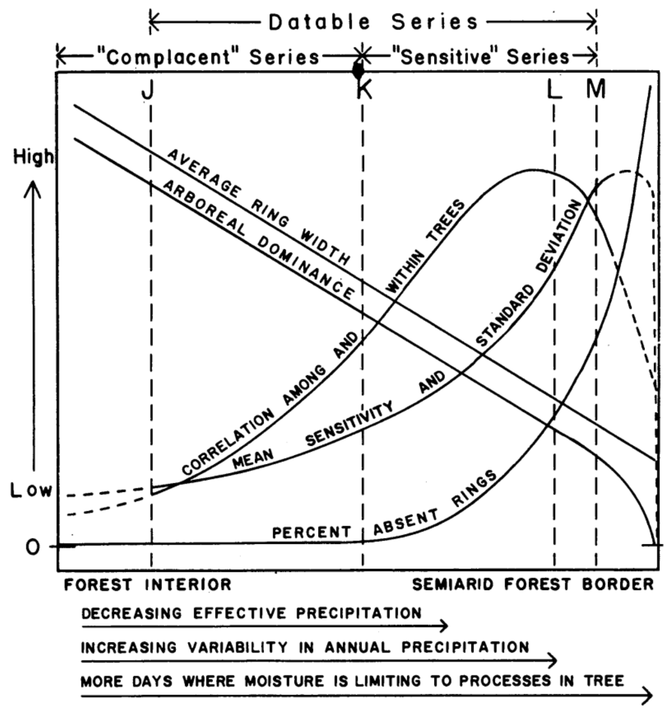

Figure 1. Diagram of changes in tree-ring characteristics along a transect from the forest interior to the semiarid forest border (Fritts *et al.* 1965).

and Tainer 1988). In agreement with previous studies, Wilson and Hopfmueller (2001) also found that the low elevation chronologies had a stronger response to precipitation than higher sites at the Bavarian Forest in Germany. They suggested that ring patterns obtained from low sites could not be used to date tree rings from high sites.

However, gradient characteristics of climate-tree growth relationship were not always apparent or easily tested. Even if all sites are geographically located in a gradient, other environmental factors may be greatly influential on a local scale. For example, in northern Fennoscandia, a west-to-east sampling area was chosen to examine the spatiotemporal variability in tree-ring chronologies. From the Atlantic coast to the Scandes interior side, no clear gradient features of the climate-tree growth relationship was observed (Macias *et al*.

2004). But a principal component that represented the west and east separation along the gradient of the Scandes showed a strengthening oceanic-continental climatic gradient in the analysis period of 1961–1991 (Macias *et al*. 2004). The Scandes Mountains played an important role in this tree-ring network to determine the climate response pattern of trees.

Examining temporal characteristics can improve the formulation of hypotheses on the effects of climate change on tree growth over time (Mäkinen 2002). Climatic shifts over time can be deciphered from tree-growth responses. Hofgaard *et al*. (1999) identified a shift around 1875, which was abrupt and characterized by a turbulent climatic period. Tree-ring data from black spruce (*Picea mariana* (Mill.) BSP) and jack pine (*Pinus baksiana* Lamb.) along a latitudinal transect in eastern Canada were used to examine spatial and temporal tree-growth responses to climate change. The researchers noticed that a long and gradual climatic gradient shifted to a short gradient with clear segregation between the southern and northern parts of the transect around 1875, and they discussed that this observed pattern was likely related to a large-scale shift in the mean position of the Arctic Front that occurred at the end of the 1800s (Hofgaard *et al*. 1999). The position of the arctic air mass changed gradually during their study period of 1825–1993, and the growth of the forests was controlled by accordingly different climates. During the Little Ice Age, cold and dry climate primarily affected the forests due to the arctic air's mean position south of 48°N; around 1875, the gradient was in a transition zone between dry arctic air and moist air of southern origin; during the mid-20th century, moist and warm air masses dominated the gradient because the mean position of the arctic air moved to north of 50°N (Hofgaard *et al*. 1999).

Many temperature reconstructions have revealed characteristics of climate variability for the last millennium, which, in general, include a long-term cooling trend from A.D. 1000 to 1900 and a marked warming trend in the 20th century, with short-term and multidecadal fluctuations superimposed over time (Mann *et al*. 1999, Briffa 2000, Jones *et al*. 2001, Alverson *et al.* 2003). However, the response of trees to climate variations is not always consistent among studies, and sometimes it challenges widely accepted ideas. Briffa *et al.* (1990) reconstructed the mean summer (April-August) temperature of northern Fennoscandia since A.D. 500 using tree-ring width and density data, but their results challenged the existence of two widely established climatic periods, the Medieval Warm Epoch (A.D. 1000–1300) and the Little Ice Age (A.D. 1550–1850). Absence or offset of these two major climate excursions demonstrated that climate information abstracted from tree growth might not agree with common climatic features, but in another way, it probably can help to reexamine the popular ideas on climate history.

To study climate change, it is necessary to understand more than just temperature changes. The behavior of other internal factors in the climate system, such as oceanic-atmospheric oscillations, can trigger significant responses in trees as well (Mann and Park 1996). In recent decades, dendroclimatological research has began focusing on the climatic information about major modes of general circulation dynamics linked to the North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), and El Niño-Southern Oscillation (Cook *et al.* 1998, Briffa 2000, D'Arrigo *et al.* 2001). Such large-scale climate oscillations and their revelations in dendroclimatic analyses will be addressed in the next chapter.

1.3 Research Questions and Objectives

Over the past few decades, many studies have investigated climatic oscillations shown in tree-ring records (Viau *et al*. 2002, Li *et al*. 2007). Such dendroclimatic studies on large spatial and temporal scales are promising in the southeastern United States (Hawley 1938, Stahle and Cleaveland 1992). Dynamics of climatic fluctuation patterns primarily regulate temperature, precipitation, and natural disturbances on vegetation in this region; thus, regional tree growth can be expected to respond both to fundamental climatic variables and to large-scale climate oscillations. My research examined the gradient characteristics of climate-tree growth relationship along a longitudinal transect across the southeastern U.S.

The United States Environmental Protection Agency (U.S. EPA) (Omernik 1987) delineated the mid-Atlantic and the southeast as five ecoregions: Middle Atlantic Coastal Plain, Southeastern Plains, Piedmont, Northern Piedmont, and Blue Ridge Mountain (Figure 2; Griffith *et al.* 2003). This classification depicted a gradient of geography and landscape mosaic types from the Atlantic Coast to the highest elevations in the eastern United States. A common characteristic of these five ecoregions is the temperate climate and the dominance of mixed deciduous/coniferous forests (Loveland *et al.* 2002, Griffith *et al.* 2003). My study area concentrates on a longitudinal transect, which crosses through the Coastal Plain in North Carolina into the western Great Smoky Mountains, and lies across four of the ecoregions, except for the North Piedmont. The landscape can greatly influence tree growth and create local and regional differences in climate. In other words, climatic controls in trees may respond differently to ecosystem processes that operate in the more diverse landscapes of the southeastern U.S. Therefore, it is important to consider the effects of topographic and ecological influences on vegetation (Mermoz *et al*. 2005).

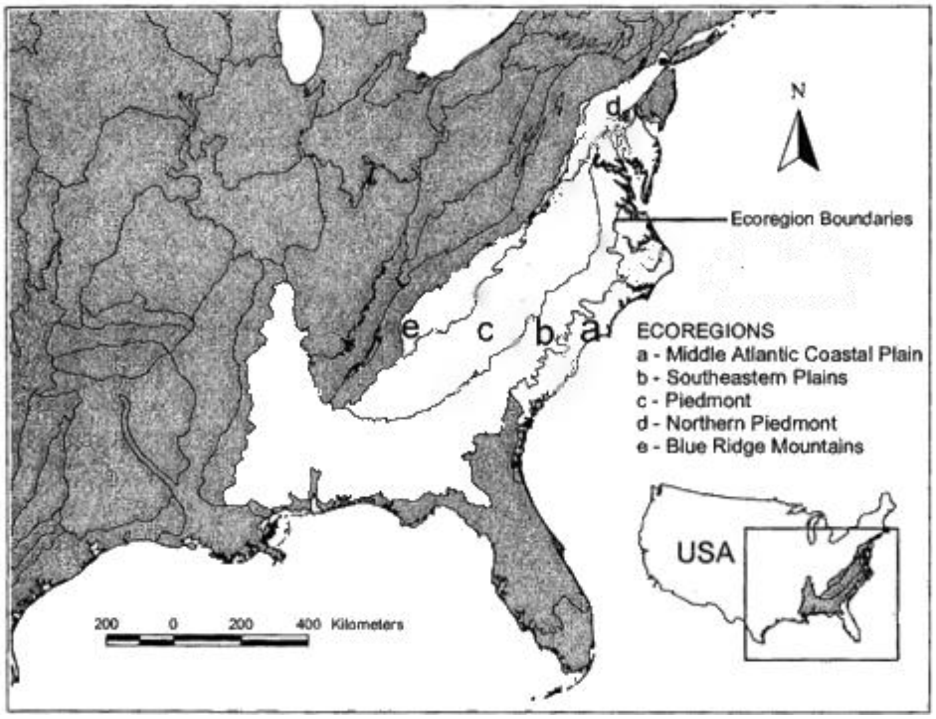

Figure 2. The five ecoregions in the mid-Atlantic and southeastern United States, delineated by U.S. EPA (Omernik 1987).

Air circulations that mainly affect the study region move from the subtropical ocean areas, including the Gulf of Mexico and west-central Atlantic Ocean, upward and westward into the southeastern United States with high moisture and heat. Trees that grow in this area were thought to form closed canopies and not to have a high sensitivity to climatic factors. However, as air masses move from the ocean to the land, the strength and effects of these oceanic-atmospheric circulations may decrease along the way from coast to interior. In addition, the southern Appalachian Mountains may block the air masses. The effects of climate forcing factors on tree growth may vary depending on the distance from the ocean and the tree location. Accordingly, the major questions for this study are whether a difference exists among climate influences on trees between various sites from coastal plain to inland mountains, and, if so, does the climatic variable(s) have a gradient characteristic of climate responses along the transect?

Research questions addressed the spatial variations in the relationship between climate and tree growth. Temporal characteristics of the responses are also of importance to understanding the impacts of climate change on temperate forests. The three main objectives of this research are:

1) Characterize the response of a network of tree-ring chronologies in the southeastern U.S. to past climate, especially to some large-scale oceanic-atmospheric oscillations, such as the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO);

2) Examine the gradient change of climatic factors from the coastal to inland locations in the Southeast, and discuss possible reasons;

3) Examine temporal changes of the climate-tree growth relationship, and conduct a preliminarily test of the possibility of reconstructing some climate variable for the region.

1.4 Justification

Vegetation in the southeastern United States consists mainly of closed canopy forests, which have been mostly avoided for dendroclimatic reconstructions because competition for light and episodic disturbances may affect tree growth and mask tree response to climatic variations (Fritts 1976, Speer *et al.* 2009). In recent decades, several dendroclimatic analyses have been conducted in the southeastern United States and have successfully demonstrated the potential for using southeastern tree species to investigate past climate (Tryon and True

1958, Lanasa 1971, Schwegler 1983, Stahle and Cleaveland 1992, Pan *et al.* 1997, Speer *et al.* 2009). For example, in the 1980s, reduction in radial growth of southern pines in the Piedmont region of the southeastern United States was documented in several studies (Sheffield *et al.* 1985, Sheffield and Cost 1987), and Zahner *et al.* (1989) investigated and explained possible reasons for the growth decline using dendrochronological techniques. Undisturbed even-aged loblolly pines from the Piedmont region of Georgia, South Carolina, and North Carolina were selected to build a short chronology, spanning 1949–1984. Using simulation models, Zahner *et al.* (1989) analyzed the annual variation and the multiple-year, lagged cumulative effect of climate on trees. They found that the significant decline in radial growth was primarily associated with changes in stand density, distinct climatic intervals, and the passage of time. Furthermore, Speer *et al*. (2009) compared the strength and clarity of climate response among five oak species in the southern Appalachian Mountains. Chronology statistics showed the site-species chronologies had an average interseries correlation of 0.56 and average mean sensitivity of 0.20, while the regional-species chronologies had values of 0.43 and 0.19, respectively. Their research provides evidence that hardwood species are a valuable resource for dendrochronological studies in the Southeast. However, it is still insufficient for our understanding of the climatic response by trees in the region. A much better understanding is needed on how ring width variations can be used to make inferences of past climate in this particular region, especially across a large spatial scale.

Impacts of environmental factors are known to gradually change across altitudinal, latitudinal, or longitudinal gradients. Effects of changing climate cause different responses by trees along these gradients. Studying a network of tree-ring chronologies is a useful method in dendroclimatology to reveal environmental gradient features. Many studies have shown the validity of examining different climatic responses or shifts of dominant limiting factors along environmental transects (Fritts *et al*. 1965, Hopfmueller 2001, Mäkinen *et al*. 2002, Helama *et al*. 2005, Wilson and Filippo *et al.* 2007). However, little research has examined responses to climatic variables in tree-ring records across a coastal-inland gradient. This thesis examined a small network of tree-ring data from the Coastal Plain to the interior montane area, and discussed related influences of biotic and abiotic components.

Besides the impacts of oceanic-atmospheric oscillation, other abiotic factors also play an important role in tree growth. Compared to the highly studied Southwest of the U.S, the situation for the Southeast is more complex because of the many variables to which the trees are possibly responding, such as topography, microenvironment, and various natural and human disturbances. Also, I was curious about whether temperature or precipitation signals were related to variations of climate oscillations, and whether temporal shifts of climatic variables reflected by tree growth would coincide with the phase change of climate oscillations. All facts and considerations above indicated that the dendroclimatic analysis for the southeastern U.S. was worthy, and the spatial variation of climate responses by trees along a coastal-inland transect was interesting to study.

CHAPTER 2

CLIMATE PATTERNS THAT MAY AFFECT THE SOUTHEASTERN U.S.

2.1 North Atlantic Oscillation (NAO)

The North Atlantic Oscillation is a large-scale fluctuation in atmospheric mass that was discovered by Gilbert Walker in the 1920s (Rogers 1984). The NAO index was originally and simply designated as the pressure difference between the Azores High and Icelandic Low (Walker 1924, Walker and Bliss 1932). Currently, the NAO index is calculated from the normalized sea level pressure (SLP) difference between the Azores region and Icelandic region for the 4-month winter (December–March) season (Hurrell 1995). Therefore, the NAO is an important indicator of climate variability between the subtropical high and the polar low, especially during wintertime in the Northern Hemisphere.

The NAO can be measured and classified into two phases, positive and negative, each with an inconsistent duration. The NAO was studied as a 1.7–7.5 year climate teleconnection (Walker 1924, Lamb and Peppler 1987). However, the existence of 7-year, 25-year, 70-year, and other spectral peaks was noted in later studies (Rogers 1984, Cook *et al.* 1998, Cook *et al.* 2002). Cook *et al.* (2002) pointed out that the NAO during the twentieth century has been anomalously strong, with persistent periods of positive and negative phases, while no such features were found prior to 1900. They suggested that the frequency variability of the NAO was associated with the relative length of climate record being studied compared with the NAO series.

Dynamics of the NAO influence air temperature, circulation of winds, ocean currents, and precipitation patterns over the region in the North Atlantic. According to the dynamics of the high and low pressures, the influence of NAO ranges from central North America to Europe in the North Atlantic region. During positive phases of the NAO (positive values of the NAO index), the pressure gradient from subtropical high to polar low in autumn and winter is accentuated. The positive phase is caused by stronger-than-average westerlies over middle latitudes associated with low pressure anomalies over the region of the Icelandic low, and high pressure anomalies across the subtropical Atlantic. This large difference of pressure between the Azores and Iceland brings more frequent and stronger winter storms crossing the Atlantic on a more northerly track (Hurrell and van Loon 1997). Positive phases of the NAO are associated with nearly all of the cooling trend in the northwest Atlantic and the warm, wet winters across Europe and downstream over Eurasia (van Loon and Rogers 1978, Hurrell 1996, Hurrell and van Loon 1997). The eastern U.S., including the southern Appalachians, experiences mild and wet winter conditions. Conversely, during the negative phases of NAO, the pressure difference between the two pressure areas is weakened, and the NAO brings fewer and weaker storms on a more southerly track. It causes extreme cold winters in northern Europe, and moist mild winters in the Mediterranean and northern Canada. In the eastern U.S., negative NAO phases bring more cold air and snowy weather conditions (Rogers and van Loon 1979, Hurrell and van Loon 1997).

Researchers have found that the NAO is recorded by tree rings (Cook *et al.* 1998, Touchan *et al.* 2003, Linderholm *et al.* 2003). For example, correlation analyses between northern Fennoscandia chronologies and monthly NAO indices revealed that positive NAO at the previous early winter enhanced radial growth, while negative NAO at the spring limited the growth (Macias *et al*. 2004). However, few studies focused on the relationship between NAO and tree growth in the southeastern U.S. Surprisingly, Grissino-Mayer *et al.*

(2007) found a NAO signal in a shortleaf pine chronology from Great Smoky Mountains National Park (GSMNP), Tennessee. A significant positive relationship between tree growth and NAO was also found at some locations in GSMNP (Biermann 2009). As a driver of winter climate for the southeastern U.S, the effects of the NAO in this region need more research.

2.2 Atlantic Multidecadal Oscillation (AMO)

The Atlantic Multidecadal Oscillation refers to the oscillatory patterns of sea surface temperature (SST) variability between the equator and Greenland in the North Atlantic. Distinguished from the NAO, the AMO is a longer time-scale oceanic phenomenon with duration of 65 to 80 years (Enfield *et al.* 2001). Although the concept of the AMO was created in recent decades, the AMO behavior has been noticed for half a century, based on the anomalies of North Atlantic instrumental SST records during the past 150 years (Kerr 2000). More recently, researchers examined both modeled and observed sea surface temperature anomalies (SSTAs) and successfully identified 65–70/80 year cycles in the region, referred to as the AMO (Schlesinger and Ramankutty 1994, Andronova and Schlesinger 2000, Delworth and Mann 2000, Dima and Lohmann 2007).

Over the previous 150 years, climate swings of the AMO have completed several cycles, and each cycle lasted roughly 50 years longer or shorter. The AMO index can be expressed by the 10-year running mean of detrended Atlantic SSTAs north of the equator (0–70°) (Enfield *et al.* 2001). This low-frequency SST variability is characterized by warm and cool phases, having 20–30 year periods for each phase. During the instrumental period (1856–present), it has been widely accepted that warm phases occurred between 1860–1880 and 1930–1960, while cool phases occurred during 1905–1925 and 1960–1990. Since the mid-1990s, the AMO has been staying at a warm phase (Enfield *et al.* 2001, Gray *et al.* 2004). Drought and hurricane occurrences are closely related to the AMO. When the AMO is positive (warm North Atlantic), precipitation becomes lower-than-average over most of the North America, but higher in Florida and the Pacific Northwest. The number of tropical storms is much greater in warm phases than during cool phases, and the Atlantic hurricane activity is several times increased compared with normal years (Goldenberg *et al.* 2001). Warm phases of AMO also bring drier and warmer conditions to the following summer over western Europe (Cassou *et al.* 2005), and at the same time bring enhanced rainfall in the Sahel. In northern Asia, more frequent drought occurs (Kerr 2000, Gray *et al.* 2004). Two of the most severe droughts of the 20th century, the Dust Bowl of the 1930s and the severe drought of the 1950s, occurred over the conterminous United States. These events are mainly attributable to the positive AMO, accompanied by effects of the Pacific Decadal Oscillation (McCabe *et al.* 2004). Conversely, cool phases of the AMO (negative AMO index) correspond with increased precipitation over much of the U.S, and droughts and wildfires are more frequent in central and south Florida and the Pacific Northwest (Enfield *et al.* 2001). Also, hurricanes are fewer, while frequent droughts occur in the Sahel of northern Africa (Gray 1990). In the southeastern U.S., droughts are more frequent during warm phases, while wet and mild conditions appear during cool phases.

The AMO signal has been identified in several proxy records and reconstructed for past centuries (Stocker and Mysak 1992, Delworth and Mann 2000, Lohmann *et al.* 2004, Gray *et al.* 2004). Researchers found that the AMO often operates in relation with other climate oscillations, such as the NAO, PDO, and ENSO. For example, McCabe *et al.* (2004)

concluded that 52% of drought variability in the lower U.S. can be attributed to the AMO and PDO. SSTAs in the North Atlantic have a great influence on drought conditions in the U.S. Tree-ring data have shown major shifts of the AMO during recent centuries (Gray 1990, Enfield *et al.* 2001, Goldenberg *et al.* 2001, Gray *et al.* 2004, McCabe *et al.* 2004), which demonstrates the potential of using predicted AMO to manage future climate change.

2.3 Pacific Decadal Oscillation (PDO)

In the late 1990s, fisheries scientist Steven Hare found that large-scale salmon-production variability was driven by climatic processes in the northeastern Pacific Ocean, and coined the term Pacific Decadal Oscillation (PDO) to name this long-lived pattern of climatic variability (Hare and Francis 1995). Generally speaking, the PDO describes the interdecadal climate variability in the North Pacific, and operates over periodicities of 20–30 years. The PDO index is derived from the leading Principal Component of monthly SSTAs in the North Pacific, poleward of 20 °N (Mantua *et al.* 1997). The behavior of the PDO has been well-studied in recent decades, but the causes for this climate oscillation are still not clear. Although the PDO and the El Niño-Southern Oscillation (ENSO) operate over different temporal scales, both have similar spatial ranges of climate effects, and the PDO can be well modeled by direct forcing of ENSO (Mantua *et al.* 1997, Newman *et al.* 2003). Mantua (1999) summarized climate anomalies of North America associated with extreme phases of the PDO, and stated that, in October–March, southeastern U.S. air temperature would be below average during warm PDOs and above average during cool PDOs. However, by itself, the PDO generally does not have a major influence in the southeastern U.S. Significant climate impacts over the Southeast may happen with a combination with PDO and other oscillations, such as AMO (McCabe *et al.* 2004).

The PDO dominates extratropical regions of the North Pacific, and some evidence also shows its symmetrical impacts over the Southern Hemisphere, including the mid-latitude South Pacific Ocean, Australia, and South America (Mantua and Hare 2002). Wintertime SST, SLP, surface wind stress, and other factors constitute the anomalous pattern during different phases of the PDO. Warm phases of the PDO feature higher mean SSTs over almost the entire tropical Pacific and along the west coast of the Americas, and lower mean SSTs over the remainder of the extratropical Pacific (Zhang *et al.* 1997). During warm PDOs, lower-than-average November-to-March pressure over the North Pacific enhances counterclockwise wind. Over the northern subtropical Pacific, SLP is higher and clockwise winds are enhanced (Mantua and Hare 2002). In the United States, positive PDO phases coincide with wet and cool conditions in the southern tier of states, especially in the southwest. It consequently contributes to the rapid accumulation of plant fuels. A positive PDO also causes dry, warm conditions in the northwest, which directly produces weather conducive to wildfire (Mantua 1999).

During cool phases of the PDO, anomalies of SST, SLP, and wind stress patterns are the opposite of those during warm PDO phases (Mantua and Hare 2002). Cool phases occurred from 1890–1924 and 1947–1976, while warm phases occurred from 1925–1946 and 1977 through the mid-1990s (Hare and Francis 1995, Mantua *et al.* 1997, Minobe 1997, Gedalof and Smith 2001, Knapp *et al.* 2002). Recent observations indicate that the PDO was shifting into a negative mode after the 1990s (Mantua 1999). Reconstructed PDO series for earlier centuries from proxy data are not consistent in identifying warm and cool periods (Biondi *et al.* 2001, Evans *et al.* 2001, Gedalof and Smith 2001).

Tree-ring data have been widely used to extend the sequence of the PDO back in time and describe its variability at decadal timescales (D'Arrigo *et al.* 2001, Pohl *et al.* 2002, Jacoby *et al.* 2004, MacDonald and Case 2005). For example, Biondi *et al.* (2001) reconstructed the PDO index back to A.D. 1661 from tree-ring chronologies from southern California and Baja California and found that the dominant mode of tree-ring variability matches the observed PDO closely.

2.4 El Niño-Southern Oscillation (ENSO)

The El Niño-Southern Oscillation (ENSO) is a climate fluctuation characterized with anomalous SST, SLP, and other related patterns across the tropical Pacific Ocean. This climate phenomenon has been noticed and widely studied since the 1920s (Walker 1924, Walker and Bliss 1932). Differentiated from the long-term PDO, the ENSO occurs every 3 to 7 years (Lough 1992, Green *et al.* 1997). The Southern Oscillation Index (SOI) is used to indicate ENSO phases and is measured by calculating differences in pressure observed between Tahiti and Darwin, Australia. Though the ENSO originates in the Pacific Ocean, it exerts the greatest influence on global climate of all oscillations yet identified (Alexander *et al.* 2002).

The ENSO is composed of two coupled components: El Niño (or La Niña) and the Southern Oscillation. The warming or cooling of the sea surface in the tropical eastern Pacific Ocean affects sea surface pressure in the western Pacific. Under normal conditions of the Pacific Ocean, the Walker circulation around the equator causes easterly trade winds at the sea surface, which transport warm water and air towards the west. Therefore, the warm uplifting air mass in the west produces rainfall, while in the eastern Pacific the descending airflow brings dry and cold weather. Also, the water off of the western coast of the South America is relatively cool compared to the western Pacific near Indonesia and the Philippines (Aguado and Burt 2007).

ENSO has two phases: El Niño and La Niña. El Niño is the warm event, which causes sudden warming of surface waters in the central and eastern Pacific and colder-than-average water in the western Pacific. Also, the direction of the Walker circulation is reversed, and trade winds move from west to east at the surface. Global impacts of the El Niño events include warm and wet winter months along the west coast of the South America, fewer tropical storms during fall west of Japan and Korea (Wu *et al.* 2004), and drier conditions in parts of Southeast Asia and northern Australia. In the United States, El Niño creates warmer-than-average winters in the upper Midwest states and the Northwest, significantly wetter winters in the Southwest, and wetter and cooler winters in the Southeast and the northern Gulf of Mexico (Ropelewski and Halpert 1986). La Niña is the cool phase, during which much higher-than-normal SLP and colder SST appear over the larger area of the eastern Pacific, and warm water is located further west than usual (Philander 1983). La Niña causes mostly the opposite effects of El Niño. For example, coastal regions of South America experience more droughts, and rainfall increases across the Midwest United States and decreases in the South.

Tree rings have been used as a proxy for past climate in areas affected by ENSO (D'Arrigo and Jacoby 1991, Schöngart *et al.* 2004, Wilson *et al.* 2010). Many studies revealed past ENSO events from reconstructions of temperature or precipitation (Diaz *et al.*

2001, Cleaveland *et al.* 2003). However, it has been hard to detect the ENSO signal in the southeastern U.S. because its impact is small in this area (Mo *et al.* 2009). On the other hand, in general, unusually cold temperatures and increased moisture in the Southeast can be partly attributed to El Niño conditions in the tropical Pacific (Goddard *et al.* 2006, Seager *et al.* 2009). Even when an ENSO-related signal was found in the proxy record, some studies revealed that the ENSO response was not consistent over time (Ropelewski and Halpert 1986, Hu and Feng 2001, Wilson *et al.* 2010).

CHAPTER 3

STUDY SITE DESCRIPTION

The response of tree growth to climate can vary depending on the geographical region in which the stand is located. In this study, I examined the gradient of climate response by trees from the coast to inland montane areas by analyzing samples from three sites positioned along a longitudinal transect from eastern North Carolina to eastern Tennessee (Figure 3). The transect spans four of the five ecoregions in the southeastern United States, as classified by the U.S. EPA (Figure 2; Omernik 1987). From east to west these are the Middle Atlantic Coastal Plain, Southeastern Plains, Piedmont, and Blue Ridge Mountains. These four southeastern ecoregions generally have more similarities than differences in terms of geology, climate, and biogeographical features, with the greatest difference existing between the coastal region and the inland mountain region. Two sites used in this research are located in part of the southern Appalachian Mountains within the Blue Ridge region, and the third site is in the Coastal Plain.

3.1 Southern Appalachian Mountains

The southern Appalachians are a part of the Appalachian mountain chain that arose about 300 million years ago by tectonic collisions, becoming the backbone of the eastern United States. Defined by the mountain boundaries, the range of this physical province is clearly delimited. It encompasses over 38 million acres in the mountainous portion of six states, ranging from Virginia to northwest Alabama (Southern Appalachian Forest Coalition 2010). Two national parks and eight national forests are contained in this region. The U.S.

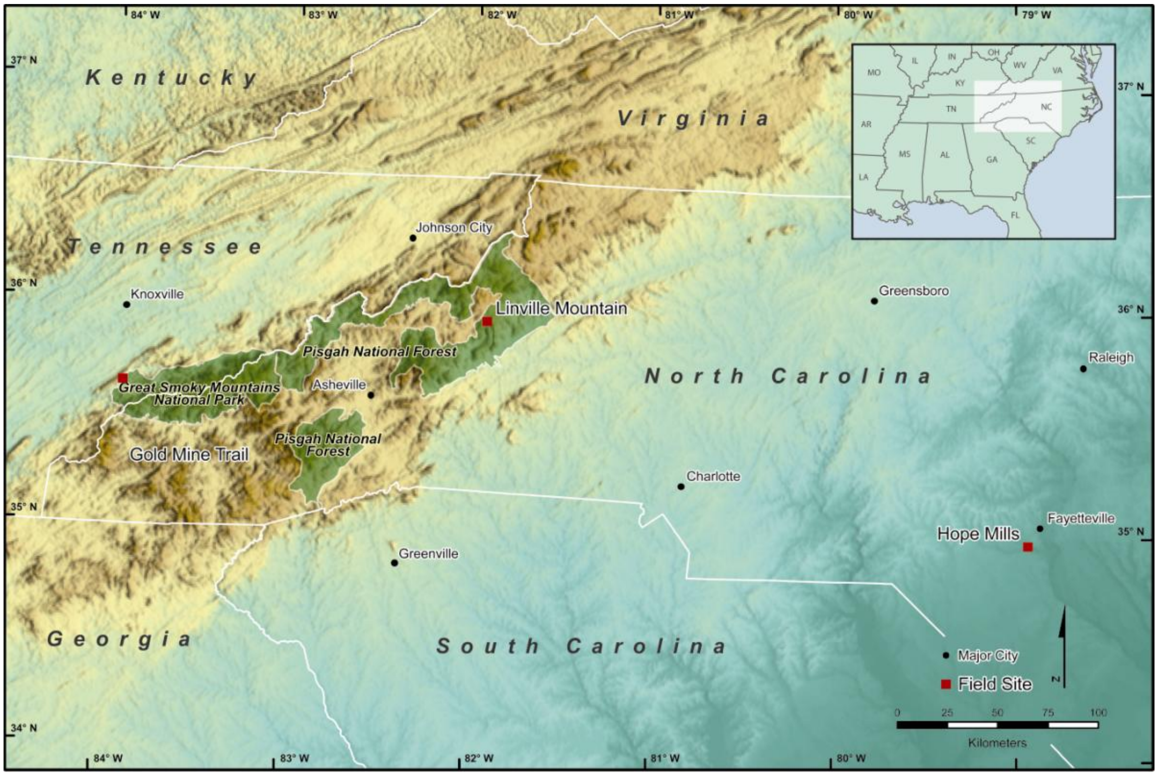

Figure 3. Map of the three sites Hope Mills, Linville Mountain, and Gold Mine Trail in the southeastern U.S. (Map produced by Matthew Kookogey, from the University of Tennessee, Department of Geography Cartographic Services Laboratory.)

Geological Survey defines the Appalachian area as consisting of 13 physiographic provinces, and the southernmost portions of both the Ridge and Valley and Blue Ridge Provinces make up the southern Appalachians (Armbrister 2002). The Ridge and Valley Province is characterized by mountains with long, even ridges and continuous valleys in between. The Blue Ridge Province is bordered on the west by the Ridge and Valley Province and contains the two national parks, the Great Smoky Mountains and Shenandoah National Parks.

Moist winds blow from the Atlantic Ocean and the Gulf of Mexico. Precipitation averages 1,500 to 2,030 mm a year, falling as snow in winter and covering higher elevations; annual mean temperatures fluctuate from 7 to 9.5 ℃ (McCracken *et al.* 1962). Mild climate conditions enhance the great biological diversity and high species richness of the southern

Appalachian Mountains. It is reported that this region might contain more than 20,000 species of plants and animals, with at least 400 to 500 endemic species (SAMAB 1996). The canopy of southern Appalachians forests is composed of deciduous broad-leaved trees and evergreen conifers. Shrubs, grasses, mosses, and liverworts prosper beneath the overstory canopy. Before the introduced chestnut blight, the American chestnut tree (*Castanea dentata* (Marsh.) Borkh.) was dominant. Today, chestnut oak (*Quercus montana* Willd.), northern red oak (*Quercus rubra* L.), red maple (*Acer rubrum* L.), and tulip tree (*Liriodendron tulipifera* L.) have replaced the chestnut as primary deciduous species in these forests (Nelson 1955, Speer *et al.* 2009). The dominant pine (*Pinus* spp.) species include white pine (*Pinus strobus* L.), pitch pine (*Pinus rigida* Mill.), Table Mountain pine (*Pinus pungens* Lamb.), and shortleaf pine (*Pinus echinata* Mill.). Spruce (*Picea* spp.), fir (*Abies* spp.), and hemlock (*Tsuga* spp.) species grow at higher elevations, but the numbers of these species are decreasing from non-native insect outbreaks and shrinking habitat caused by climate change (Hollingsworth and Hain 1991, McLaughlin *et al.* 1998, Wear and Greis 2002).

The mountains were once the home of thousands of Native Americans, of which the largest group was the Cherokee Nation. During the 18th century, Europeans trickled in and drove most of the Cherokees away (Horan 1997). The Appalachian Mountains acted as a barrier to the movement of Europeans westward in the quest for new lands to settle, and also to those searching for gold. Thus, the original forests in this area were highly disturbed by widespread deforestation for land clearing at that time (Abrams *et al*. 1995).

3.1.1 Great Smoky Mountains National Park (GSMNP)

Part of the Blue Ridge Mountains, GSMNP comprises nearly 207,200 hectares that are divided almost equally between eastern Tennessee and western North Carolina (NPS 2010). Since establishment as a national park by the United States Congress in 1934, the GSMNP has been designated an International Biosphere Reserve, World Heritage Site, and State Natural Heritage Area by both Tennessee and North Carolina (NPS 2010). From the period of Native American habitation to today's prosperous times with eight to ten million visitors to the park annually, the human-environment interaction has been changing and developing in many ways. The GSMNP is one of the largest protected land areas in the eastern United States, and is a unique sanctuary for thousands of species.

3.1.1.1 Geology

The topography of GSMNP is predominantly chains of mountains stretching from the northeast to the southwest. The elevation of these mountains ranges from 267 m at the mouth of Abrams Creek in the western part of the park, to 2,025 m at Clingmans Dome, the highest point in Tennessee (NPS 2010). The Great Smoky Mountains are among the oldest mountains on Earth. About 300 million years ago, in the later part of the Paleozoic Era, tectonic movements brought two continents, the original North America and northwest Africa together, forming Pangaea, and the tremendous pressure thrust compressed and uplifted sedimentary rocks into large mountain ranges (King *et al.* 1968). This entire belt of folded and faulted rocks extends over 3,218 km, from what is now Maine to Georgia, and formed the beginning of the Appalachian Mountains (Walker 1991). Wind, rain, freezing, and thawing have since eroded the surface areas and cut once bulky mountains into valleys and ridges.

The Great Smoky Mountains are built of medium grade, metamorphosed sedimentary rocks of Neoproterozoic to early Cambrian age with isolated areas of Mesoproterozoic gneiss (King *et al.* 1968). These bedrock types include resistant, quartz-rich, metamorphosed conglomeratic sandstones, slates, limestones, and dolostones (King 1964, Matmon *et al.* 2003). Most of the rocks are between 450 and 800 million years in age (NPS 2010). Because of the varied topography, different locations may produce different types of soils. For example, Ultisols are developed on valley bottoms and are well-weathered with high moisture content and low fertility. Inceptisols may form on steep slopes with thin and barely distinct soil horizons (Christopherson 2006, Biermann 2009).

3.1.1.2 Climate

The GSMNP has a mean annual temperature of 12.2 ℃, but temperatures can easily vary 5–11 ℃ from mountain base to top. Rainfall averages 1,400 mm per year in the lowlands and 2,160 mm per year at higher elevations (NPS 2010). The precipitation at the base of the mountains is not vastly different from that of the adjacent valley area, but it increases sharply with altitude (Shanks 1954). In Thornthwaite's climate classification system, much of this region belongs to the humid mesothermal climate group, but the higher elevations are classified as a perhumid microthermal climate (Shanks 1954, Barden 1974). Along with the great variation of temperature and precipitation at different aspects and altitudes, seasonal changes of climate in GSMNP have their own patterns and complexity. The arrival of spring can be as early as January or as late as March, when flowers start to bloom. The weather between March and May is unpredictable, and temperatures can be below freezing in March and as high as 26.7 ℃ in mid-April (NPS 2010). July and August normally have the greatest rainfall and thunderstorms, and daily high temperatures can reach higher than 32 ℃. Rainfall in summer months (June–August) averages between 100 and 130 mm in a month, but extreme events can produce as much as 380 mm a month. Summer temperatures have normal daily highs between 25 ℃ and 29 ℃ and daily lows between 11 ℃ and 16 ℃ (NPS 2010). Fall in GSMNP is from September to mid-November. In winter, precipitation falls as snow or rain. Normal daily highs are between 9 ℃ and 16 ℃, and normal daily lows are between –4 ℃ and 1 ℃ (NPS 2010). This variation of seasonal weather conditions through the different elevations of the GSMNP helps maintain for the great diversity of flora and fauna at all times.

Studies have shown that the average annual temperature in the Southeast has increased by about 1.12 ℃ since 1970, with the greatest increase occurring in the winter (Karl *et al.* 2009). Climate change may be influencing the distribution and composition of species. In addition, air quality could be worsened with increasing temperatures.

3.1.1.3 Vegetation

Nearly 95% of the GSMNP is covered by temperate and boreal forests, which serve as a natural habitat for a great diversity of animal and plant species. Approximately 1,600 species of flowering plants, including 100 native trees, and 66 native mammals, 240 species of birds, over 80 species of the herpetofauna, and diverse invertebrates reflect the richness of this park (Walker 1991).

Vegetation changes with changing elevation, rainfall, temperature, geology, slope, and aspect. Deciduous broad-leaved hardwoods, evergreen coniferous forests, grasslands, open meadows, and bare rock cliffs can all be found within GSMNP. The park contains five major distinct forest types: cove hardwood forest, hemlock forest, pine-oak forest, northern hardwood forest, and spruce-fir forest (Keller 2004). The ecozone for the cove hardwood forest is sheltered valleys with deep rich soils (coves). More than 80 tree species can be found within this type, and common species include tulip tree, yellow buckeye (*Aesculus octandra* Marsh.), black cherry (*Prunus serotina* Ehrh.), Carolina silverbell (*Halesia carolina* L.), basswood (*Tilia americana* L.), dogwood (*Cornus florida* L.), and southern magnolia (*Magnolia grandiflora* L.) (Woods and Shanks 1959). The hemlock forest mostly consists of pure eastern hemlock (*Tsuga canadensis* (L.) Carrière). The oak-pine forests replace the cove hardwoods along a gradient from mesic to xeric, and dominate western, exposed, excessively well-drained slopes and ridges where fire regularly occurs. Typical species include red oak, scarlet oak (*Quercus coccinea* Münchh.), black oak (*Quercus velutina* Lam.), and chestnut oak, along with Table Mountain pine, pitch pine, and eastern white pine, with some hickory (*Carya* spp.) (Harrod *et al.* 1998).

With elevation, mixed hardwood forests transition to northern hardwoods between 1,100 and 1,550 m. American beech (*Fagus grandifolia* Ehrh.), yellow birch (*Betula alleghanensis* Britton), and sugar maple (*Acer saccharum* Marsh.) dominate here (Speer *et al.* 2009). At the highest forest range, Fraser fir (*Abies fraseri* (Pursh) Poir.) and red spruce (*Picea rubens* Sarg.) are the two major tree species. This type of forest in GSMNP once flourished in a large area at elevations above 1,370 m, but is threatened by air pollution and warming climate (Wear and Greis 2002). On the driest high slopes in the eastern and western end of the park, heath balds and grassy balds are found that contain *Rhododendron* species, mountain laurel (*Kalmia latifolia* L.), sandmyrtle (*Leiophyllum buxfolium* (Bergius) Elliot), blueberry (*Vaccinium* spp.), and huckleberry (*Gaylussacia* spp.) (Woods and Shanks 1959).

3.1.1.4 Land-use History

Prehistoric Indians were nomadic hunter-gathers with limited consumption of natural resources. The Cherokee Indian nation developed its own advanced culture, including agriculture, politics, transportation, and handicraft industry (Harmon 1982). Although the first Europeans, under the command of Hernando de Soto, came in contact with the Cherokee in 1540, European settlers in large numbers gradually began to move into the region by the mid-18th century (Walker 1991). Most Native Americans were then forcibly relocated to the west, with only a few remaining. Profound effects on nature have occurred since the mid-1800s from heavy forest clearing for pasturing livestock and for lumbering activities. The mountain landscape was devastated over that period until the federal government purchased the land in the early 1900s and the GSMNP was established in 1934 (NPS 2010).

Fire suppression, initiated in the 1930s, was a primary factor leading to degraded pine forests and the dominance of hardwoods in the park. Table Mountain pine and pitch pine, two native species that rely on regular fire occurrence for regeneration, have been drastically declining in numbers (Welch *et al.* 2000, DeWeese 2007). Fire suppression failed to preserve the entire ecosystem under natural conditions, and is being abandoned after decades of use. Furthermore, park managers are now returning fires to the landscape using prescribed burns to clear built-up woody debris and re-invigorate these fire-dependent species (NPS 2010).

3.1.2 The Pisgah National Forest

Pisgah National Forest is located on the eastern side of the southern Appalachian Mountains and is completely contained within the state of North Carolina. The total area of the forest is 207,470 hectares and it is mostly the mountainous terrain of the southern Appalachians (U.S. Forest Service 2010). The Pisgah National Forest was established in 1916 and is administered by the United States Forest Service. Because of its proximity to GSMNP, its geographic characteristics are similar to those of GSMNP.

3.1.2.1 Geology

Pisgah National Forest (Figure 3) is located in the southern range of the Blue Ridge Mountains, which is also the eastern edge of the southern Appalachian Mountains. The forest covers low mountains, and elevation ranges from 300 to 1,800 m. Rugged mountainous topography in this area is evidence of intense physical and chemical weathering of the landscape. Created during the same tectonic event as the Great Smoky Mountains 200–300 million years ago, the Blue Ridge Mountains also have significant elevation differences, characterized by serpentine river flows in valleys and deep gorges, such as the 600-m-deep Linville Gorge. Bedrock in the mountains of western North Carolina mainly consists of sedimentary and metamorphic rocks of the Blue Ridge Belt geological unit (U.S. Geological Survey 1998). The study site, near the Linville Gorge in the Pisgah National Forest, is underlain by the Chilhowee Group (including upper Chilhowee and lower Chilhowee) of early Cambrian age. The lithology includes arenite, siltstone, shale, gneiss, and granitic gneiss (U.S. Geological Survey 1998). Cook *et al*. (1979) determined that, in the region of the Blue Ridge and Inner Piedmont, crystalline thrust sheets overlay extensive sedimentary rocks of the central and southern Appalachians.

Because of its rugged landscape and topographic complexity, the soil of the Pisgah National Forest is not very fertile. Newell and Peet (1998) noted that places above and below highly dissected slopes have Typic or Lithic Dystrochrept soils, and soils within the slopes form a complex of coarse and thin Typic and Lithic Dystrochrepts. Some lower-slopes are Typic Hapludults formed from colluvium and alluvium. River floodplains have Typic Udifluvent soils formed from coarse alluvium (Knight 2006).

3.1.2.2 Climate

Thornthwaite (1948) classified the climate of the southern Appalachians as "mesothermal perhumid." In the Köppen-Geiger climate classification system, this region is identified as "Cfb: temperate oceanic climate." In general, the climate characteristics of the area include hot humid summers, short mild winters, and relatively long spring and fall seasons. The annual mean precipitation in this region is among the highest in the eastern United States, ranging from 1,270–1,500 mm, but in the southern section of the Pisgah National Forest it can be over 2,000 mm (Southeastern Forest Experiment Station 1994). Precipitation is distributed almost evenly throughout the year. Summer precipitation is mostly produced from orographic lifting of moist air passing over the mountains. Winter precipitation patterns are affected by both warm maritime air masses from the Gulf of Mexico and cold continental masses from Canada (Brody 1984). Most winter precipitation falls as snow, but relatively little accumulates. The mean annual temperature ranges from 10 to 16 ℃. During winter, the daytime temperature could average below 2 ℃, and during summer it can be below 24 ℃. Thunderstorms are frequent and unpredictable in summer.

3.1.2.3 Vegetation

Vegetation patterns of this area consist of deciduous forests and mixed forests that transition to montane spruce-fir forests at the highest elevations. Small pastures occur on the valley bottoms (Leigh and Webb 2006). Braun (1950) observed four forest types in the Linville area: hemlock bottoms, chestnut slope, sugar maple slope, and mountain. “Hemlock bottoms” refers to those broad valleys with extensive, nearly level bottomlands on the high plateau and where most of the large trees are hemlock (*Tsuga* spp.), yellow birch, and beech, and the undergrowth is made up almost exclusively of Rhododendron (*Rhododendron* L.). The “chestnut slope” is the section from the hemlock bottoms to the tops of some of the lower mountains in the area, and mostly on the southeast, south, southwest, and west exposures. Chestnut and red oak were the two dominant species of these relatively high elevations, although mature chestnut trees have completely been extirpated (Braun 1950). The “sugar maple slope” type occupies the northwest slopes of the mountains and a few other isolated patches. Hemlock, yellow birch, and sugar maple are most abundant among the overstory. The “mountain” type of forest covers the upper slopes with red spruce, Fraser fir, and Carolina hemlock (*Tsuga caroliniana* Engelm.). Vegetation change in this region has been associated with climate change, fire, storm damage, and tree cutting by people since the beginning of the Holocene (Delcourt and Delcourt 2004).

3.1.2.4 Land-use History

Thousands of years ago, ancestors of the Cherokee Indians inhabited the area of today's Pisgah National Forest and extensively used the land for agriculture and hunting. European settlement intruded in the late 1700s (Yarnell 1998). Today in western North Carolina, many eastern Cherokee Indians live within a reservation. Limited by the mountainous terrain, residential population grew relatively slowly. However, the favorable climate and the rich timber resources attracted people to come here for tourism and logging, starting in the early 1900s (Yarnell 1998). The Pisgah National Forest was established in 1916, but some of the forest tracts had been among the first purchases by the Forest Service under the Weeks Act of 1911 (U.S. Forest Service 2010). The 1890s–1920s period saw extensive logging and intense fires in the southern Appalachians (Williams 1998). The very heavy cutting of the forest early in last century was a major disturbance to the old-growth forests. Another major disturbance was the chestnut blight, first reported in 1926 in western North Carolina, which resulted in the decimation of the chestnut species (Keever 1953). Severe drought events also affected the composition of the vegetation of the region in the past.

Studies from fire scars in tree rings showed evidence of drought years and fire occurrences, for example, the extreme dry years from 1925 to 1930 (Barden 1977). Presettlement fires across the southern Appalachians were ignited by both lightning strikes and Native Americans (Newell and Peet 1998). Since the mid-20th century, fire suppression has changed the wildfire dynamics, leading to changes in plant communities. Many yellow pine stands prospered during 1890s–1920s, but after several decades of fire exclusion, hardwoods are now replacing the pine stands (Lafon *et al*. 2007).

3.2 The Coastal Plain Region in North Carolina

Part of the Atlantic Coastal Plain, eastern North Carolina has a relatively flat landscape that is greatly influenced by the ocean. Based on elevation differences, this region is divided into the Inner Coastal Plain Province and the Outer Coastal Plain Province by the North Carolina Geological Survey (Medina *et al.* 2004). One of my study sites is located in the inner Coastal Plain, which consists of step-like planar terraces that dip gently towards the ocean. Elevations range from 8 to 183 m above mean sea level (Medina *et al.* 2004). Because of the flat terrain, favorable climate, and relatively fertile soil, the Coastal Plain is primarily used for farming.

3.2.1 Geology

The rocks of the Coastal Plain are primarily marine sedimentary rocks that gradually thicken to the west. Relatively recent surficial sands were then deposited unevenly on older rocky strata. The most common sediment types in this region are sand, clay, and limestone in the southern section (U.S. Geological Survey 1998). Six sea terraces characterize the rolling topography from the Outer Bank area to further inland (Wells 1928). The three older, higher, and more inland terraces are called the upper Coastal Plain, while the three that are younger, lower, and nearer the ocean are called the lower Coastal Plain (Wells 1928). The lower and intermediate terraces are flatter and do not have well-defined drainageways, but instead have extensive swamp areas (Hanna and Obenshain 1957). In the upper Coastal Plain, the soils are better drained, and the Coastal Plain sediments lie on top of Piedmont saprolite, which is decomposed rock formed in place. Because of the varying topography from flat land to small hills, the soil patterns in this transitional zone between the Coastal Plain and the Piedmont are complicated and change depending on location (Gilliam *et al.* 1997).

3.2.2 Climate

Eastern North Carolina is mainly affected by two major air masses. One is the continental polar air mass from northwestern Canada and Alaska, which moves southeastward across the central U.S. Most of North Carolina, however, is protected by the mountain ranges in the west from the frequent outbreaks of cold air in winters. The other major and perhaps more important air mass is the maritime tropical air mass from the Caribbean Sea, which is associated with the Bermuda High, and which brings warm and humid climate to the region in summers (Christopherson 2006). Another tropical air mass from the Gulf of Mexico might also play a role in bringing hot humid summers, mild winters, and most of the precipitation in the Coastal Plain area of North Carolina. Precipitation is abundant here, averaging approximately 1,270 mm annually (Hanna and Obenshain 1957). Summer has the greatest amount of rainfall, which mostly occurs with thunderstorms and occasional hurricanes, especially in July. In winter, snow is rare near the coast, but its occurrence changes with the distance from the ocean and with altitude. Average January temperature is about 8 ℃ and average July temperature is about 29 ℃. The Atlantic Ocean modifies winter temperatures in eastern North Carolina by raising mean winter temperature and decreasing the average diurnal temperature range (North Carolina State University 2010). Humidity is relatively high and also changes with distance from the ocean: annual average humidity is highest along the immediate coast (75%) and lowest in the higher elevation mountain areas (10%) (North Carolina State University 2010). Hurricanes occasionally hit the coastal region and usually bring heavy rains and strong winds.

3.2.3 Vegetation

The Coastal Plain area is the most diverse region in terms of vegetation types in temperate North America, and is characterized by high species richness and an abundance of endemic plants. Community physiognomy varies across the landscape from grasslands and savannas to shrublands, to needle- and broadleaf woodlands and to rich mesophytic forest (Barbour and Billings 2000). This variation in vegetation is primarily a consequence of gradients in physical and chemical characteristics of climate, soils, and hydrology. Sandhill, sand pine scrub, and xeric hardwood forest are three major types of vegetation in the Coastal Plain region, and the study area lies within the ecosystem of Sandhill pine forests in xeric sand communities. Vegetations in this ecosystem primarily include longleaf pine, wiregrass (*Aristida stricta* Michx.), turkey oak (*Quercus laevis* Walter), black gum (*Nyssa sylvatica* Marsh.), staggerbush (*Lyonia mariana* (L.) D. Don), dwarf huckleberry (*Gaylussacia dumosa* (Andrews) Torr. & A. Gray), blackjack oak (*Quercus marilandica* Münchh.), bluejack oak (*Quercus incana* Bartram), and sweetgum (*Liquidambar styraciflua* L.) (Barbour and Billings 2000).

Moisture availability, edaphic conditions, and disturbance regimes are all important factors that may influence forest composition on the Coastal Plain (Wyant *et al.* 1991). As one of the native pine species preferred for dendrochronological study in this region, longleaf pine was once the dominant species after the retreat of the Wisconsin glacial period. These trees provide much information for studies on changing climate, fire or hurricane disturbance, and vegetation succession. Unfortunately, the number of longleaf pines has been declining remarkably with climate change and other disturbances in recent decades (Wahlenberg 1946, Myers and van Lear 1998, Gresham *et al.* 1991, Mitchell and Duncan 2009).

3.2.4 Land-use History

About 10,000–12,000 years ago, humans populated the southern Coastal Plain at about the same time longleaf pine woodland began to appear after glacial retreat. The indigenous populations used fire as their primary tool of landscape management (van Lear *et al.* 2005). During the 1700s, Europeans spread along the Atlantic coast and inland towards the Appalachian Mountains. The expansion westward was accelerated during the 1800s (Williams 1989). European settlers greatly influenced the land as they gradually cleared the forest and developed agricultural fields. This forest exploitation was exacerbated with the advent of the industrial revolution in the mid- to late 19th century, when more people came for logging, turpentine, and transportation operations. This land use changed a large proportion of the old-growth forest to second-growth forest (Brudvig and Damschen 2010). For example, in the post-World War II era, loblolly pine and slash pine (*Pinus elliottii* Engelm.) were widely used in the paper and pulp industry. This resulted in a change from older, multi-aged native stands of longleaf pine to young, even-aged plantations of loblolly and slash pine (Earley 2004).

Fire played an important role in the land-use history of the Coastal Plain. Human-caused fire was used to reduce fuels and wildfire risk, enhance hunting of wildlife and herding, and cultivate plants (Mitchell and Duncan 2009). Lightning and drought have also been linked to fires (Komarek 1974). However, fire suppression policies in forests during the early decades of the 20th century reduced the frequency of fires, but increased the severity of understory burns due to the accumulated organic fuels, which also resulted in considerable pine mortality (Brown 2000, Mitchell and Duncan 2009).

3.3 Study Sites

3.3.1 Hope Mills Crib Dam, North Carolina

The Hope Mills crib dam is located in the town of Hope Mills in south-central North Carolina (Figure 3; Table 1). This location is within the Inner Coastal Plain region, which is relatively higher and drier compared with the Outer Coastal Plain region in North Carolina. The Sandhills in the southwestern corner of the Inner Coastal Plain contains the specific study site. The Sandhills generally divide the Piedmont from the Coastal Plain. Because of the rich, sandy soil, the once dominant longleaf pine, loblolly pine, turkey oak, and blackjack oak were largely replaced by farmland and urban areas (Noel *et al.* 1998). Elevations near the study site range from sea level to 100 m. Average monthly temperatures range from 12 ℃ in January to 33 ℃ in July, and monthly precipitation totals range from 70 mm to 146 mm (van de Gevel *et al.* 2009). Periodic hurricanes and lightning-caused fires are the major natural disturbances to the local ecosystems.

The Hope Mills dam was first built in 1839 to power local cotton mills owned by the Rockfish Mills Company. It had a rock-crib design, and the structure built of large cross-stacked logs supported the integrity of the earthen dam (van de Gevel *et al.* 2009). In May 2003, a flood caused by rainfall during an intense thunderstorm destroyed the newer, overlying concrete dam, exposing the original longleaf pine logs. Van de Gevel *et al.* (2009) used some of the well-preserved logs along with nearby living longleaf pines to develop a

Table 1. Descriptive information about three study sites.

Location	Site	Site Code	Latitude, Longitude	Elevation	Species
Coastal	Hope Mills	HMC	N34.9725°, W78.9458°	80-100 m	*Pinus palustris* Mill.
Middle	Linville Mountain	LMP	N35.9497°, W81.9290°	800-1,000 m	*Pinus pungens* Lamb.
Inland	Gold Mine Trail	GMT	N35.3820°, W83.5477°	460-600 m	*Pinus echinata* Mill.

multi-century longleaf pine tree-ring chronology.

Longleaf pines are native to this area and ideal for dendrochronological studies in the southeastern U.S. Previous research showed that longleaf pine radial growth is particularly sensitive to drought (Devall *et al.* 1991, Foster and Brooks 2001) and to winter and spring precipitation (Meldahl *et al.* 1999). The El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO) have also been shown to significantly affect longleaf pine growth on the Coastal Plain (Henderson 2006, van de Gevel *et al.* 2009).

3.3.2 Linville Mountain in Pisgah National Forest, North Carolina

The sample site of Linville Mountain is located close to the intersection of Avery County, Burke County, and McDowell County in North Carolina (Figure 3). The site is part of the Pisgah National Forest and belongs to the Linville Gorge Wilderness Area (LGWA), designated in 1951 by U.S. Forest Service. Bisected by the Linville River, Linville Mountain is on the west side of the gorge while the Jonas Ridge is on the east. The terrain is generally characterized by steep slopes and rugged topography. Elevations range from 390 m at the river to 1,250 m on Gingercake Mountain in the LGWA. Annual precipitation ranges from

125 to 162 cm and peaks in summer. Average June to August minimum temperature is as high as 17 ℃, and average minimum temperature in February ranges from –2 to 0 ℃ (Newell and Peet 1998).

The hardwood-pine forest type is well-developed in this area of low precipitation and infertile soils. This oak-pine mixture type of forest includes Table Mountain pine, pitch pine, scarlet oak, chestnut oak, red maple, black gum, and sourwood (*Oxydendrum arboreum* (L.) DC.) as dominant species (Dumas *et al.* 2007). Under the historical regime of frequent fires (7–12 year mean fire interval) at Linville Mountain, some endemic fire-adapted species grew here and still remain on the landscape (Harmon 1982). Zobel (1969) recognized the importance of the fire for establishing Table Mountain pine stands, but suggested that permanent, self-maintaining stands might only exist on rock outcrops or shale slopes where hardwood species grow poorly. In recent years, pine stands are being replaced by hardwoods because of previous decades of fire exclusion and climate change. This drought-tolerant and shade-intolerant species can be found on ridge tops, west- or southwest-facing slopes, and other xeric sites in the form of small patches within forests of hardwood trees (Lafon and Kutac 2003).

3.3.3 Gold Mine Trail in Great Smoky Mountains National Park, Tennessee

The Gold Mine Trail study site is located in the western edge of the Great Smoky Mountains National Park (Figure 3). It has gentle to flat slopes with elevations ranging between 460 and 600 m (Table 1). The vegetation community includes an understory of white pine, red maple, laurel (*Rhododendron maximum* L.), and mountain laurel (Grissino-Mayer *et al.* 2007). Dominant species in the canopy at this site consist of shortleaf pine, pitch pine, Virginia pine (*Pinus virginiana* Mill.), white oak (*Quercus alba* L.), black oak, chestnut oak, northern red oak, scarlet oak, and eastern hemlock (Grissino-Mayer *et al.* 2007, White 2007, Biermann 2009).

Shortleaf pine is a native species in the southeastern United States and has been used largely for commercial purposes. The species grows in fairly humid regions. It can adapt to a great variety of soil conditions, such as soil types under the Ultisols order, but it grows best on deep, well-drained soils having fine sandy loam or silty loam textures (Burns and Honkala 1990). The Gold Mine Trail site has deep soils, reaching bedrock at 75–100 cm (Biermann 2009, Web Soil Survey 2009).

The southern pine beetle (*Dendroctonus frontalis*) occasionally causes great losses of shortleaf pines, especially coincident with other disturbances such as ice storms and wildfire. For example, when ice storms and southern pine beetle outbreaks occur in xeric pine-oak forests, the successional trend may be skewed towards oak domination. If fire also occurs, the trend will be towards pine domination (Williams 1998, Waldron *et al.* 2007). Shortleaf pine is generally fire resistant, and fire scars found on individual trees provide evidence to study forest ecology (Lafon *et al.* 2005, DeWeese *et al.* 2010). The forest was also likely disturbed by farming and livestock grazing, although logging was minimal and many old trees remain at the site (Biermann 2009).

CHAPTER 4

METHODS

4.1 Field Methods

Fieldwork was conducted at Linville Mountain in the Pisgah National Forest for chronology development. In July 2009, a field team (consisting of Dr. Henri Grissino-Mayer, Dr. Charles Lafon, William Flatley, Ashley Pipkin, and myself) collected samples and site information. Fieldwork for the other two sites had already been completed by others. The Gold Mine Trail chronology was developed from 117 shortleaf and pitch pines cores collected in 2005–2007 by members of the Laboratory of Tree-Ring Science (LTRS) at the University of Tennessee. Lisa LaForest and Jessica Slayton developed the Gold Mine Trail chronology, which now spans A.D. 1684–2006. The Hope Mills tree-ring chronology was developed by Saskia van de Gevel from logs obtained from the crib dam and from nearby living longleaf pines (van de Gevel *et al*. 2009).

4.1.1 Site Selection

At Linville Mountain, tree cores were collected from three stands to develop a Table Mountain pine chronology. Our site selection strategy was to focus on the western slopes of the mountain where moisture availability is more limiting than the eastern side. Additionally, temperature may be a limiting factor for tree growth at 800–1,000 m elevation near the upper limit of the occurrence of pines. The relative lack of disturbance was also an important factor in choosing the study stands. The only species sampled was Table Mountain pine throughout three sampling stands.

Because of the rugged and forested landscape, it is difficult for humans and livestock to access these sites. The Linville Mountain area has experienced relatively little livestock grazing or human disturbances in recent decades. Since it was designated as a National Wilderness Area, most of its woodland is growing under natural conditions. Fire is a frequent natural disturbance to the forests, with fires occurring every 7–12 years on average (Harmon 1982). Scouting from an overview spot, we can easily identify large areas of dead trees killed by the last fire event (Figure 4).

Figure 4. Overview from the top of Linville Mountain. Young plants are sprouting under the fire-killed overstory forests. (Photo © Yanan Li)

4.1.2 Collecting Samples

We collected samples using 4.3 mm and 5.15 mm diameter Haglof increment borers. Only living Table Mountain pine trees with diameters greater than 20 cm at breast height were sampled. We collected two radii from each tree by either coring twice on opposite sides of the tree, or by coring straight through the diameter. All cores were taken at or below 30 cm near the base of the tree (Figure 5). Also, cores were collected parallel to the slope contour to minimize the effects of reaction wood on the growth patterns (Fritts 1976). After extracting the cores, we placed them immediately into paper straws and labeled the straws with the tree identification, dates, collector's initials, and other features when necessary. We collected 49 cores at the Linville Mountain A stand (LMA), 17 cores at Linville Mountain B (LMB), and 25 cores at Linville Mountain C (LMC), for a total of 91 cores from 38 living Table Mountain pines.

4.2 Laboratory Methods

4.2.1 Sample Processing and Preparation

In the laboratory, I air-dried all samples in straws for two days. The cores were then removed from their straws and glued individually onto wooden core mounts. The tracheid cells within the cores were positioned vertically with respect to the core mount to ensure a transverse view of the wood surface (Speer 2010). The corresponding ID and other information were transcribed onto the core mount before the core was glued in the groove. I then progressively sanded each mounted core using ANSI 100-grit (125.0–149.0 µm) to ANSI 400-grit (20.6–23.6 µm) sandpaper in the wood shop to produce a smooth surface on which the rings were clearly visible and identifiable (Orvis and Grissino-Mayer 2002). Cellular features of each core were examined under 10x magnification using a stereoscopic microscope. If the bark was present, I assigned a calendar year for each ring by counting backwards from the most recent year's growth near the bark. If bark was missing, each ring was assigned a floating number, beginning with year one at the innermost ring. I then

Figure 5. A core being extracted from the base of a Table Mountain pine on Linville Mountain. (Photo © H.D. Grissino-Mayer)

measured the ring widths on each core to 0.001 mm using a Velmex measuring station with MEASURE J2X software.

4.2.2 Crossdating and Chronology Construction

Using crossdating, I assigned a calendar year to each individual ring by matching ring growth patterns across samples. The crossdating accuracy was verified using COFECHA, a software program that uses segmented time series analysis and correlation analyses to determine if ring-width patterns match across samples (Holmes 1983, Grissino-Mayer 2001). First, the samples from the same stand were crossdated using a combination of visual and statistical techniques (Stokes and Smiley 1996). The visual crossdating involved documenting characteristic patterns of wide and narrow rings and matching these patterns between samples (Yamaguchi 1991). For each stand, it was helpful to start with a small number of the most easily-dated and relatively older samples and then to gradually incorporate more samples (Fritts 1976). The statistical crossdating was accomplished using ring-width measurements and COFECHA. I used 50-year segments with 25-year overlaps in COFECHA to test the correlation between each series and the average of all other series at each stand. Segments with correlation coefficients below 0.33 ($p<0.05$) were flagged as potential crossdating errors. I visually checked each core with flagged segments carefully under a microscope and re-measured it when necessary. False rings, micro-rings, double rings, or breaks were all present among my samples.

I focused on two parameters, average mean sensitivity and interseries correlation, to judge crossdating quality when interpreting the COFECHA results. Average mean sensitivity is a measure of the strength of the year-to-year variability in all series, and interseries correlation is the average of all Pearson correlation coefficients calculated for each series compared to all other series in the chronology (Grissino-Mayer 2001). In the Southeast, a mean sensitivity of 0.15–0.20 is common, but values between 0.25 and 0.35 are best for crossdating and climate analysis (Biermann 2009). Interseries correlations greater than 0.40 suggest successful crossdating and likely a regional climate signal (Grissino-Mayer 2001). Some samples with flagged segments but no evidence of misdating (always low correlation coefficients) were eliminated from constructing the chronology. Short cores and cores with too many cracks were also eliminated from further analyses to ensure that the master chronologies contained a strong climate signal. I successfully crossdated 41 series from LMA, 17 series from LMB, and 25 series from LMC for use in chronology construction (Table 2). I then combined these 83 series together to create one master chronology for Linville Mountain site (designated “LMP”).

Table 2. COFECHA results for three stands and the composite on Linville Mountain.

Stand	Number of Samples	Number of Trees	M.S.	r	Flagged in COFECHA
LMA	41	18	0.26	0.54	10
LMB	17	9	0.29	0.53	2
LMC	25	11	0.30	0.58	1
LMP	**83**	**38**	**0.27**	**0.54**	**16**

To develop the LMP master chronology, I standardized all crossdated measurement series to remove age-related growth trends (Fritts 1976). Standardization converts the ring width measurements into dimensionless tree-ring indices. The program ARSTAN was used to produce the standardized tree-ring index chronology (Cook 1985). I used a cubic smoothing spline of 80 years, which preserved 50% of the variance over 75% of mean series length to detrend all series. This detrending curve was more flexible compared with some conservative methods, such as linear regression lines or negative exponential curves, and it removed the long-term nonclimatic variations in growth (Figure 6; Fritts 1976). ARSTAN generated three chronology types: standard (STD), residual (RES), and arstan (ARS). In this study, a standard chronology was used for the Linville Mountain site in further analyses.

4.3 Climate Analysis

4.3.1 Climate Data

The climate-tree growth relationship for each of the three chronologies was analyzed using divisional monthly climate data obtained from the National Climatic Data Center (NCDC 2009). For the Gold Mine Trail site, I used climate data from NOAA Climate Division 1 (Eastern Tennessee). For the Linville Mountain site, I used climate data from NOAA Climate Division 2 (the North Carolina Northern Mountains). For the Hope Mills site,

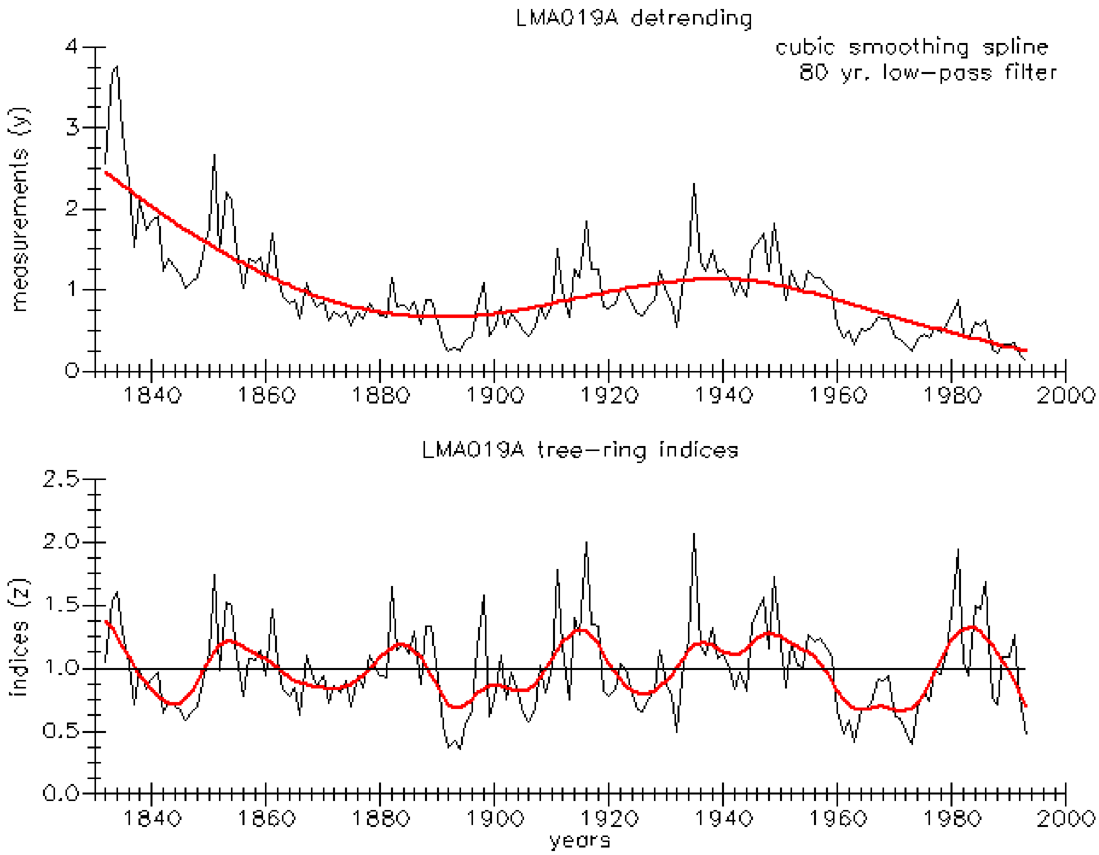

Figure 6. Using the program ARSTAN, the raw ring-width series were detrended with a cubic smoothing spline of 80 years (taking series LMA019A as an example here). The top graph shows the raw ring-width series and the detrending curve fitted to the series; the bottom graph shows the standardized tree-ring indices after detrending.

I used climate data from NOAA Climate Division 6 (the North Carolina Southern Coastal Plain). Climate variables analyzed included monthly mean temperature, monthly total precipitation, and monthly Palmer Drought Severity Index (PDSI). The PDSI is a drought index that incorporates temperature, precipitation, and evapotranspiration as an estimate of soil moisture availability and describes drought (negative values) and wet (positive values) conditions during the growing season (Palmer 1965). It is commonly used in dendroclimatic studies. All climate data were from the years 1895 to 2009.

I also analyzed the relationship between the chronologies and the following oceanic-atmospheric oscillation index data to detect the variability of regional climate impacts:

- NAO: monthly normalized indices based on the difference in sea level pressure between Ponta Delgada, Azores and Akureyri, Iceland from 1874–2005 (Rogers 1984, Rogers 2005).
- AMO: anomalies of sea surface temperature of North Atlantic Ocean, obtained from the Kaplan SST dataset. I used the period of 1861–2004 (Kaplan *et al.* 1998, NOAA 2009).
- PDO: derived as the leading PC of monthly SST anomalies in the North Pacific Ocean, poleward of 20 °N latitude. I used the period of 1900–2009 (JISAO 2009).
- ENSO: monthly Southern Oscillation Index (SOI) for the Niño 3.4 region, calculated from sea level pressure anomalies between Tahiti and Darwin, Australia. SOI data are available from 1951 to 2009 (NOAA 2009).

4.3.2 Correlation Analysis

Pearson correlation coefficients were calculated between climatic variables and ring-width indices in DENDROCLIM2002, a dendroclimatic analysis program (Biondi 1997, Biondi and Waikul 2004). For each site, monthly mean temperature, monthly total precipitation, and PDSI divisional data from 1895 to 2009 were correlated with the respective chronology indices. The period analyzed was May of the previous year through December of the current year, purposely including the previous growing season due to its influence on current growth. Statistically significant coefficients indicated a confident association between a given climate variable in a particular month and tree growth, but more often, the climate effect on tree growth is stronger in the form of a multi-month seasonal signal (Grissino-Mayer and Butler 1993, Grissino-Mayer 1995).

4.3.3 Response Function Analysis (RFA)

The response function analysis in tree-ring studies used principal components multiple regression to remove effects of interdependence among the climate variables (Fritts 1976, Grissino-Mayer *et al.* 1989). It is a complementary technique of correlation analysis. Its purpose is also to determine the climate variables that significantly affect tree growth. The RFA examined climate data and growth indices from prior years to develop a biological model of tree growth (Grissino-Mayer and Fritts 1995). A bootstrap method provided confidence intervals for the response coefficients (Biondi and Waikul 2004). I conducted the response function analysis in DENDROCLIM2002 using the master chronologies and respective 20 monthly variables for mean temperature, total precipitation, PDSI, NAO, AMO, PDO, and ENSO indices. The 20 months started from May of the previous growing season and ended with December of the current year.

The correlation analysis and the RFA are both used to establish the relationships between tree-ring indices and individual climate variables, but they differ greatly based on the statistical calculations. Correlations test the linear association between chronologies and climate and how trees respond to each individual variable. Correlation is statistically more straightforward and is a more easily interpreted approach to quantifying the growth-climate link (Blasing *et al*. 1984). The RFA is a multivariate regression approach, in which time-series of monthly climate data are first subjected to Principal Components Analysis to remove interdependence within these data (Norton and Ogden 1987). Differences in the two techniques can cause very different patterns of climatic responses.

4.3.4 Moving Correlation and Response Function Analyses

DENDROCLIM2002 has the ability to test for temporal changes of climate-tree growth relationships (Biondi and Waikul 2004). This is advantageous because one limiting factor found in a certain period rarely remains consistent over time, and it is important to examine the temporal stability of climate-tree growth relationships. After the initial correlation and response function analyses, I conducted moving correlation and response function analyses in DENDROCLIM2002 between tree-growth and monthly temperature, precipitation, PDSI, NAO, AMO, PDO, and SOI from previous May to current December. The base length of moving intervals was 40 years, which satisfied the conditions (<80% of all available years; ≥twice the number of predictors) suggested by Biondi and Waikul (2004). The full-length period entered for the DENDROCLIM2002 analysis was determined by the common interval of the climate data and tree-ring index. For temperature, precipitation, and PDSI, the analysis period was 1895 to the end of each chronology (GMT: 2006, LMP: 2008, HMC: 2003). For the climate oscillations, the beginning years of analysis agreed with the first year of the climate data, and the ending year varied corresponding to the last year of the chronology and climate oscillation data (Table 3). Results of the analyses were plotted in graphs using color-coded symbols to indicate coefficient values. Each climatic variable combined with one chronology was used to generate two plots, one for moving correlation analysis results, and the other for moving response function analysis results.

Table 3. Time spans in moving correlation and response function analyses in DENDROCLIM2002.

	Temperature	Precipitation	PDSI	NAO	AMO	PDO	SOI
GMT	1895–2006	1895–2006	1895–2006	1874–2005	1861–2004	1900–2006	1951–2006
LMP	1895–2008	1895–2006	1895–2006	1874–2005	1861–2004	1900–2008	1951–2008
HMC	1895–2003	1895–2006	1895–2006	1874–2003	1861–2003	1900–2003	1951–2003

4.3.5 Climate Response of the Composite Chronology

The composite chronology averaged from the three individual chronologies was used to examine the regional climate responses by pine trees along the longitudinal gradient in the Southeast. Correlation and response function analyses were conducted in DENDROCLIM2002 between the composite chronology and climate oscillation indices from previous May to current December. Although the climate responses might vary among the individual sites according to their local environments and other factors, climate analyses for the composite chronology will help reveal the strength of the climate response within the entire larger combined stands.

CHAPTER 5

RESULTS

5.1 Crossdating and Chronology Development

Eight of the 91 cores collected were eliminated from constructing the Linville Mountain chronology because some had too many cracks that affected the observation of complete and clear rings, or some series were too short and complacent to correlate well with others. For the LMB and LMC sites, all cores measured were retained for chronology building because of the accurate visual crossdating and COFECHA verification. Eventually, 83 cores from 38 trees were crossdated for the Linville Mountain site. Visual, graphical, and statistical crossdating were aided by extremely narrow rings formed in A.D. 1883, 1891, 1902, 1930, 1932, 1986, and 1998. The patterns of marker rings showed, for example, consecutive narrow rings from 1843 to1847, and a narrow 1883 ring between wide 1882 and 1884 rings.

The Linville Mountain chronology spans A.D. 1810 to 2008 (Figure 7a). The highest sample depth (78 series) occurs between A.D. 1958–1965. Of the 83 series in the chronology, 25 are over 150 years in length. The longest (LMA004B) has 194 years while the shortest (LMA027C) has 45 years. The average length of the 83 series is 106.8 years. The series intercorrelation is 0.54, while the average mean sensitivity is 0.27. Sixteen segments were detected as potential problems in COFECHA (Table 2). The average first-order autocorrelation was 0.36, which is relatively high for the southeastern U.S, indicating relatively strong persistence through years of growth (Grissino-Mayer 2001). To maintain consistency with the chronology type of other sites, a standard chronology was chosen for

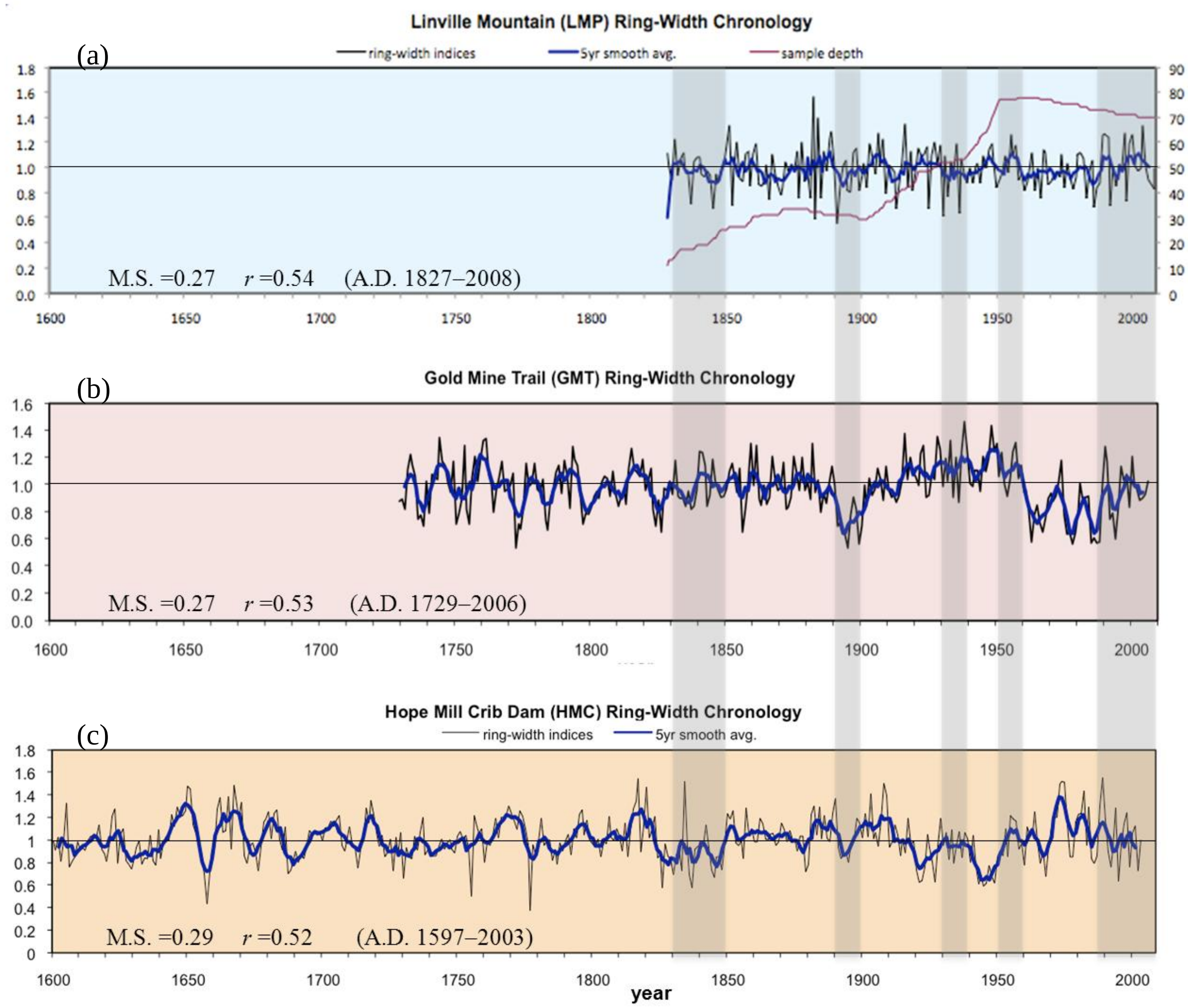

Figure 7(a). Standard chronology of the Linville Mountain site, and sample depth is indicated in red line;
Figure 7(b). Standard chronology of the Gold Mine Trail site;
Figure 7(c). Standard chronology of the Hope Mills site.
Note: The highlighted columns are the periods (1830s–1840s, 1890s, 1930s, 1950s, post-1990s) with extreme climatic events. The horizontal line cross the chronologies is the average ring width index value of 1.0.

the Linville Mountain site. The years A.D. 1810 to 1827 were excluded from the final chronology because the ring indices for those years did not have adequate sample depth based on the Subsample Signal Strength (Wigley *et al.* 1984).

At the Gold Mine Trail site, 187 series from 117 yellow pine trees were used for chronology construction by Jessica Slayton and Lisa LaForest (Figure 7b). The chronology spans from A.D. 1684 to 2006, with an average interseries correlation of 0.53 and average mean sensitivity of 0.27 (Table 4). The standard chronology of Gold Mine Trail had at least 10 ring-width series of sample depth for each year (Biermann 2009). For the Hope Mills chronology, 21 series from 12 crib dam logs were anchored in time by 18 series from living trees collected near the Big Rockfish Presbyterian Church (van de Gevel 2009). A total of 39 series were combined to create the site chronology. The chronology spans from A.D. 1597 to 2003 (Figure 7c), with an average interseries correlation of 0.53 and average mean sensitivity of 0.29 (Table 4) (van de Gevel 2009). Given the high levels of interseries correlations and mean sensitivities, all three chronologies had relatively high statistical quality for the southeastern U.S.

The common period of these three chronologies was A.D. 1827–2003. Ring-width indices in this period were averaged to produce a composite chronology (Figure 8). This chronology, which may represent the regional trend of tree growth, was tentatively used to examine the response of oceanic-atmospheric effects by trees in the southeastern region.

Table 4. Basic information for the three chronologies.

Site Chronology	Number of Series/Trees	Time Span	Interseries Correlation	Mean Sensitivity
Hope Mills	39/*	1597–2003	0.53	0.29
Linville Mountain	83/38	1810–2008	0.54	0.27
Gold Mine Trail	187/117	1684–2006	0.53	0.27

*: 21 out of 39 series at the Hope Mills site were from 12 crib dam logs.

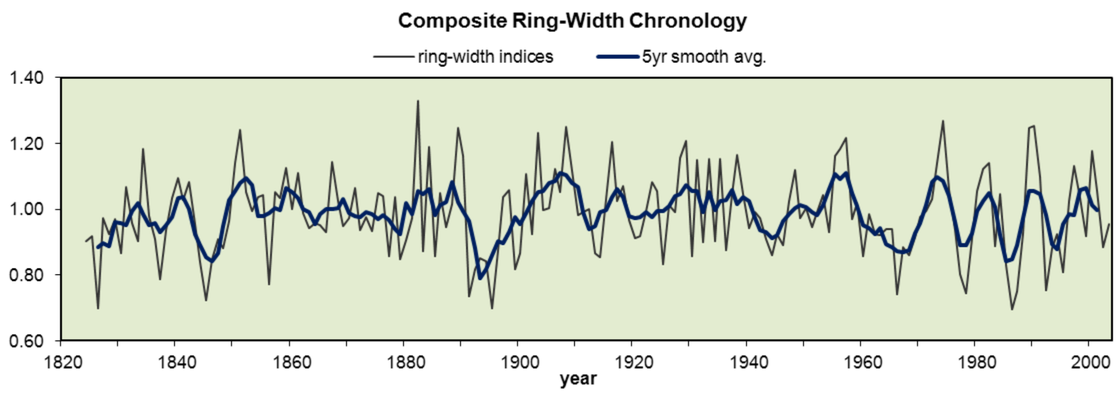

Figure 8. The composite chronology derived from average ring-width indices from the Hope Mills, Linville Mountain, and Gold Mine Trail chronologies.

5.2 Hope Mills

5.2.1 Monthly Temperature, Precipitation, and PDSI Responses

At the Hope Mills site, tree growth showed much greater correlations with PDSI than with either temperature or precipitation during the current year (Figure 9). PDSI was positively correlated with annual growth from March to December, except November. The most significant association ($P<0.01$) occurred during the growing season from April to June and during summer in August and September. The previous summer PDSI was weakly correlated with tree growth, while temperature in previous August had a statistically significant positive but weak correlation ($r=0.19$, $P<0.05$). Previous June and October temperatures had significant negative correlations with tree growth. High rainfall or snowfall amount in February can help above-average growth of longleaf pine, but increased precipitation in November was significantly associated with below-average growth. In general, correlation analysis showed that, for the Coastal Plain site, moisture availability in the growing season and extended summer was the primary limiting factor on annual ring-growth.

Results from response function analysis showed fewer statistically significant climatic variables. PDSI showed no influence in response function analysis (Figure 10). Temperature variables also showed no statistically significant associations with tree growth. The only significant climatic variable in the response analysis was November precipitation, which also existed in the correlation analysis. Results of the response function analysis indicated that temperature and moisture availability barely drove longleaf pine growth, but precipitation in November was the primary limiting factor and had a negative relationship with tree growth.

5.2.2 Monthly NAO, AMO, PDO, and ENSO Responses

Correlation analysis between monthly oscillation index data and the Hope Mills chronology suggested a complex relationship between large-scale climate patterns and coastal pine growth (Figure 11). The AMO index, a measure of the sea surface temperature anomalies in the North Atlantic, showed strongly negative relationships with tree growth in previous October, current February, and September through December. The NAO, an indicator of sea surface pressure variability during wintertime in the Northern Hemisphere, showed a significant negative correlation with ring growth in April ($r = -0.19$, $P<0.05$) and significant positive correlations in August ($r=0.21$, $P<0.05$) and October ($r=0.16$, $P<0.05$). The PDO was only weakly negatively correlated during December ($r = -0.19$, $P<0.05$), which suggested that pine growth in Hope Mills was less associated with climate variability in the Pacific Ocean. The SOI, as a measure of the strength of ENSO, had positive correlations with growth during previous September, November, December, and current October. This indicates that during La Niña years (positive SOI) tree growth tends to be above average,

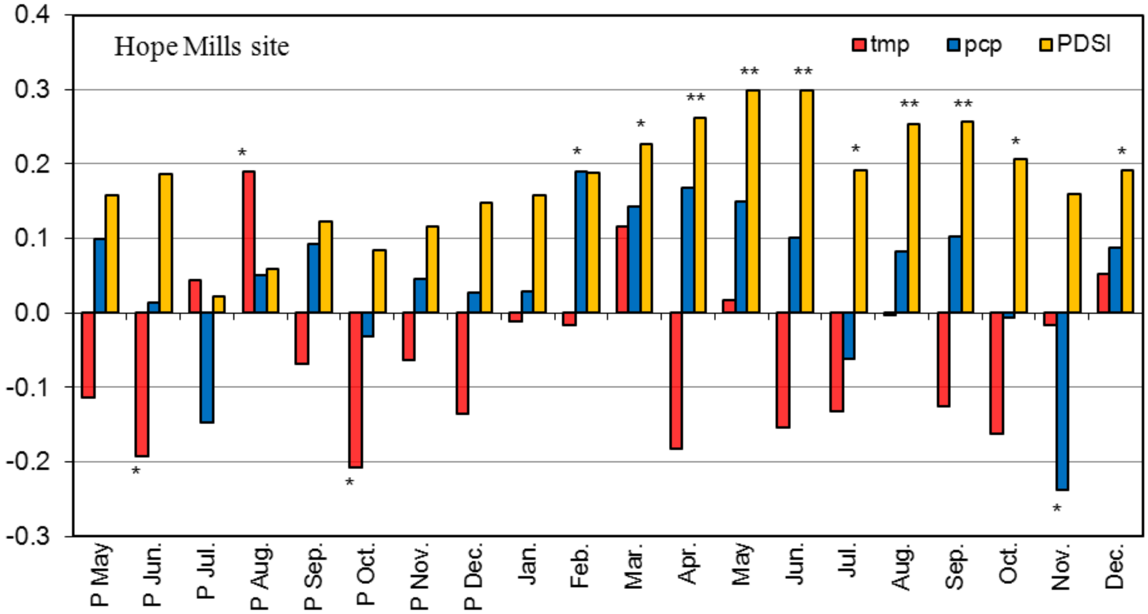

Figure 9. Correlation coefficients between the Hope Mills chronology and monthly temperature (tmp), precipitation (pcp), and PDSI from previous May to current December (1895–2003) (*: P<0.05; **: P<0.01).

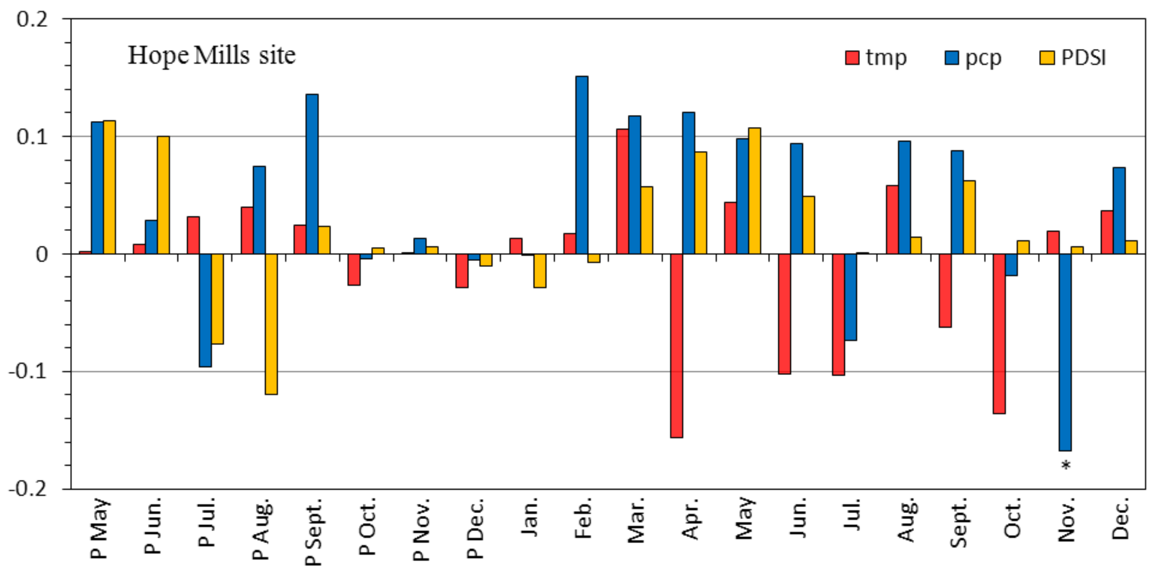

Figure 10. Response function coefficients for the Hope Mills site (1895–2003) (*: P<0.05).

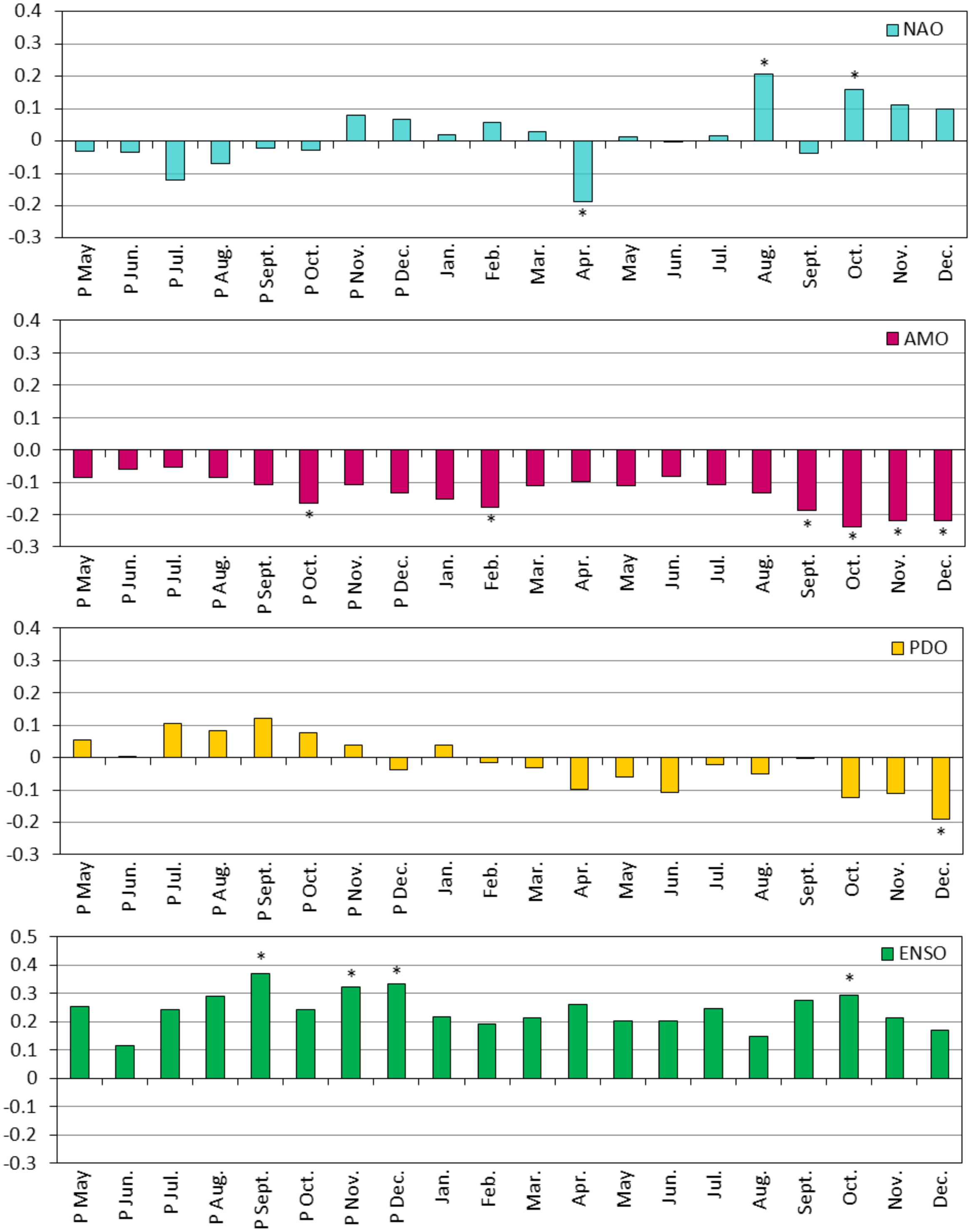

Figure 11. Correlation coefficients between monthly oscillation index values and the Hope Mills chronology (*: P<0.05).

while during El Niño years tree growth is below average. Overall, the Hope Mills chronology had the strongest correlation with AMO, less strong correlation with ENSO, but very weak correlations with NAO and PDO.

5.2.3 Moving Interval Analysis

Results of the moving interval analysis showed temporal changes or shifts in the climate-tree growth relationship for the Coastal Plain area. Previous September temperature was negatively correlated with growth between ca. 1907 and 1967, but in the following 30 years, from the 1960s to the early 1990s, beginning in the mid-1940s (Figure 12). The relationship between temperature and tree growth at the Hope Mills site was more negative rather than positive, which indicates that high temperatures in those summer months limit tree growth.

Several short-term shifts were also found in the correlation results with precipitation (Figure 13). The positive correlation between growing season (February to May) precipitation and tree growth was insignificant in the early 20^{th} century, but weakly strengthened. After the 1980s, the negative correlations between growth and previous July, previous December, and current July precipitation no longer existed; instead, low precipitation in current November began to limit the growth and this association was significant throughout the rest of the analysis period (Figure 13). The April to October PDSI of the current year was correlated strongly with tree growth in the 1890s–1940s, but the association faded in the next 30 years (Figure 14). Since the late 1970s, the positive relationship between current year PDSI and tree growth again became statistically significant during the growing season.

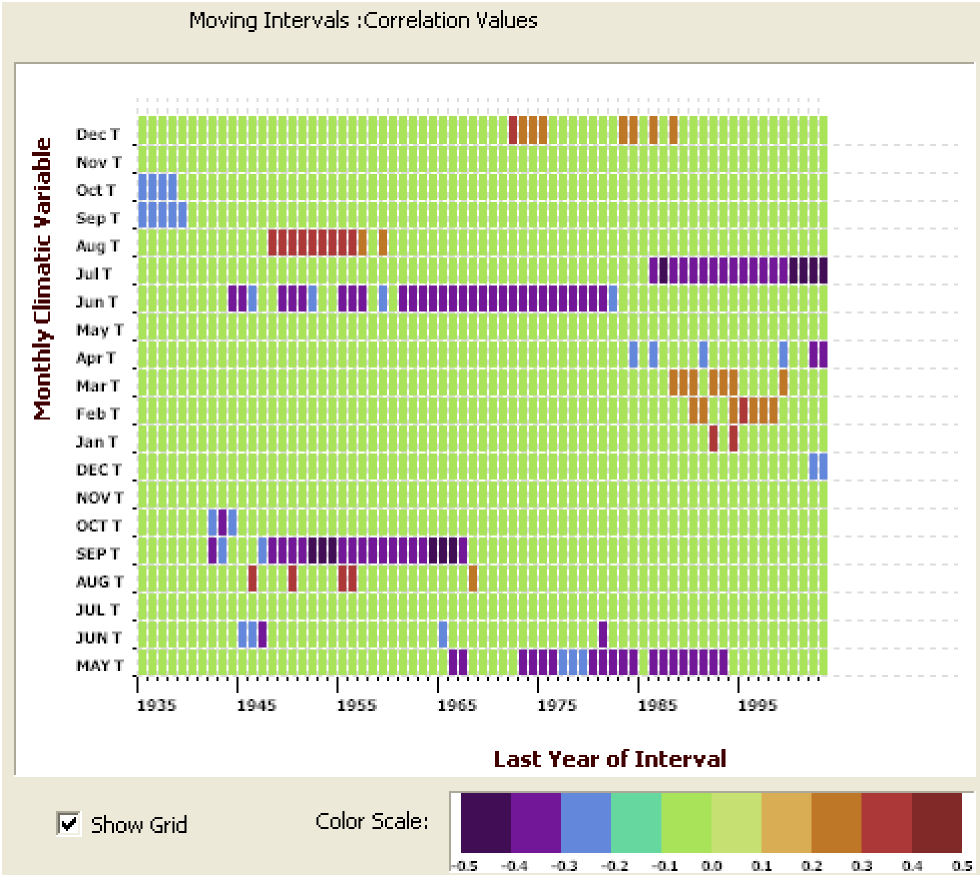

Figure 12. Moving correlation analysis between temperature and the Hope Mills chronology, using 40-year moving intervals, from 1895 to 2003. Monthly temperature is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1935 represents the period from 1895 to 1935. Different colors in the grid represent different levels of the correlation coefficient.

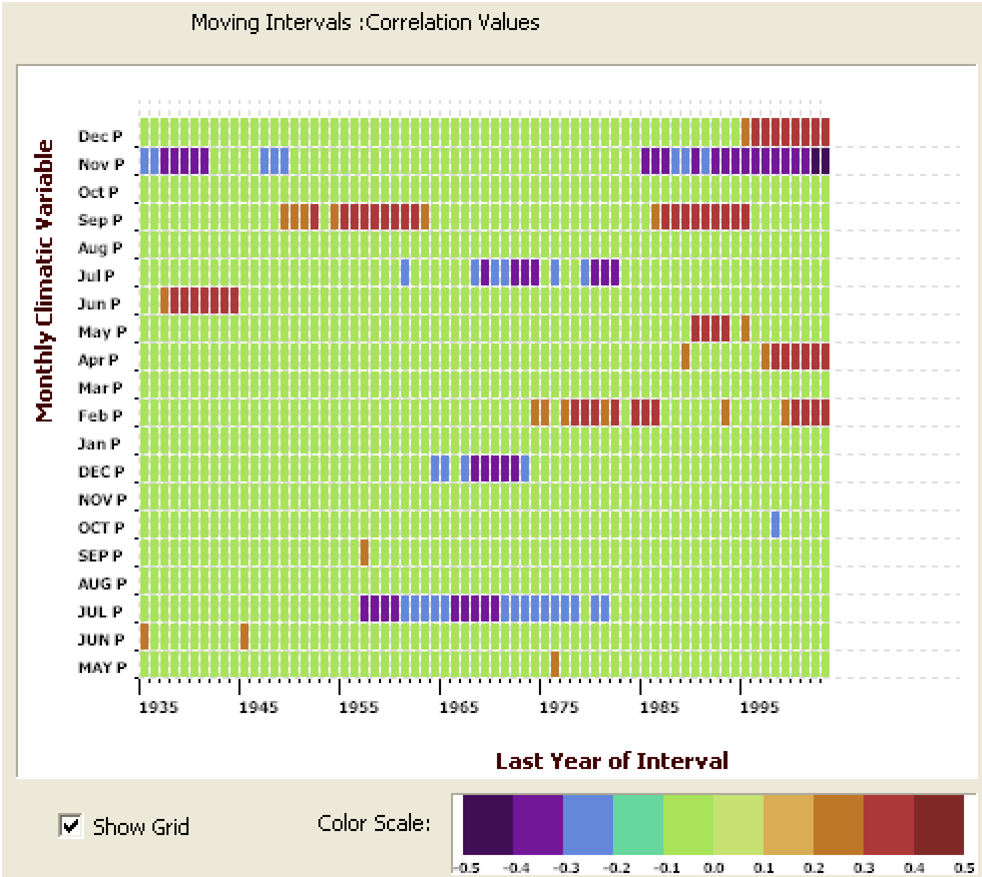

Figure 13. Moving correlation analysis between precipitation and the Hope Mills chronology using 40-year moving intervals, from 1895 to 2003. Monthly precipitation is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1935 represents the period from 1895 to 1935. Different colors in the grid represent different levels of the correlation coefficient.

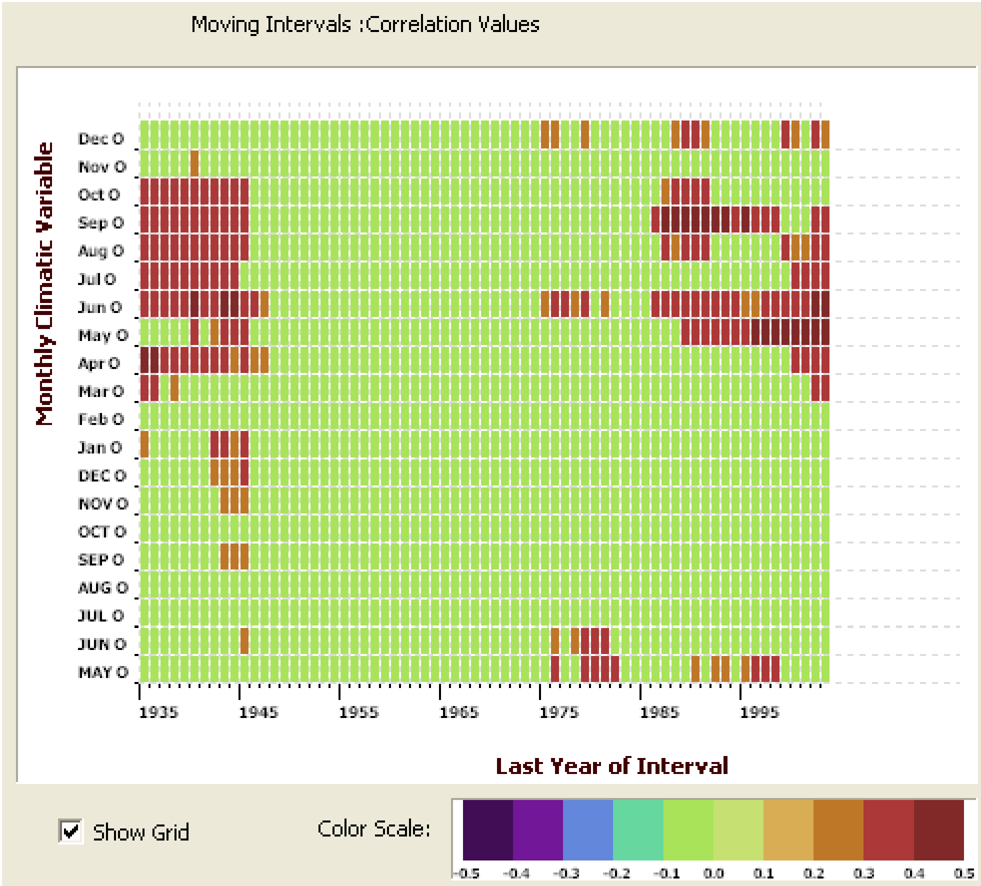

Figure 14. Moving correlation analysis between PDSI and the Hope Mills chronology using 40-year moving intervals, from 1895 to 2003. Monthly PDSI is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1935 represents the period from 1895 to 1935. Different colors in the grid represent different levels of the correlation coefficient.

The relationship between the NAO and tree growth at the Hope Mills site was not stable over time (Figure 15). The significant negative association, suggesting that tree growth tends to be reduced during the warm phase of the NAO, shifted in the 1910s from the previous summer to current spring months, but the relationship ended during the mid-1980s. In addition, previous October NAO was negatively correlated with the growth from 1900 to 1950. For the positive relationships, beginning ca. 1940, winter (January and February) and August NAO were significantly correlated with tree growth. The October NAO, both in the previous and current year, showed a positive relationship during certain periods. The previous and current May were positively significant from 1930–1980s (Figure 15). The negative and positive correlations in different months sometimes grouped together to influence tree growth.

The moving correlations between AMO indices and the Hope Mills chronology showed two major patterns of significant relationships between 1856 and 2003. From the previous late summer to the end of the current growing season, the AMO index values showed statistically significant positive correlations with tree growth from the 1880s to 1920 (Figure 16). Since the late 1930s, the many significant negative correlations between AMO and tree growth across all months indicated more an annual influence on tree growth rather than a monthly or seasonal influence. But this negative association weakened around the 1980s, except that the relationship with the March and April AMO values lasted to the end of study period (Figure 16). Basically, cool phases of the AMO correspond with increased precipitation over much of the U.S, which cause faster tree growth, while warm phases of the AMO bring abnormally less precipitation in North America, producing lower-than-average tree growth.

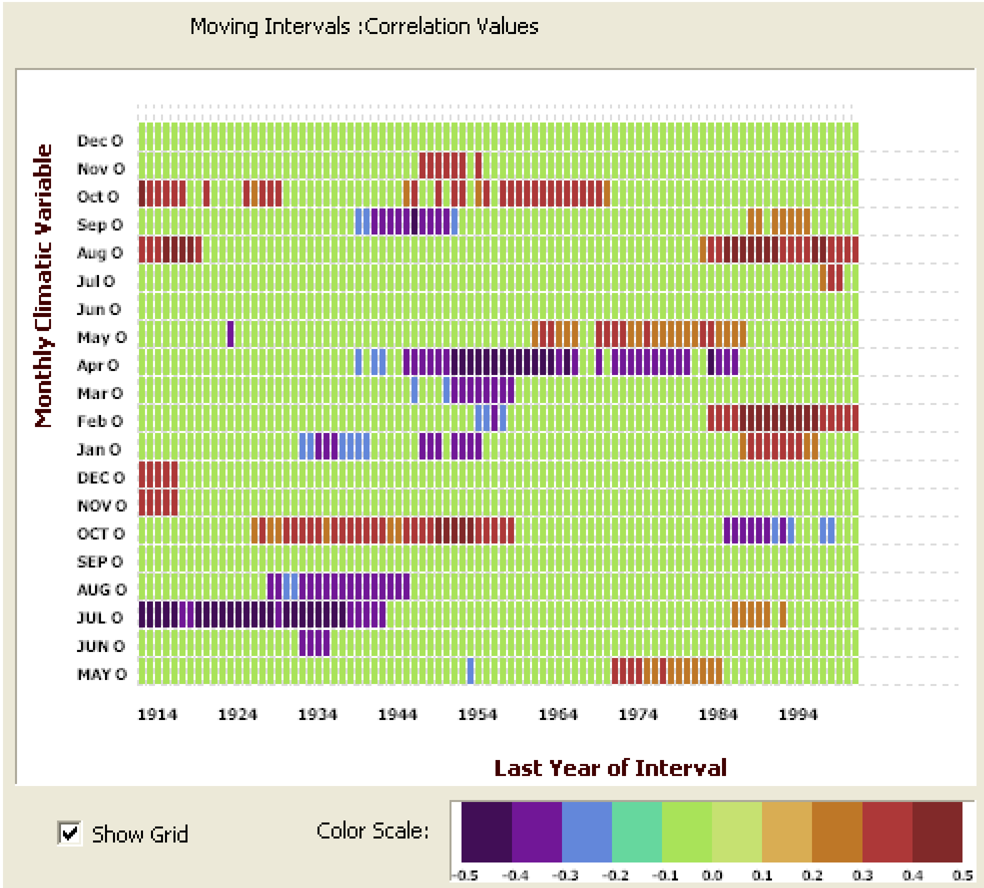

Figure 15. Moving correlation analysis between the NAO index and the Hope Mills chronology using 40-year moving intervals, from 1874 to 2003. Monthly NAO index is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1914 represents the period from 1874 to 1914. Different colors in the grid represent different levels of the correlation coefficient.

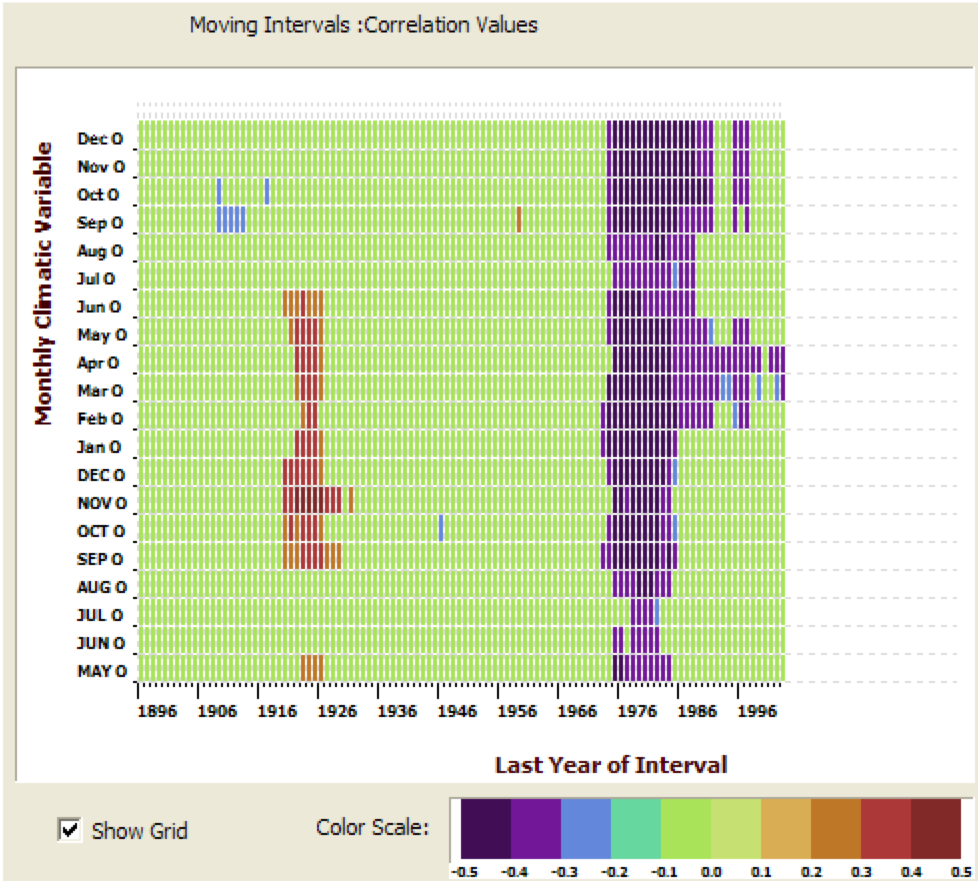

Figure 16. Moving correlation analysis between the AMO index and the Hope Mills chronology using 40-year moving intervals, from 1856 to 2003. Monthly AMO index is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1896 represents the period from 1856 to 1896. Different colors in the grid represent different levels of the correlation coefficient.

Few statistically significant correlations between the PDO index and the chronology were found before the mid-1930s, but I observed significant negative correlations in some decades afterward (Figure 17). The PDO index values of previous May through July and current March through June were significantly negatively correlated with tree growth in years around 1935–1980. During 1950–2000, the negative relationship shifted to February, early summers, and early winters. Positive PDO values in these seasons coincided with below-average ring growth (Figure 17). But overall, the strength of the association between growth and the PDO index was the weakest compared to the three other oscillations.

Although the SOI had the shortest period of analysis, it showed strong positive correlations with tree growth in months of previous August to current April, and current September and October (Figure 18). Since the late 1990s, significant correlations were generally weakened and significant months were reduced to previous September, November, and December. The positive relationship with current fall SOI was also weakened since the mid-1990s. In general, higher SOI values favored tree growth at Hope Mills.

5.3 Linville Mountain

5.3.1 Monthly Temperature, Precipitation, and PDSI Responses

Correlations showed that of 20 climatic variables analyzed, summer temperature, PDSI, and early summer precipitation exhibited the strongest seasonal relationships with radial growth (Figure 19). Temperatures from June through September of the current year were significantly negatively correlated with tree growth, while the association with March temperature was significantly positive. Precipitation in June and July were significantly positively correlated with growth (both $r=0.21$, $P<0.05$). High summer temperatures

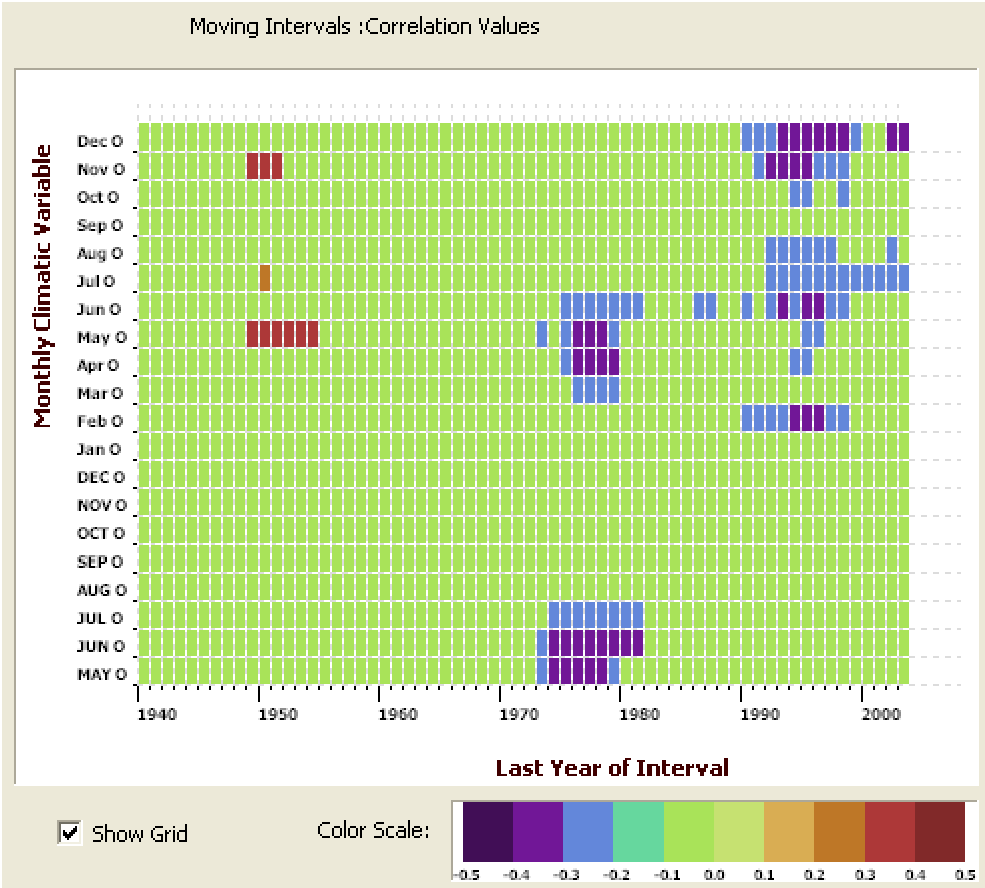

Figure 17. Moving correlation analysis between the PDO index and the Hope Mills chronology using 40-year moving intervals, from 1900 to 2003. Monthly PDO index is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1940 represents the period from 1900 to 1940. Different colors in the grid represent different levels of the correlation coefficient.

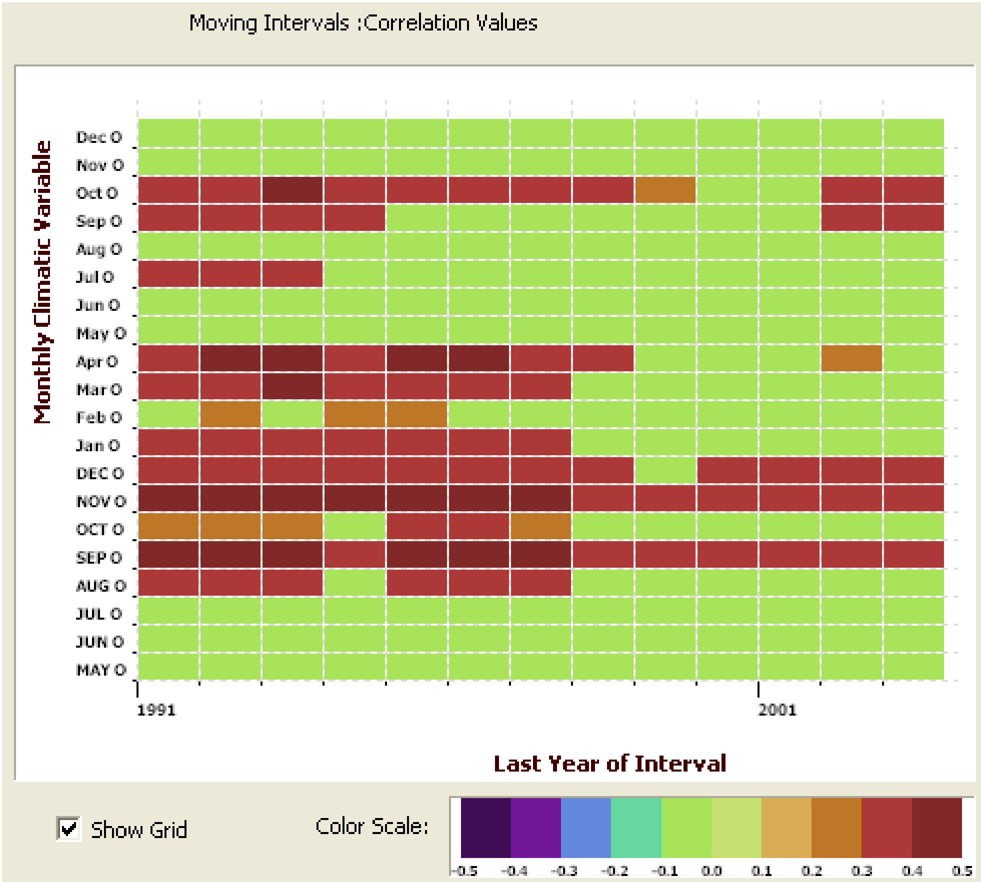

Figure 18. Moving correlation analysis between the Southern Oscillation Index (SOI) and the Hope Mills chronology using 40-year moving intervals, from 1951 to 2003. Monthly SOI is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1991 represents the period from 1951 to 1991. Different colors in the grid represent different levels of the correlation coefficient.

combined with low early summer precipitation induce drought conditions, which can be indicated by low values of PDSI. A positive relationship between PDSI and tree growth was found from June through September of the current growing season. Consequently, low values of PDSI in summer would coincide with below-average growth.

Results of the response function analysis did not show similarly high coefficients during summer of the current year for temperature and PDSI (Figure 20). Only July precipitation had a weak positive association with tree growth ($r=0.17$, $P<0.05$). A significant positive relationship between March temperature and radial growth was again detected, and is the only significant temperature variable ($r=0.19$, $P<0.05$). For PDSI, response function analysis revealed a weakly negative relationship between previous July PDSI and ring growth ($r= -0.12$, $P<0.05$) (Figure 20).

5.3.2 Monthly NAO, AMO, PDO, and ENSO Responses

Correlation analysis between four climate oscillation indices and the Linville Mountain chronology indicated different characteristics from that of the Coastal Plain site. At this site, ENSO exhibited the strongest relationship with tree growth (Figure 21). The significant positive correlations were evident from previous May until current February, but after winter, no significant relationships with SOI were found. The highest coefficients occurred in July and October of the previous year ($r_{P\ Jul.}=0.53$, $r_{P\ Oct.}=0.44$, $P<0.01$). The relationship between PDO and tree growth was the second strongest among these four. Unlike the Coastal Plain site, the coefficients of 20 PDO variables and the growth correlations were all negative. Significant negative values were found in September and December of the previous year, and February and April of the current year. The Linville

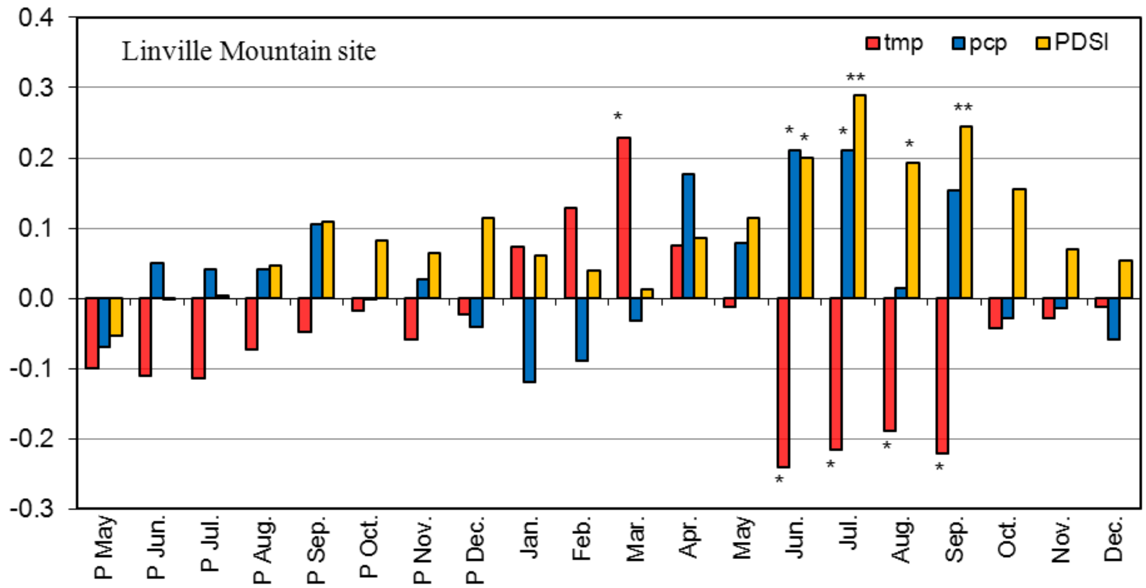

Figure 19. Correlations between the Linville Mountain chronology and monthly temperature (tmp), precipitation (pcp), and PDSI from previous May to current December (1895–2008) (*: P<0.05; **: P<0.01).

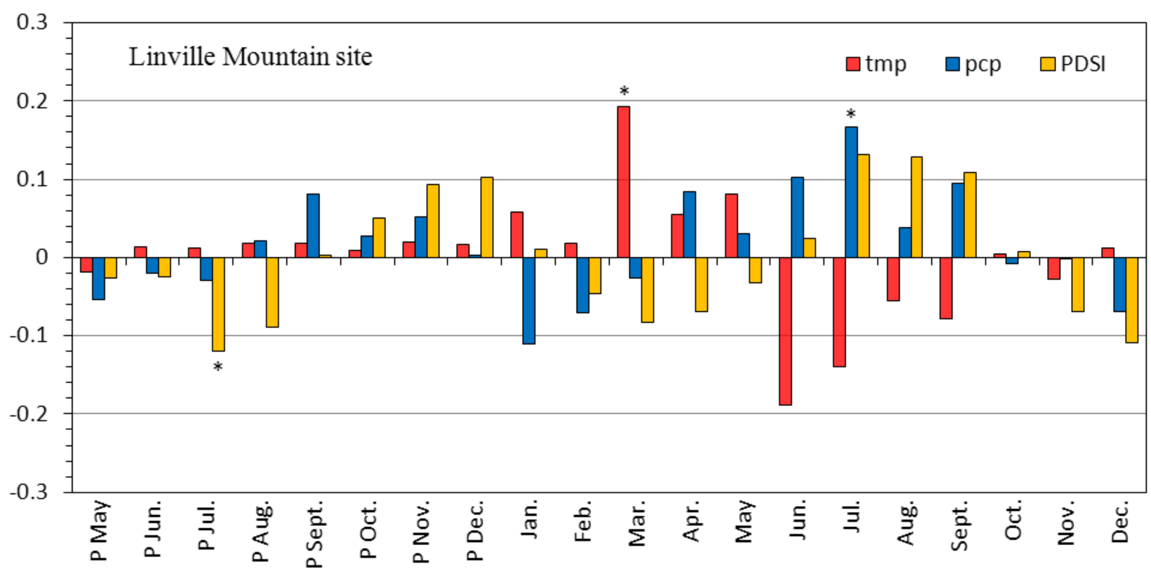

Figure 20. Response function coefficients for the Linville Mountain site (1895–2008) (*: P<0.05).

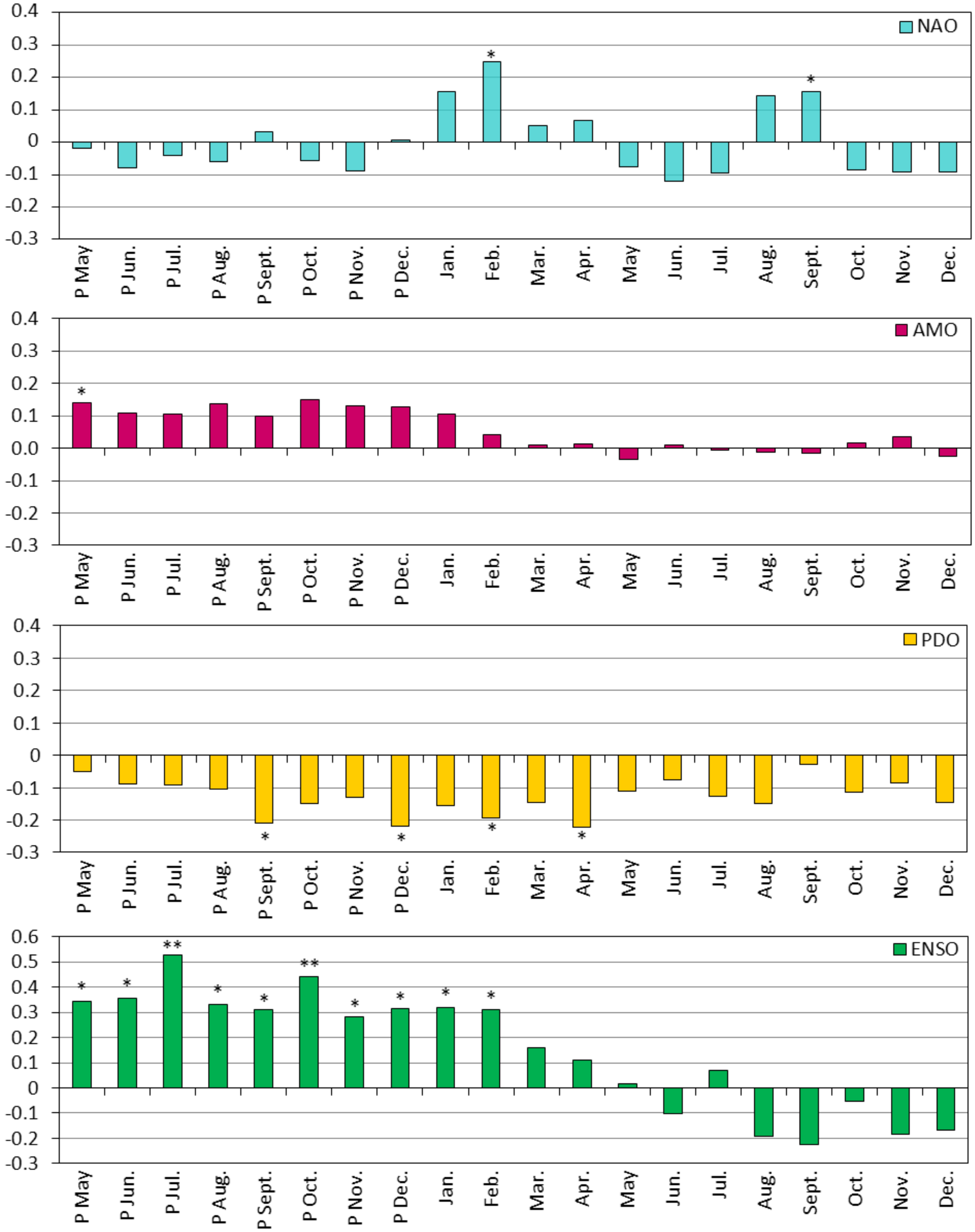

Figure 21. Correlation coefficients between monthly oscillation index values and the Linville Mountain chronology (*: P<0.05).

Mountain chronology was not strongly correlated with AMO index values. Previous May was the only month that showed a significant but weak positive association with tree growth, although other months in the previous year had similar values of coefficients. The correlation coefficients for months of the current year were all around zero, indicating a lack of linear association (Figure 21). February ($r=0.25$, $P<0.05$) and September ($r=0.16$, $P<0.05$) NAO indices were also found to be significant to tree growth, suggesting that the positive phases of the NAO coincided with increased tree growth, while negative phases tended to coincide with narrow rings.

5.3.3 Moving Interval Analysis

The pattern of temporal switches of climatic limiting factors on tree growth at the Linville Mountain site was less complex than at the Coastal Plain site, and was generally more easily identified. Long-term continuously significant temperature responses were found at Linville Mountain from 1895 to the 1970s (Figure 22). June and July temperatures were negatively correlated with growth from 1895 to 1975, suggesting that high temperatures in early summer contributed to decreased radial growth. Similar significant correlations between growth and September temperature appeared since ca. 1907, and lasted longer than the June and July signals until the last year of the analysis period. However, the correlation strength weakened beginning ca. 1950. Temperatures from January to March exhibited significantly positive correlations with tree growth since the 1950s.

Correlations between precipitation and tree growth exhibited an abrupt weakening in the late 1960s (Figure 23). In the early half of the 20th century, April–June and September precipitation showed strong positive correlations, while previous May precipitation showed negative correlations. In the latter half of the century, few significant, long-term relationships existed any longer, and weak negative correlations between August and November precipitation and tree growth appeared since late 1950s. PDSI did not show the bimodal significant correlation patches with growth over time. The period from 1895 to the 1970s exhibited significant positive relationships between PDSI and tree growth (Figure 24).

The Linville Mountain chronology did not show any consistent relationship with the NAO over time (Figure 25). In addition, the number of significant relationships at this site was much fewer than that at the Hope Mills site. The negative correlations between growth and NAO index values were significant in previous November and December from 1890 to 1960 and in current June from the 1920s to the last year analyzed. Significantly positive correlations in winter and summer existed before the first half of the 20th century and reappeared in a few of the most recent decades.

The relationships between the Linville Mountain chronology and AMO shifted over time (Figure 26). In general, negative correlations in the current summer switched to positive correlations in months of the previous year during the middle of the 20th century. Since the 1960s, previous May through December and the current summer months were strengthened and showed statistically significant correlations with tree growth. The Linville Mountain chronology exhibited significant climate-growth relationships more in a seasonal form rather than in an annual form.

Moving correlations between PDO index values and the Linville chronology were all negative (Figure 27). A winter PDO signal appeared since 1925 and strengthened in the mid-1940s, and then the significant relationship lasted to the last year analyzed. April PDO also showed a long-term significant correlation with tree growth since the mid-1910s. Previous

May to winter SOI values were consistently and positively correlated with tree growth over the entire analysis period (Figure 28), except the significance of previous November and December began about 1960. Negative correlations between tree growth and September and November SOI existed from 1955 to 2000. Overall, the positive relationship were dominant, indicating La Niña years tended to have increased tree growth, while El Niño years coincided with below-average annual growth.

5.4 Gold Mine Trail

5.4.1 Monthly Temperature, Precipitation, and PDSI Responses

Both correlation analysis and response function analysis indicated that tree growth at the Gold Mine Trail site was correlated more with temperature variables than with precipitation or PDSI (Figures 29 and 30). The most significant variables among the 60 analyzed were January ($r=0.43$, $P<0.01$) and February ($r=0.39$, $P<0.01$) mean temperatures. Warmer winters before the growing season were associated with increased radial growth, while colder winters tended to bring low increment growth. Winter precipitation and PDSI did not have strong correlations with growth. The response function coefficients complemented the results of the correlation analysis. Again, winter temperature (January and February) had the highest coefficients, suggesting that warmer winters lead to increased annual growth (Figure 30). No monthly precipitation or PDSI variables among these 20 months were significantly correlated with growth at the Gold Mine Trail site. Therefore, winter temperature is the only driving factor for yellow pine growth at this site.

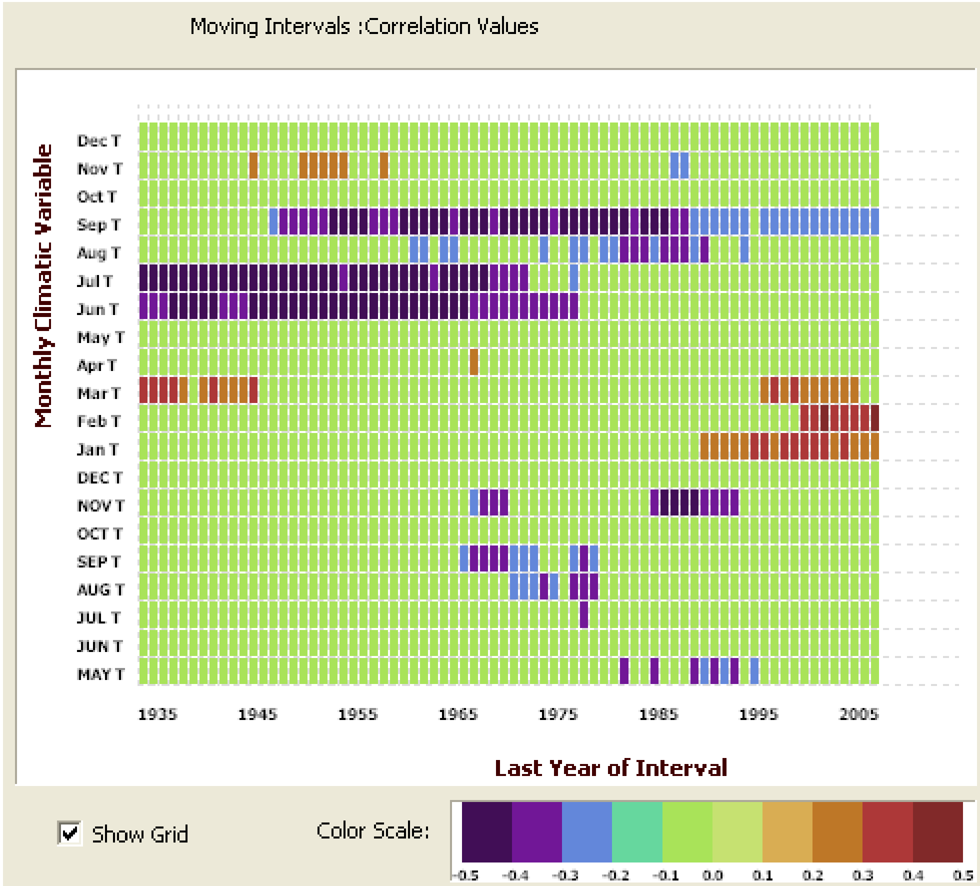

Figure 22. Moving correlation analysis between temperature and the Linville Mountain chronology, using 40-year moving intervals, from 1895 to 2008. Monthly temperature is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1935 represents the period from 1895 to 1935. Different colors in the grid represent different levels of the correlation coefficient.

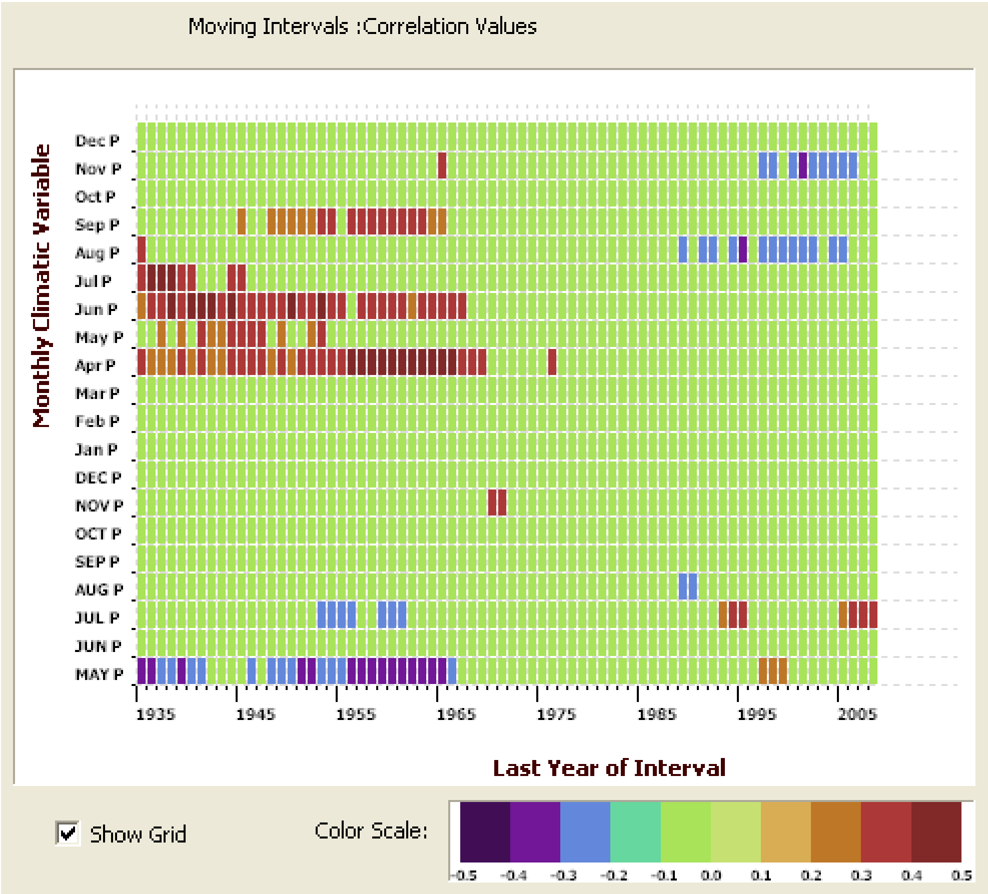

Figure 23. Moving correlation analysis between precipitation and the Linville Mountain chronology using 40-year moving intervals, from 1895 to 2008. Monthly precipitation is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1935 represents the period from 1895 to 1935. Different colors in the grid represent different levels of the correlation coefficient.

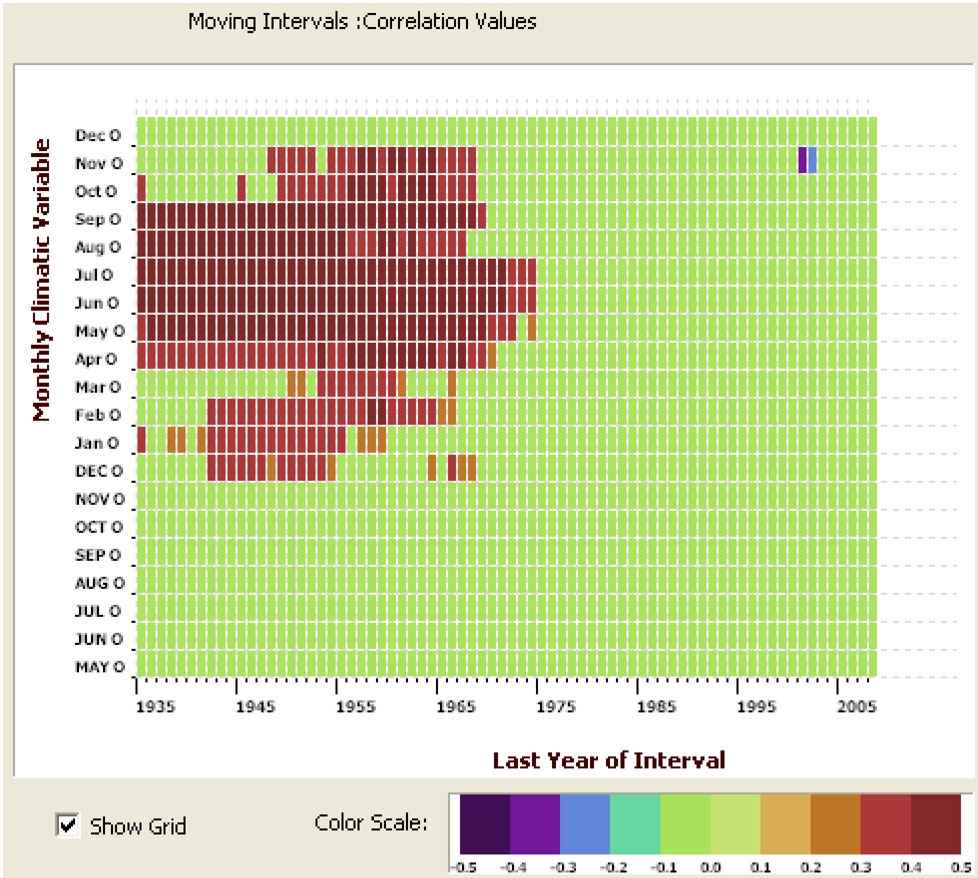

Figure 24. Moving correlation analysis between PDSI and the Linville Mountain chronology using 40-year moving intervals, from 1895 to 2008. Monthly PDSI is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1935 represents the period from 1895 to 1935. Different colors in the grid represent different levels of the correlation coefficient.

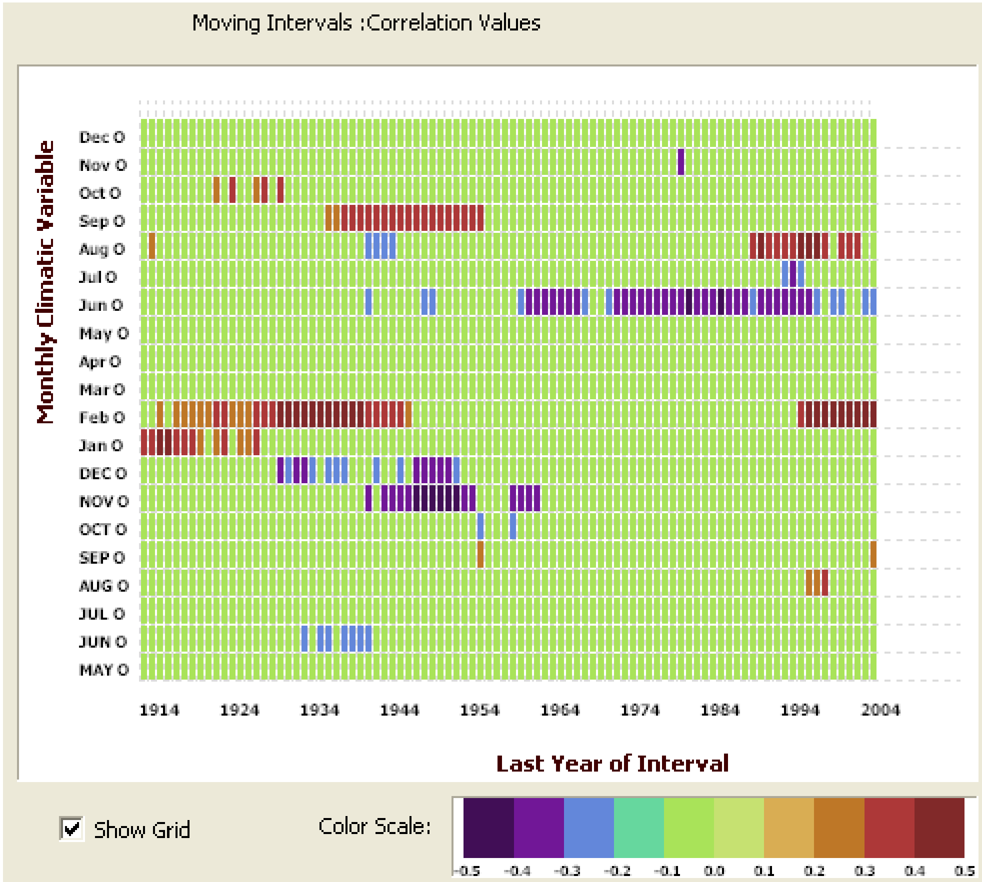

Figure 25. Moving correlation analysis between the NAO index and the Linville Mountain chronology using 40-year moving intervals, from 1874 to 2005. Monthly NAO index is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1914 represents the period from 1874 to 1914. Different colors in the grid represent different levels of the correlation coefficient.

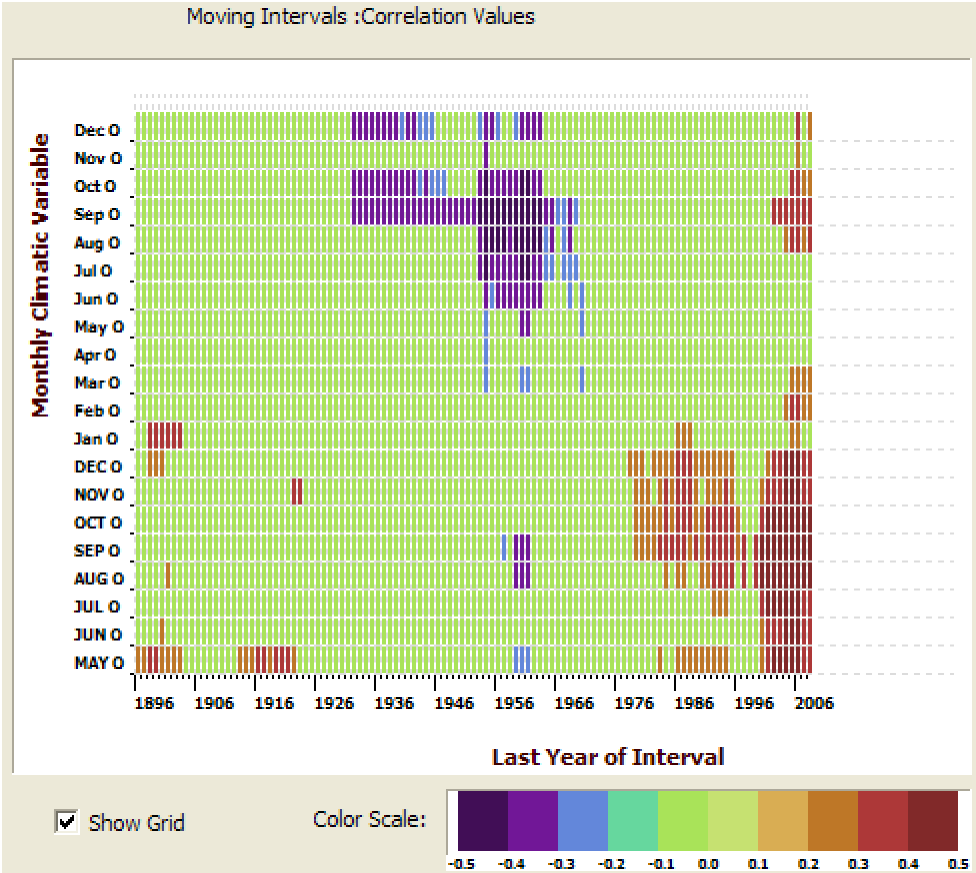

Figure 26. Moving correlation analysis between the AMO index and the Linville Mountain chronology using 40-year moving intervals, from 1856 to 2008. Monthly AMO index is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1901 represents the period from 1856 to 1896. Different colors in the grid represent different levels of the correlation coefficient.

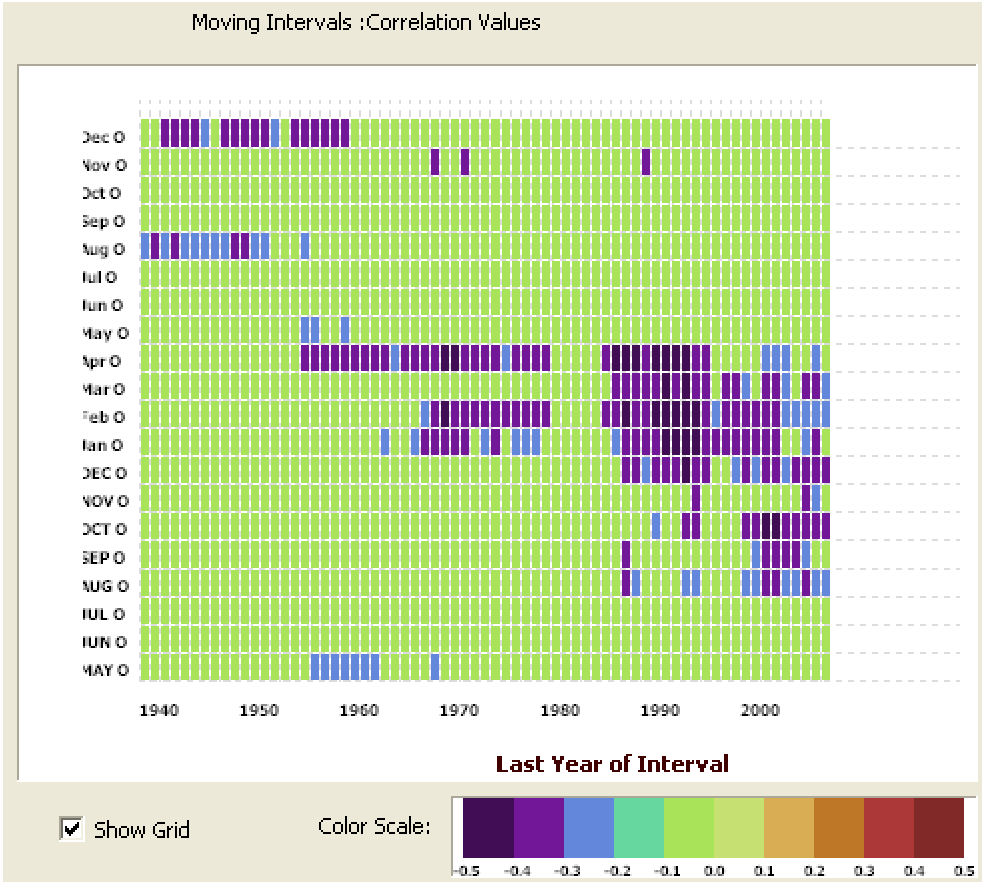

Figure 27. Moving correlation analysis between the PDO index and the Linville Mountain chronology using 40-year moving intervals, from 1900 to 2008. Monthly PDO index is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1940 represents the period from 1900 to 1940. Different colors in the grid represent different levels of the correlation coefficient.

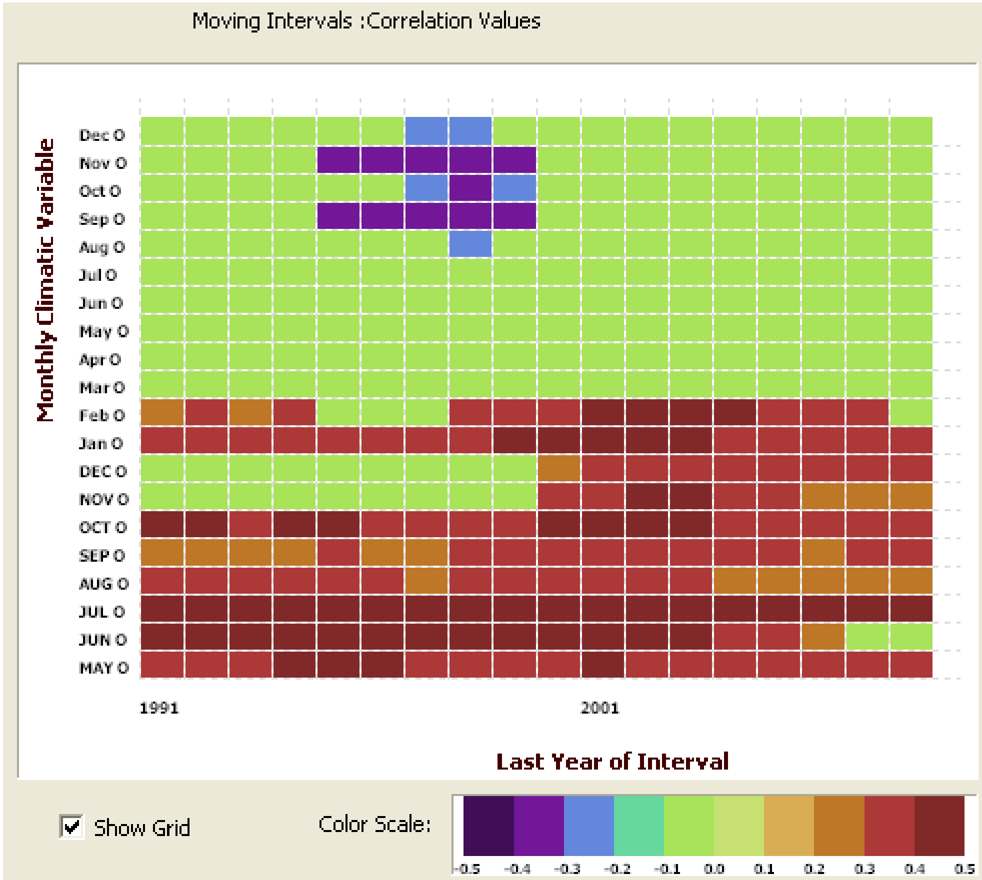

Figure 28. Moving correlation analysis between Southern Oscillation Index (SOI) and the Linville Mountain chronology using 40-year moving intervals, from 1951 to 2008. Monthly SOI is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1991 represents the period from 1951 to 1991. Different colors in the grid represent different levels of the correlation coefficient.

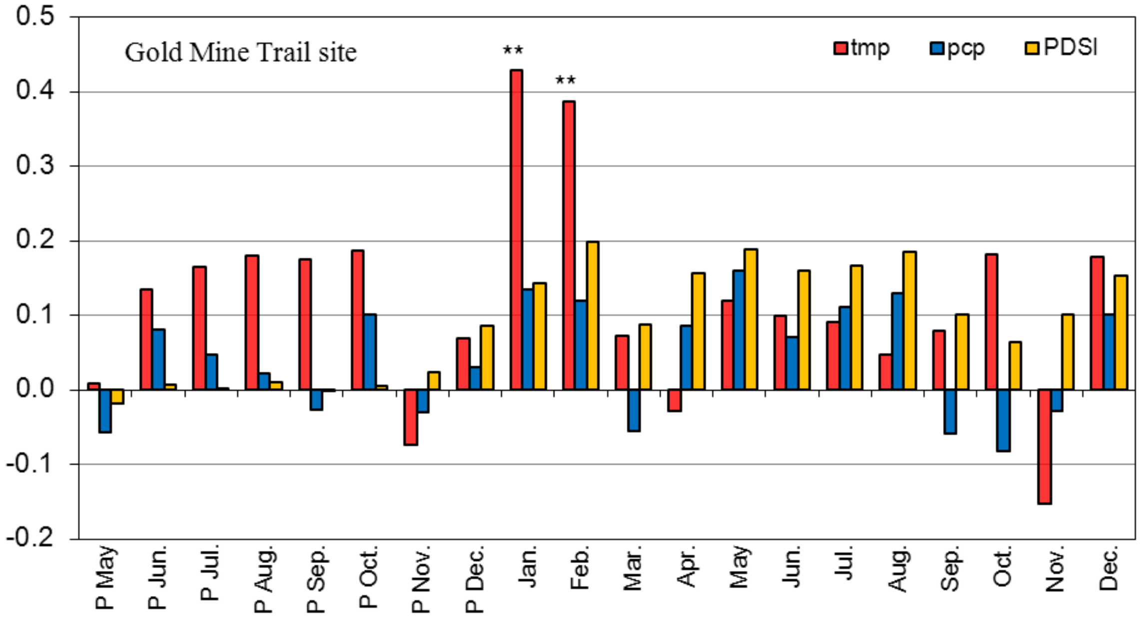

Figure 29. Correlations between the Gold Mine Trail chronology and monthly temperature (tmp), precipitation (pcp), and PDSI from previous May to current December (1895–2006) (*: P<0.05; **: P<0.01).

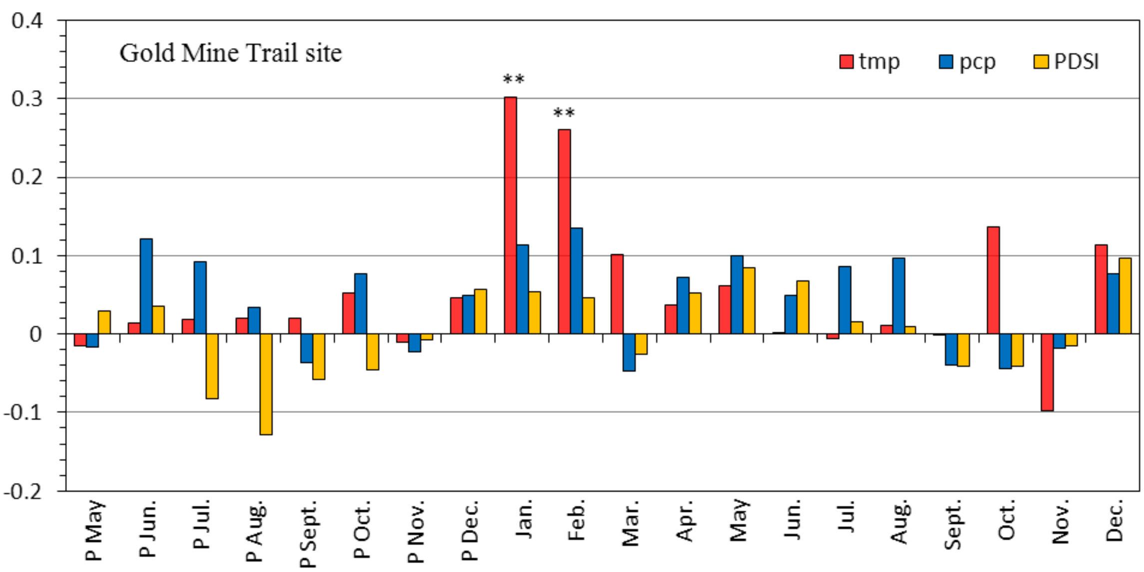

Figure 30. Response function coefficients for the Gold Mine Trail site (1895–2006) (*: P<0.05).

5.4.2 Monthly NAO, AMO, PDO, and ENSO Responses

Bootstrapped correlation analysis between monthly index values of four climate oscillations and the Gold Mine Trail chronology indicated complex oceanic-atmospheric effects and different relationships from the previous two sites (Figure 31). For NAO, previous November values were negatively correlated with growth ($r = -0.16$, $P<0.05$), while January ($r=0.25$, $P<0.05$), February ($r=0.24$, $P<0.05$), and August ($r=0.21$, $P<0.05$) were correlated positively. The AMO exhibited the strongest association with growth among the four climate oscillations because all coefficients calculated in the correlation analysis were significant ($P<0.05$), excluding current July. Correlation coefficients were all positive, suggesting that Gold Mine Trail tree growth tended to increase during warm phases of the AMO, but decreased during cool phases. Previous summer and fall AMO seemed more influential to tree growth than the AMO in the current growing season. PDO index values of early spring (January to March) and summer (July to September) were negatively associated with tree growth. Although all correlation coefficients between SOI and growth were positive, no ENSO variables were shown to significantly affect growth (Figure 31).

5.4.3 Moving Interval Analysis

Moving correlation analysis conducted in DENDROCLIM2002 showed a strengthened and continuous response to winter (January and February) temperature in the latter half of the 20^{th} century (Figure 32). From 1930 to 1980, previous summer temperature (previous July and August) and temperatures during the current growing season (May to July) showed significantly positive correlations as well. In the first half of the century, no winter temperature signals were present, but in this period PDSI and precipitation of May, July, and

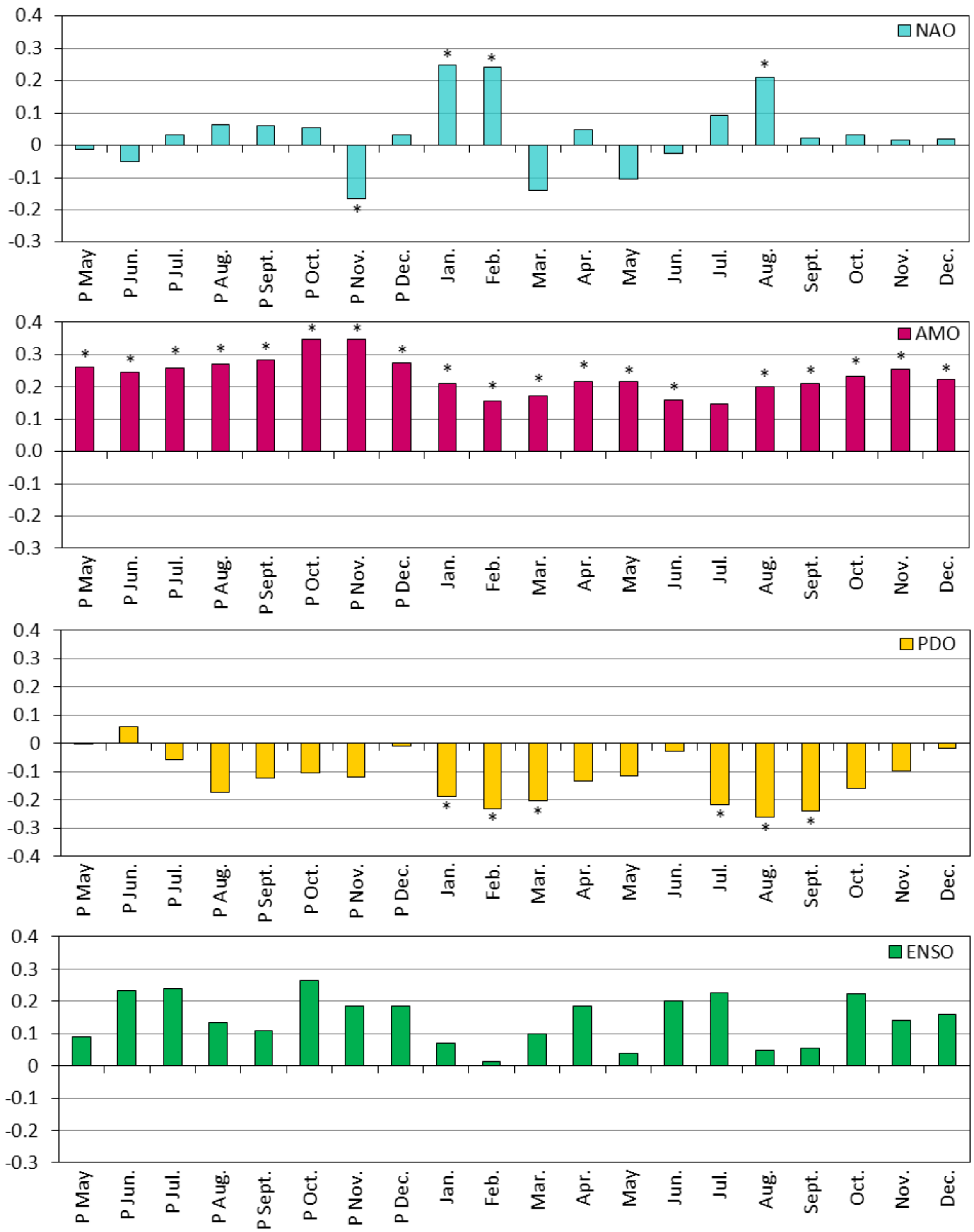

Figure 31. Correlation coefficients between monthly oscillation index values and the Gold Mine Trail chronology (*: P<0.05).

previous October were positively correlated with growth (Figures 33 and 34). The relationship between growth and precipitation and PDSI also shifted around the mid-20th century. February precipitation turned out to be more significant after the 1960s. The positive relationship between growth and December precipitation also appeared after the 1950s and lasted into recent years (Figure 33). The relationship between growth and PDSI was weakened in the mid-1950s, but was back to a similar strength of significance around 1990. Moving interval analysis suggested a strengthening of the response to both PDSI, and May and December precipitation in the second half of the 20th century (Figure 34).

Moving analyses on the four climate oscillations showed relatively more consistent significant correlations with PDO and AMO index values compared with unpatterned moving interval analysis of the NAO and ENSO. The NAO was significantly correlated with tree growth in several different months over the study period, but winter NAO values were positively correlated with growth since the 1950s (Figure 35). Summer PDO had a negative relationship with growth between 1900 and 1960, while winter PDO significantly correlated with growth from 1940 to 2006 (Figure 37). Although the negative association between PDO and tree growth was apparent over time, the stronger relationship between AMO and tree growth probably indicates that the Gold Mine Trail chronology is more responsive to climate variability in the Atlantic Ocean than the Pacific Ocean (Figure 36). Since the 1900s, the AMO index values of the previous year were consistently significantly correlated with tree growth until the beginning of the current century. During the 1930s to ca. 1990, the summer and fall seasons of the current year also showed significant positive relationships between AMO and growth. Although the positive correlations were dominant over time, a significant negative relationship existed from current July to December in the period 1880–1920s.

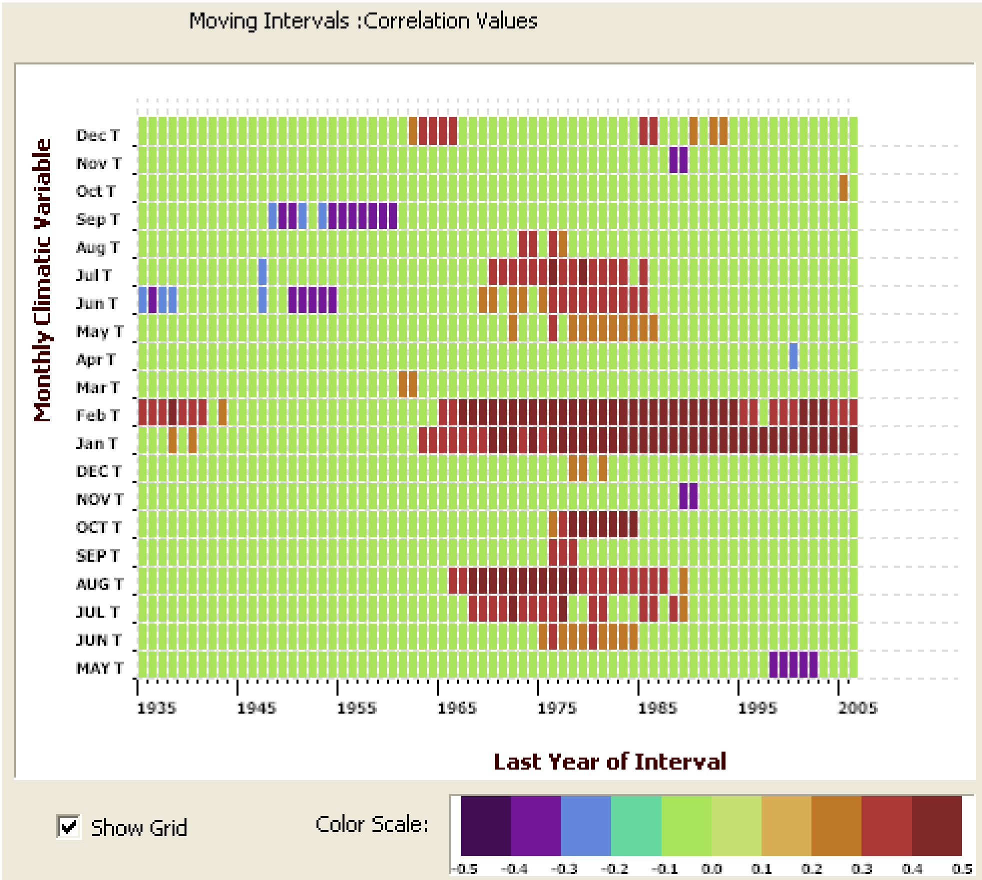

Figure 32. Moving correlation analysis between temperature and the Gold Mine Trail chronology, using 40-year moving intervals, from 1895 to 2006. Monthly temperature is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1935 represents the period from 1895 to 1935. Different colors in the grid represent different levels of the correlation coefficient.

Before the 1900s, positive correlations were scattered in several months (Figure 36). For the ENSO, previous June, July, and October SOI values were correlated positively with growth from the 1950s to mid-1990s (Figure 38). The ENSO signal was weak at the Gold Mine Trail site, and no shifts were observed over time.

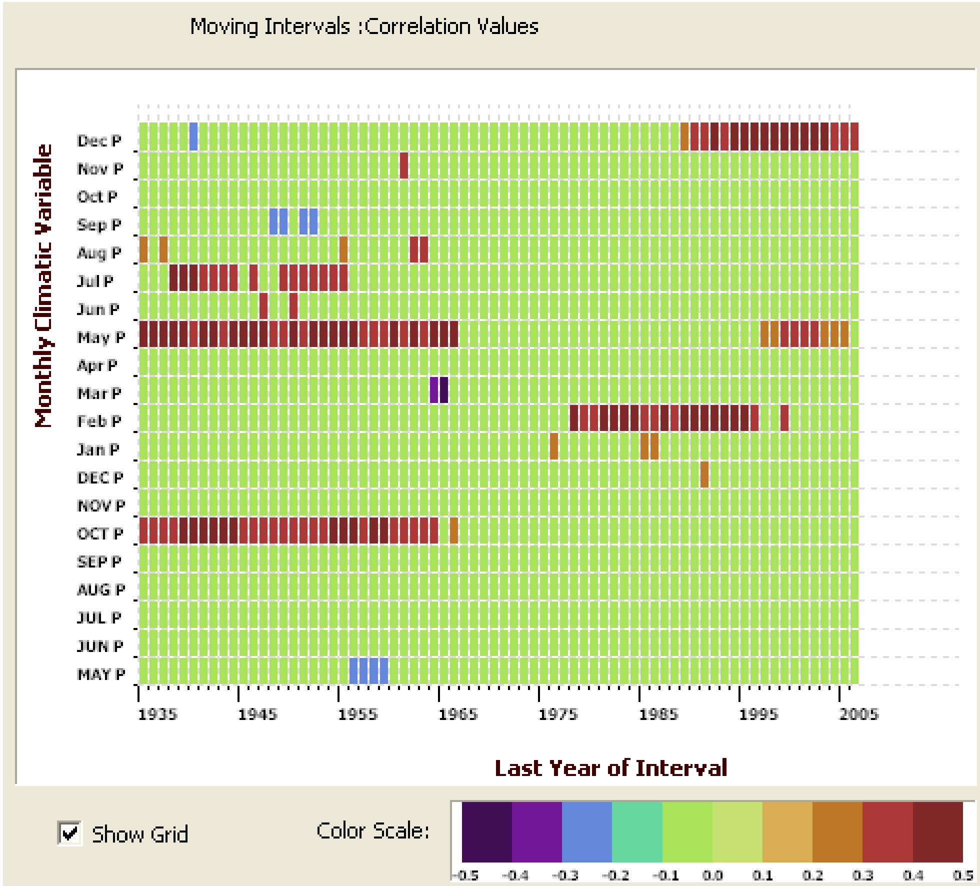

Figure 33. Moving correlation analysis between precipitation and the Gold Mine Trail chronology using 40-year moving intervals, from 1895 to 2006. Monthly precipitation is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1935 represents the period from 1895 to 1935. Different colors in the grid represent different levels of the correlation coefficient.

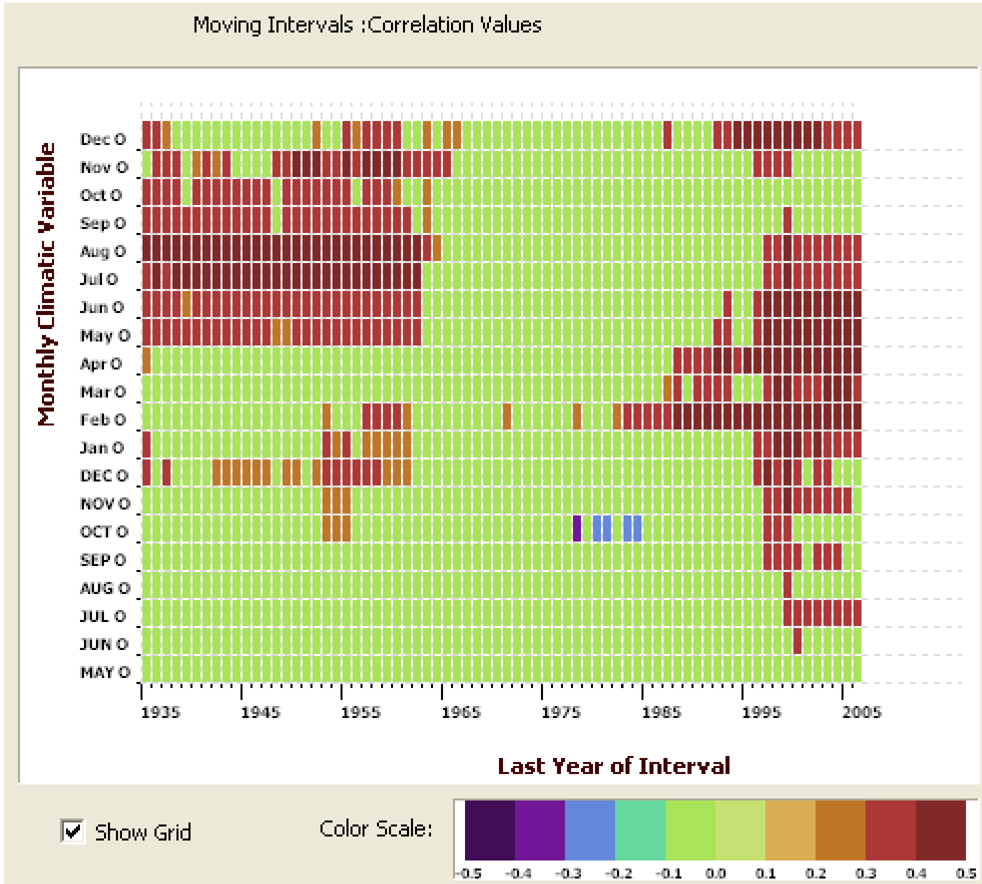

Figure 34. Moving correlation analysis between PDSI and the Gold Mine Trail chronology using 40-year moving intervals, from 1895 to 2006. Monthly PDSI is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1935 represents the period from 1895 to 1935. Different colors in the grid represent different levels of the correlation coefficient.

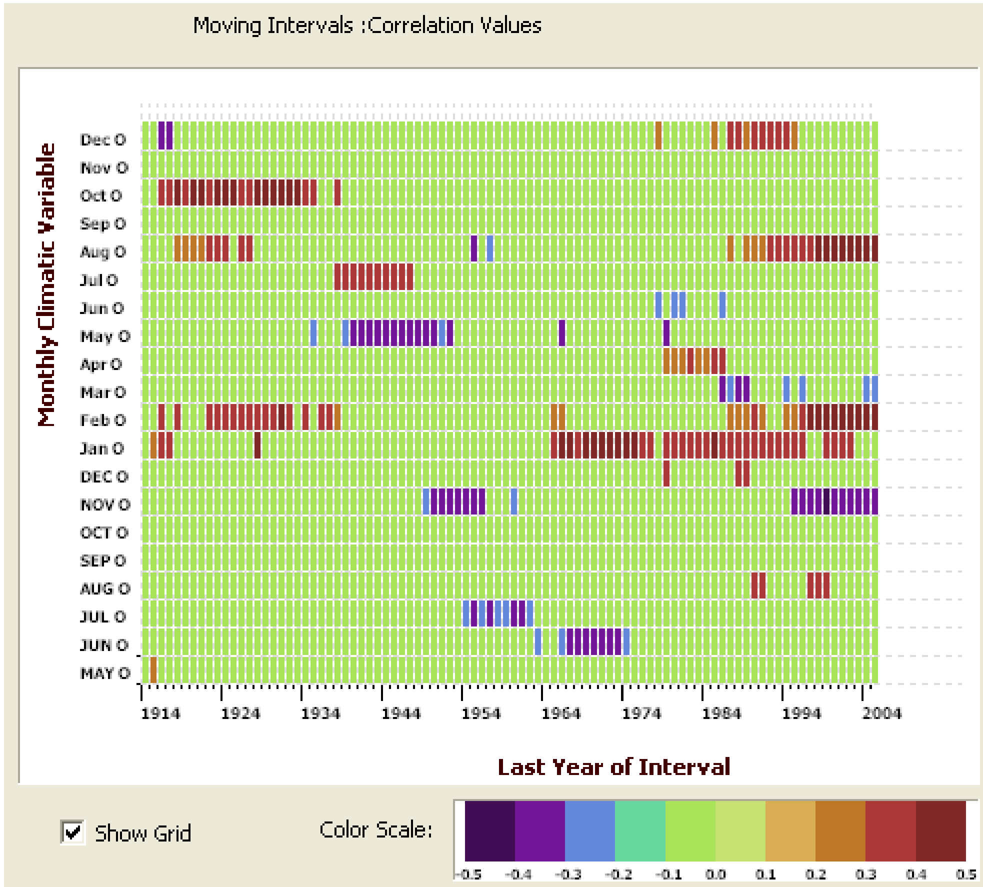

Figure 35. Moving correlation analysis between the NAO index and the Gold Mine Trail chronology using 40-year moving intervals, from 1874 to 2005. Monthly NAO index is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1914 represents the period from 1874 to 1914. Different colors in the grid represent different levels of the correlation coefficient.

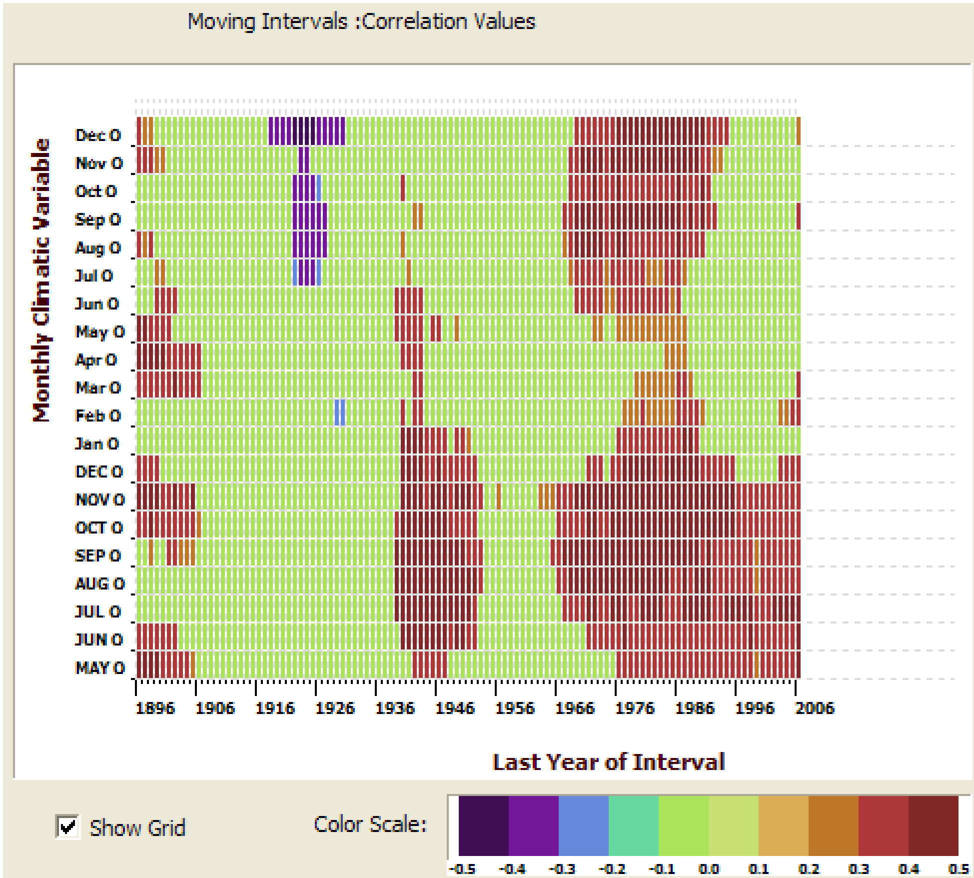

Figure 36. Moving correlation analysis between the AMO index and the Gold Mine Trail chronology using 40-year moving intervals, from 1856 to 2006. Monthly AMO index is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1901 represents the period from 1856 to 1896. Different colors in the grid represent different levels of the correlation coefficient.

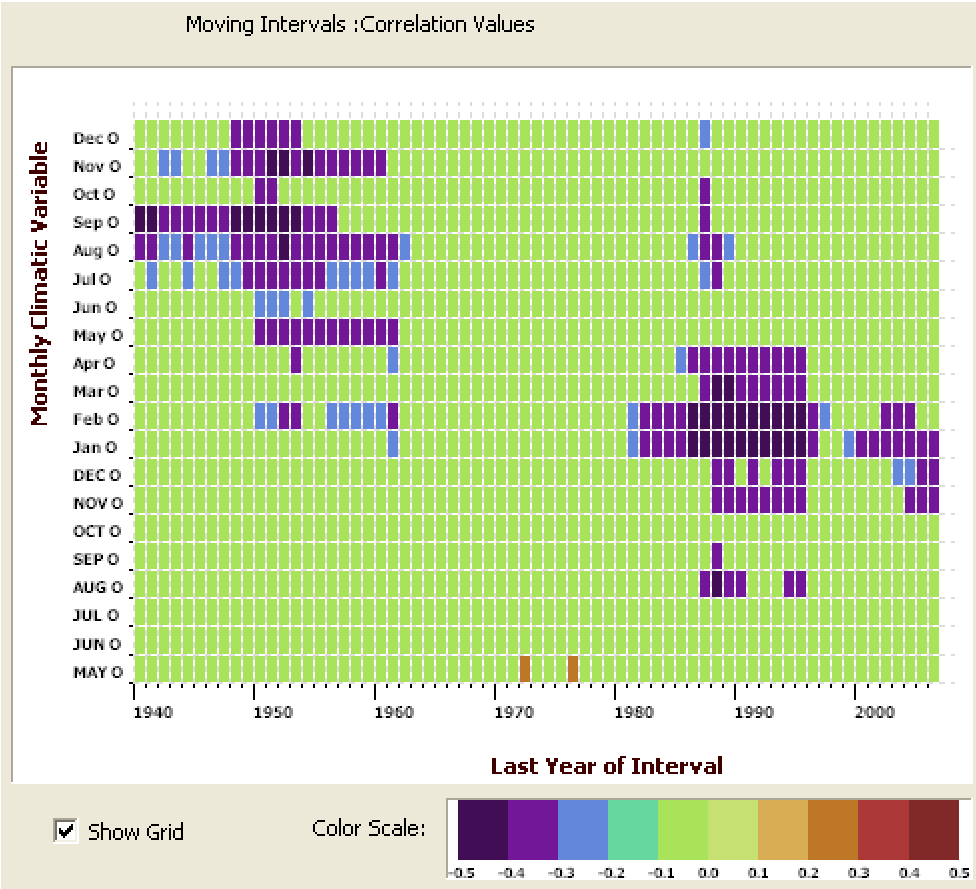

Figure 37. Moving correlation analysis between the PDO index and the Gold Mine Trail chronology using 40-year moving intervals, from 1900 to 2006. Monthly PDO index is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1940 represents the period from 1900 to 1940. Different colors in the grid represent different levels of the correlation coefficient.

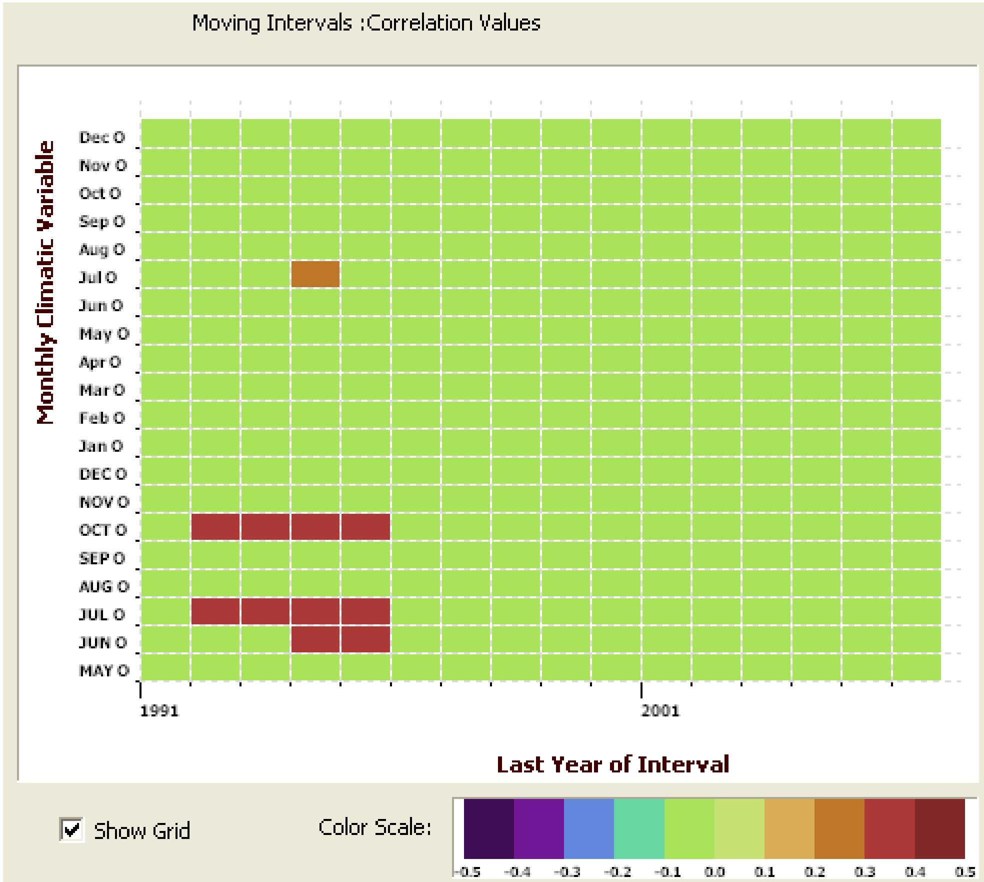

Figure 38. Moving correlation analysis between the Southern Oscillation Index (SOI) and the Gold Mine Trail chronology using 40-year moving intervals, from 1951 to 2006. Monthly SOI is listed on the y-axis, beginning with previous May (bottom) and ending with current December (top). Last years of moving intervals are listed on the x-axis. For example, a grid square marked 1991 represents the period from 1951 to 1991. Different colors in the grid represent different levels of the correlation coefficient.

5.5 Climate Responses in the Composite Chronology

The relationships between four oceanic-atmospheric oscillations and regional tree growth were preliminarily tested using the composite chronology and monthly NAO, AMO, PDO, and ENSO index data from previous May to current December. Bootstrapped correlation analysis and response function analysis were obtained using the DENDROCLIM2002 program.

Correlation results and response function results showed the same NAO variables that had significant relationships with tree growth. Winter (particularly January and February), August, and October NAO values exhibited strongly positive associations with growth (Figure 39). High index values of NAO in these months mostly coincided with increased tree growth, while low NAO values were associated with below-average growth. Significant relationships between AMO values and the composite chronology were found in months of the previous year in the correlation analysis (Figure 40). No relationships were shown in the response function analysis. Bootstrapped correlations between PDO variables and averaged ring width were negatively significant in February to May, July to August, October, and December of the current year (Figure 41). Response function analysis did not show a similar pattern. Thus, it is not convincing that higher PDO values of the current year bring decreased growth, while lower PDO values tend to cause increased growth. The SOI, a measure of the strength of ENSO, was strongly positively correlated with regional tree growth during all previous months in analysis and also during January, April, and July of the current year (Figure 42). Although the significant relationships were suggested in correlation analysis, still no evident associations were detected in the response function analysis between SOI values and growth. Basically, if the previous year is a La Niña year (high SOI value), tree growth in the region tended to increase, while growth tended to decrease during an El Niño year.

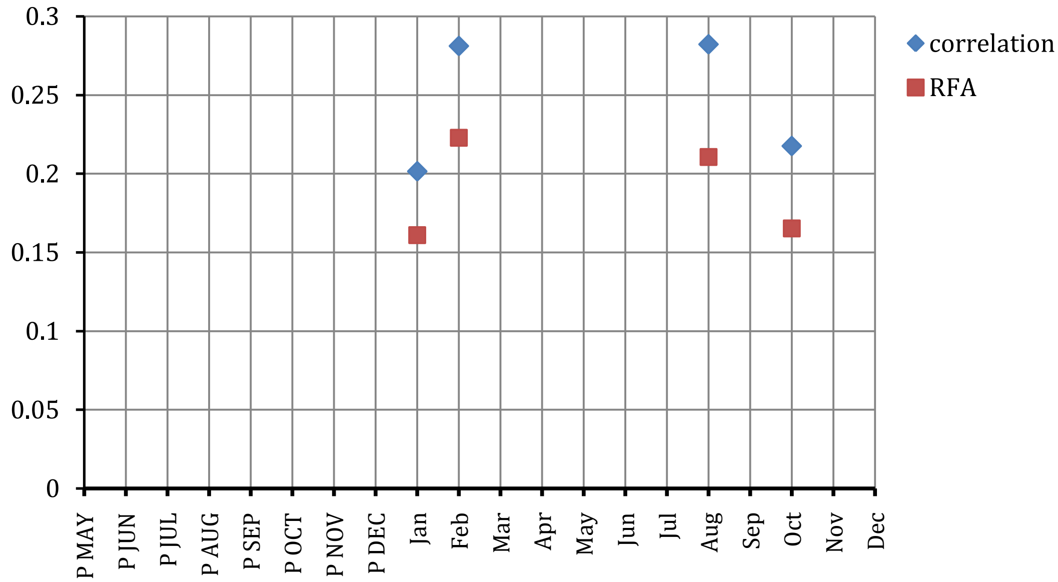

Figure 39. Correlation and response function significant coefficients between the composite chronology and monthly NAO index from the previous May to the current December (1874-2003). Coefficients with significant level higher than 5% are marked using colors, and all non-significant coefficients are marked equal to zero.

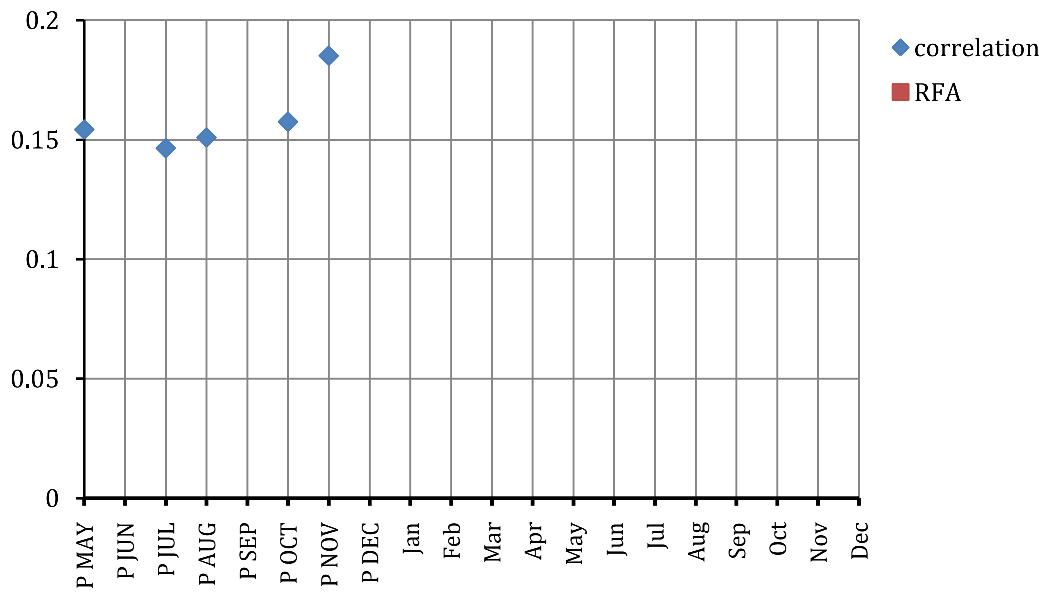

Figure 40. Correlation and response function significant coefficients between the composite chronology and monthly AMO index from the previous May to the current December (1856-2003). Coefficients with significant level higher than 5% are marked using colors, and all non-significant coefficients are marked equal to zero.

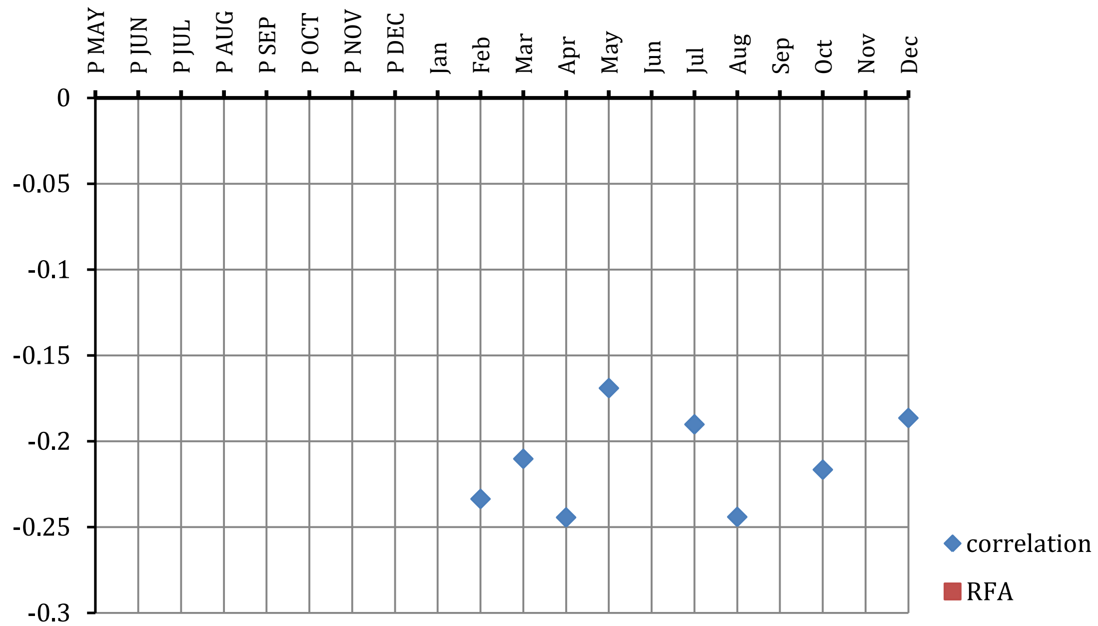

Figure 41. Correlation and response function significant coefficients between the composite chronology and monthly PDO index from the previous May to the current December (1900-2003). Coefficients with significant level higher than 5% are marked using colors, and all non-significant coefficients are marked equal to zero.

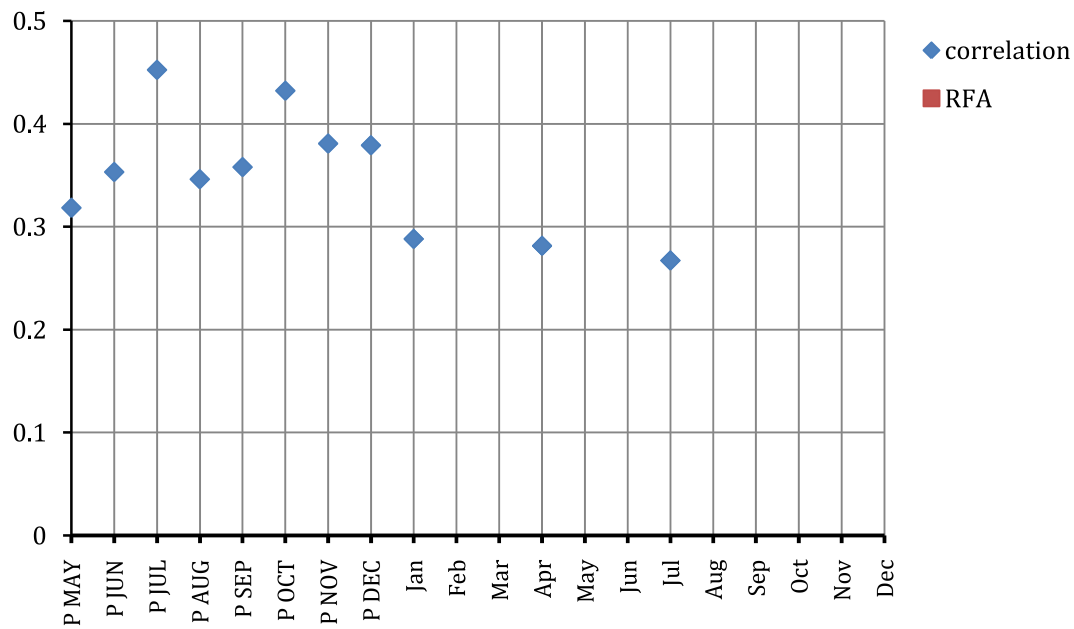

Figure 42. Correlation and response function significant coefficients between the composite chronology and monthly SOI from the previous May to the current December (1951-2003). Coefficients with significant level higher than 5% are marked using colors, and all non-significant coefficients are marked equal to zero.

CHAPTER 6

DISCUSSION

6.1 Chronologies and Extreme Climatic Events

The three sites of Hope Mills, Linville Mountain, and Gold Mine Trail yielded individual chronologies of varying lengths but similar quality in terms of mean sensitivity and interseries correlation. All three had mean sensitivity values higher than 0.27, while their interseries correlation values were higher than 0.52, both exceeding the average levels in the published dendrochronological literature for the southeastern U.S. The Hope Mills longleaf pine chronology is remarkably longer than the other two because it was built using logs from historical structures. The Linville Mountain chronology is the shortest mainly because old-growth Table Mountain pines were difficult to find in those forests. These three pine chronologies from the southeastern United States shared a common period of A.D. 1828–2003. During this period, decadal climate variability was observable, especially in the form of extreme climatic events. Trees responded to and recorded the influence of climate factors. Inspecting the chronologies, indications of severe climate episodes were evident in several decades. To aid the identification of trends in tree growth over time, smoothed 5-year moving averages were calculated.

6.1.1 The 1830s–1840s

Although chronologies in this study were too short to examine the centennial climate variability, the ending period of the Little Ice Age (A.D. 1400 to 1850) still acted as a negative effect on tree growth, as seen in the below-average ring growth for the years from ca. 1820 to 1850 (Figure 7). At the coastal Hope Mills site, constrained growth can be seen clearly during this period (Figure 7c). At the Linville Mountain site, one notable growth suppression occurred in the 1840s and lasted nearly a decade (Figure 7a). At the Gold Mine Trail site, however, the 1830s–1840s period did not show significant anomalies in radial tree growth (Figure 7b). Climate variations apparently influenced the growth. The climate of the period from the 1830s to the 1840s in the United States was previously investigated by Wahl (1968), and the results showed that climate was colder and wetter in some regions over the eastern and central parts of the country than it was in the time from 1930 to 1940. Furthermore, Wahl (1968) interpreted that the Appalachian Mountains acted as a distinct influence to the pattern of climate in this period, as shown by the decreased growth patterns within my three chronologies over the 1830s to 1840s. In my study, the reduced tree growth in the Atlantic coastal site was distinct from the growth pattern observed in the western Appalachians. Further studies in recent decades suggested that the reduced growth during the 1830s might be also tied to decadal fluctuations in North Atlantic climate (Jacoby and D'Arrigo 1992, D'Arrigo *et al.* 1996, Ruffner and Abrams 1998).

6.1.2 The 1890s

The period A.D. 1890–1900 is a notable phase with obvious decreased tree growth in all three chronologies. In the Coastal Plain site and the western southern Appalachians site, this long-term (7–10 years) below-average growth was more significant than at the eastern southern Appalachians site, for which the growth was just slightly constrained over the 1890s (Figure 7). It is also noteworthy that, although a difference in the 5-year smoothing average existed between the Linville Mountain site and the other two, the pattern of ring widths of individual years within the 1890s was very similar. For example, 1891/1892, 1895, and 1899 were years of anomalously low growth likely associated with climate anomalies. On a regional scale, the years 1894 and 1895 were reported as having widespread, severe droughts; and 1899 was the year with an influential drought in the late 1890s (Warrick 1980, Ruffner and Abrams 1998). Ruffner and Abrams (1998) provided evidence of reduced growth of chestnut oaks in central Pennsylvania consistent with the drought. On a larger spatial scale, the Northern Hemisphere temperature series over 1851–1984 from meteorological data suggested that the intervening decades of the 1880s and 1890s were the coldest of that period (Jones *et al*. 1986). Within the reconstructed Northern Hemisphere temperature series, decreased temperatures occurred before the 20th century's increasing temperature trend (Overpeck *et al.* 1997, Jones *et al*. 1998, Mann and Jones 2003). Overall, the 1890s reduced ring-growth in my chronologies could have been caused by severe short-term drought events and from the globally colder-than-normal temperatures, separately or together.

6.1.3 The Dust Bowl of the 1930s

The 1930s was a difficult time in American history in terms of both the severe climate conditions and the economic Great Depression. Beginning in 1932, extensive dirt blew from the Great Plains to the east coast and was eventually deposited in the Atlantic Ocean. From 1934 to 1936, three record drought years occurred. In 1936, a more severe storm spread out of the plains and across most of the nation (Bonnifield 1979). This long-term event of drought-induced dust storms in 1930s was named the "Dust Bowl." Technically, the Dust Bowl originally referred to the driest states of the southern Great Plains at that time, and many dust storms started there, but the entire region, and eventually the entire country, was affected (Worster 1979). Evidence of the dry conditions of the Dust Bowl was not clearly shown in these chronologies, where reduced ring growth would have been expected under such unfavorable conditions (Figure 7). The study areas might not be severely influenced by such conditions, however, and thus environmental conditions for tree growth were not changed greatly during this event. The Palmer Hydrological Drought Index map of 1934 (Figure 43), provided by the National Climatic Data Center, illustrated the mid-range or moderate drought levels in the study areas. Therefore, tree growth reflected the regional effects of this national event. Furthermore, this suggests that trees have the potential to be used to help identify the geographic range of a severe climate event.

6.1.4 Severe Drought in the 1950s

Low rainfall amounts and excessively high temperatures caused severe drought in the 1950s mainly over the Great Plains and the southwestern U.S. It was a five-year drought (1952–1956), and in three of these years, drought conditions stretched coast to coast. In the three tree-ring chronologies, the 1950s drought was illustrated at different magnitudes based on the tree-growth conditions. For the coastal Hope Mills site, values of ring indices for the entire chronology were lowest in the 1940s (Figure 7c). Radial growth of Table Mountain pines at Linville Mountain decreased in the beginning years of the 1950s, but, by 1955, growth had recovered back to an above-average level (Figure 7a). At the inland Gold Mine Trail site, ring-growth was not reduced in the 1950s, as had been expected (Figure 7b), except for the ring indices of 1953 and 1954, which were much lower than those of neighboring years. This severe drought event coincided with relatively cool surface temperatures (SSTs) in the tropical Pacific, and concurrently with relatively warm SSTs in

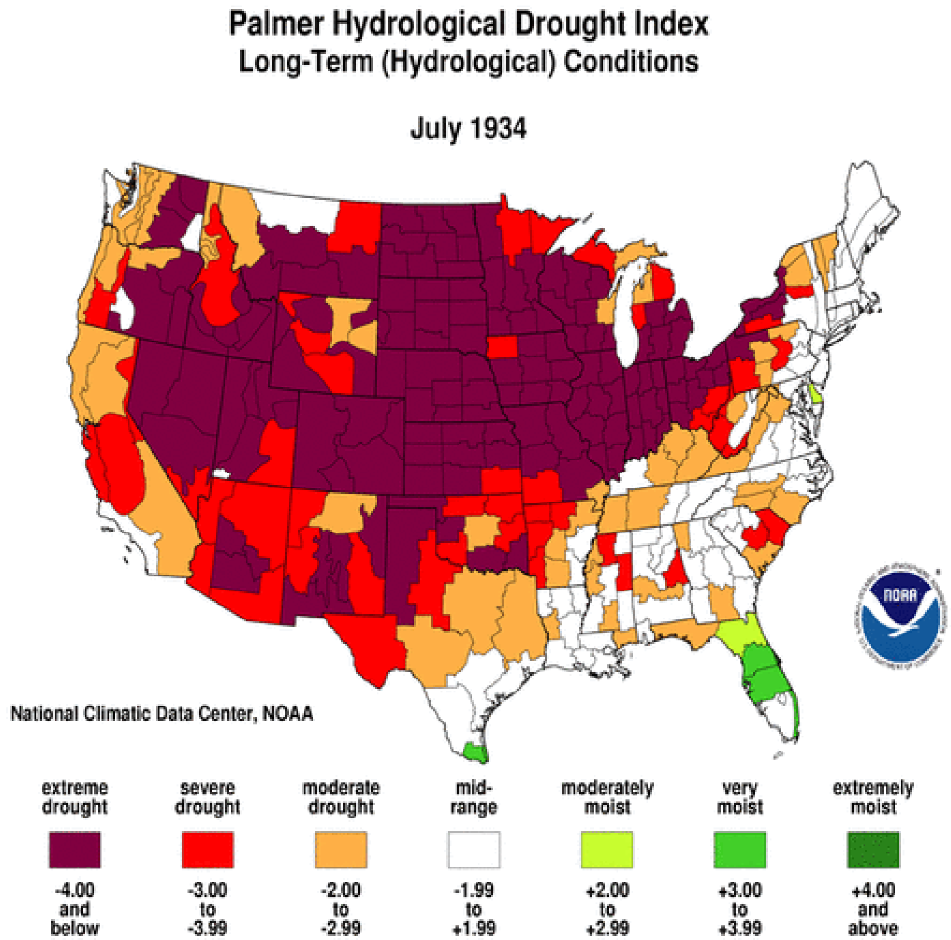

Figure 43. The Palmer Hydrological Drought Index map of 1934. As the most severe year during the Dust Bowl of 1930s, this map shows the areas with different levels of drought across the U.S. (from National Climatic Data Center, NOAA)

the North Atlantic (Diaz and Gutzler 2000). The southwestern U.S. was more affected by this severe drought than the southeastern U.S.

6.1.5 Post-1990

The trend of tree growth in the most recent two decades was interesting and consistent among three sites: tree growth was rapid in 1989–1990, followed by decreased growth in 1992/1993. A gradually increasing growth trend followed until the last year of each chronology. This pattern in these three chronologies coincided well with changes in global average temperature. The 1994 IPCC report reported global average temperature changes from 1861 to 1992 (Figure 44; IPCC 1994). Lamb (1995) interpreted the temperature pattern:

> "... After truly exceptional warmth in years 1989–91, there has been some fall of temperature world-wide, which has been attributed by many to the effects of the great volcanic eruption of Mount Pinatubo in the Philippines in June 1991."

Since the 1990s, the global warming phenomenon is apparently present in most of the climate change research (Mann *et al*. 1999, Cook *et al*. 2004, Wahl and Ammann 2007, D'Arrigo *et al*. 2008), but the "divergence" problem, which is about the inconsistency between some tree-ring variables and temperature, was also broadly observed in the late 20th century (Jacoby and D'Arrigo 1995, Briffa *et al*. 1998, Cook *et al*. 2004, D'Arrigo *et al*. 2008).

6.2 Tree-Growth Responses to Climate

Values for mean sensitivity and interseries correlations for the chronologies were similarly high at the three sites, which indicated that necessary variability existed in the tree-ring patterns caused by climate factors. Although the standard chronology type was used, low values of first-order autocorrelation at all sites suggested that the influence of the previous year's growth on the current year's growth was not dominant. Correlation and response function analyses for these three sites showed different responses to climate variables. No dominant factor among temperature, precipitation, and PDSI exhibited a limiting effect on trees throughout the study areas with any certainty. Instead, different sites had various

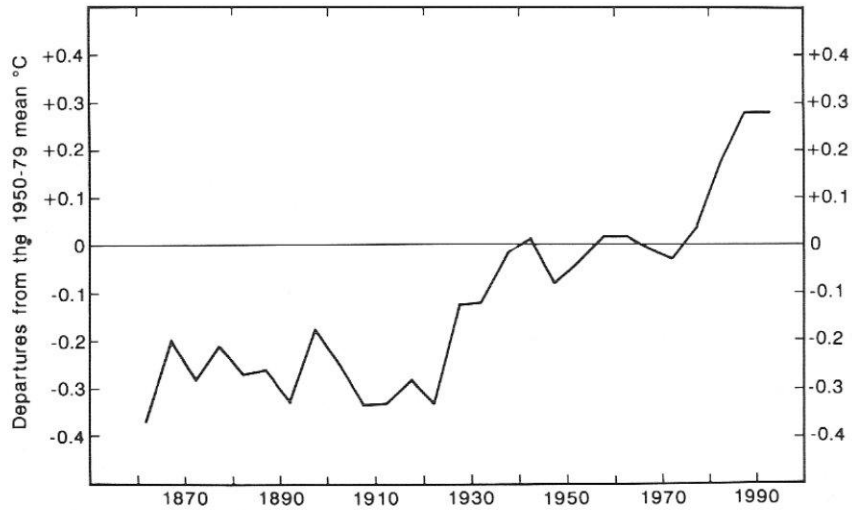

Figure 44. Changes of the world average temperature from 1861–1992. (from Supplementary Report, IPCC 1994)

climate variables that were significantly associated with tree growth. Due to climate variations in the 20th century, tree growth at all sites rarely exhibited stable long-term responses to a certain climate factor. The climate analyses between tree growth and oceanic-atmospheric oscillations data indicated some strong associations but still complex patterns. However, I detected similar patterns of moving correlation analyses for climate oscillations, suggesting the possibility of reconstructing climate.

6.2.1 Temperature, Precipitation, and PDSI

The three pine chronologies from the Southeast showed different responses to 20th century climate, but in general, tree growth in this area more closely reflects changes in temperature and PDSI than precipitation. The amount of precipitation in November was the only primary factor among all precipitation variables, especially controlling growth of longleaf pine at the Coastal Plain site. Previous dendroclimatological research on longleaf pine in the Southeast Coastal Plain has not found this November precipitation signal (Meldahl *et al*. 1999, Foster and Brooks 2001, Henderson and Grissino-Mayer 2009). At the Hope Mills site, the strongest climate-tree growth relationships were found using PDSI, which integrates temperature, precipitation, and soil moisture. My study demonstrated that longleaf pines respond positively to overall favorable conditions in the growing season and summer, but do not depend solely on either temperature or precipitation. Devall (1991), Grissino-Mayer and Butler (1993), Bhuta *et al*. (2009), and Henderson and Grissino-Mayer (2009) also identified this interactive function of temperature and precipitation signals in southern yellow pine growth for the Southeast. Summer (June–September) climate conditions on the eastern side of the southern Appalachians appear to control growth of Table Mountain pines.

Radial growth responds positively to summer precipitation and PDSI, but negatively to summer temperature. This result can be explained biologically. High temperatures and low rainfall in summer induce drought conditions with low values of PDSI, and thus cause growth reduction and a tree ring narrower than average. As expected with a winter temperature signal in the mixed pine-hardwood forests of the southeastern U.S, the shortleaf pine chronology from the Gold Mine Trail site indeed responded positively and significantly to winter (particularly January and February) temperature. This result is consistent with a few earlier studies in nearby areas (Stambaugh and Guyette 2004, Grissino-Mayer *et al*. 2007, Bhuta *et al*. 2009). However, this winter temperature signal does not prevail throughout the southeastern U.S. More primary factors that limit tree growth were identified during the growing season (Grissino-Mayer *et al*. 1989, Grissino-Mayer and Butler 1993, Pan *et al*. 1997; Speer *et al*. 2009). The disparity is probably because the western side of the Great

Smoky Mountains is drier than other southeastern regions, suggesting that the presence of a warmer winter is more important and beneficial to tree growth. Biologically, warmer winters help trees break dormancy earlier and produce wood earlier, which consequently adds more wood to an annual ring (Fritts 1976).

6.2.2 Temporal Stationarity of Responses to Temperature, Precipitation, and PDSI

The moving interval correlation analysis between the tree-ring index and individual monthly climate variables showed changes in the strength of the climate signal. The temporal non-stationarity of the climate-tree growth relationship frequently occurred over time among all sites. However, a geographical feature still can be discerned: the pattern of non-stationarity for the Coastal Plain site was very different from the other two, while the eastern and western sides of the southern Appalachians shared some similar trends.

At the Hope Mills site, precipitation did not show any long-term significant associations with longleaf pine growth, while temperature, which appeared more related to growth, shifted during the period of analysis. The Atlantic Coastal Plain has abundant rainfall during a year, so that trees are less sensitive to precipitation fluctuations. The correlation between tree growth and early summer temperature strengthened in the 1920s, but the shift from June to July in the 1980s might be related to the global warming trend, because it possibly determines and prolongs the growing season. Similar environmental conditions at the Linville Mountain and Gold Mine Trail sites contributed to the shared characteristics of temporal non-stationarity in climate responses. One common characteristic is the shift in the 1960s from a precipitation to a temperature signal, but the temperature signal is more significant at the Gold Mine Trail site during the second half of the 20th century. Another common pattern is the trend of the increasingly significant winter temperature signal since the mid-20th century. At Linville Mountain, summer (June–July and September) temperature, which once was the dominant factor, became insignificant beginning in the 1970s, while winter temperature became more important to tree growth. Precipitation during the growing season (April–June) positively influenced tree growth before the 1960s, but the relationship ceased and instead temperature became increasingly important toward the end of the 20th century. Around the first half of the 20th century, the high correlation between the tree-ring index and PDSI was apparent at both southern Appalachians sites. Stambaugh and Guyette's (2004) research found a similar phenomenon in the response to PDSI by shortleaf pine at their Missouri Ozark forest.

Decreased drought frequency and an increased global warming trend could be two explanations for the observations above. Drought during the years 1911–1912, 1920s, 1930s, and 1950s occurred in the early half of the 20th century, which explains how growing season precipitation and PDSI appear as limiting factors to tree growth in large areas of southern Appalachians forests during that period. Since the 1960s, however, climate conditions became relatively wet, so trees were no longer limited by moisture. In Ozark forests of Missouri, Stambaugh and Guyette (2004) attributed similar phenomena also to fewer droughts from 1960 to 1990. The apparent winter temperature signal after the mid-20th century might be related to a warming climate. Studies of plant physiology reported that winter photosynthesis has been observed in southeastern U.S. pines if needles are not frozen (Chabot and Hicks 1982, Havranek and Tranquillini 1995). Therefore, under a global warming scenario, conifers become more sensitive to winter temperature. When the winter is warmer than normal, a gain of photosynthates adds more wood to a ring. When the winter is cooler than normal, trees stop gaining carbohydrates in winter and start growing later than if the other situation holds. However, if future winter temperatures keep increasing, their association with tree growth should be expected to change from positive to negative because mild winters might induce potential drought stress during the growing season to limit radial growth of trees (Bhuta *et al*. 2009).

6.2.3 The NAO, AMO, PDO, and ENSO

The North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), and El Niño-Southern Oscillation (ENSO) are some of the hemispheric- to global-scale circulation patterns that have been found to affect regional climates around the world. Tree growth is related to these oceanic-atmospheric oscillations, but the situation also depends on geographical location. A study of the impact of these climate oscillations on trees provides a better understanding of large spatial scale and low frequency long-term climate variability in the region. However, the three chronologies in this study did not respond similarly to the four climate oscillation indices, although they are all located within the southeastern region of the U.S.

The Gold Mine Trail and Linville Mountain chronologies were positively related to winter (January and/or February) NAO, while the Hope Mills chronology did not show this association. Growth at all three sites exhibited a strong to weak positive relationship with summer (August, or September, or October) NAO. The winter signal of NAO was expected to be present at all sites because NAO affects winter climate in the eastern United States. Dynamics of the NAO also explained the appearance of the response to winter temperature by trees at the two more inland sites. During positive phases of the NAO, increased sea level pressure (SLP) difference between the Icelandic Low and the Azores High causes the flow of warm, moist air over the southeastern U.S, and thus warmer than normal temperatures induce above average tree growth (Rogers 1984, Hurrell and van Loon 1997, Woodhouse 1997). During the negative phases of the NAO, below average tree growth can be expected. The absence of a winter NAO signal at the Coastal Plain site may be due to oceanic effects that tend to moderate coastal temperatures and also the possible effects of human disturbances on logs extracted from the crib dam (van de Gevel *et al*. 2009).

Tree growth at Gold Mine Trail was positively related with the AMO, while growth at Hope Mills had a negative relationship. At the Linville Mountain site, tree growth had nearly no significant responses to AMO impacts. AMO indices are calculated from Atlantic sea surface temperature anomalies (SSTA) north of the equator. It is a multidecadal climatic teleconnection, and each phase can last 20 to 30 years. During the analysis period, warm phases of AMO occurred around 1860–1880 and 1930–1960, and cool phases included 1905–1925 and 1970–1990. Since the mid-1990s, the AMO shifted into a warm phase (Gray *et al*. 2004). A warm phase of AMO (featuring a warm North Atlantic) brings less precipitation and more droughts to the southeastern U.S, while a cool phase brings wet and mild conditions. Therefore, theoretically, above-average growth of trees should be expected during negative AMOs, and reduced tree growth would tend to happen during positive AMOs. This negative association between ring width and AMO was indeed shown at the coastal Hope Mills site, but for inland sites, either lack of association or a significantly positive relationship was found. One explanation could still come from geographical location. Because AMO is a measure of SSTA in North Atlantic, the Atlantic Coastal Plain could be the region that is most sensitive to the variation of AMO, or at least more sensitive than the inland area. The different responses to drought conditions at the three sites could also explain the disparity in the AMO response. The coastal site exhibited the strongest association with current year's PDSI, while the other two sites showed relatively weaker or no sensitivity at all. In such cases, warm phases of the AMO may actually favor growth, with higher temperatures at inland sites.

PDO index values were not strongly related to pine growth in the southeastern U.S, but PDO tended to show a negative relationship, without any positive tendency. In fact, PDO itself does not have a strong influence on the climate of the Southeast, but when it couples with other climate teleconnections, like AMO, the impact is significant. A great proportion of large-scale droughts in the U.S. can be associated with concurrence of different modes of the AMO and PDO (McCabe *et al*. 2004). For the southern Appalachian region, a negative or positive AMO coupled with a warm phase PDO coincides with high drought frequency with higher than 25% probability, while a cool phase of PDO with either mode of AMO tends to produce wet and mild climate conditions in this region (Figure 45). Therefore, in the more inland sites, warm phases of PDO cause high drought frequency and below-average tree growth, while cool phases of PDO induce wet and mild climate which brings above-average growth. This probably explains the tendency of the negative relationship between PDO and tree growth. At the Coastal Plain area, however, no such behavior of PDO existed, and correspondently no negative PDO-growth relationship was detected.

ENSO has spatially similar climate effects as the PDO, but is characterized by interannual behavior rather than decadal. Tree growth in the southeastern U.S. tended to be positively associated with the previous year's ENSO condition. La Niña events (positive

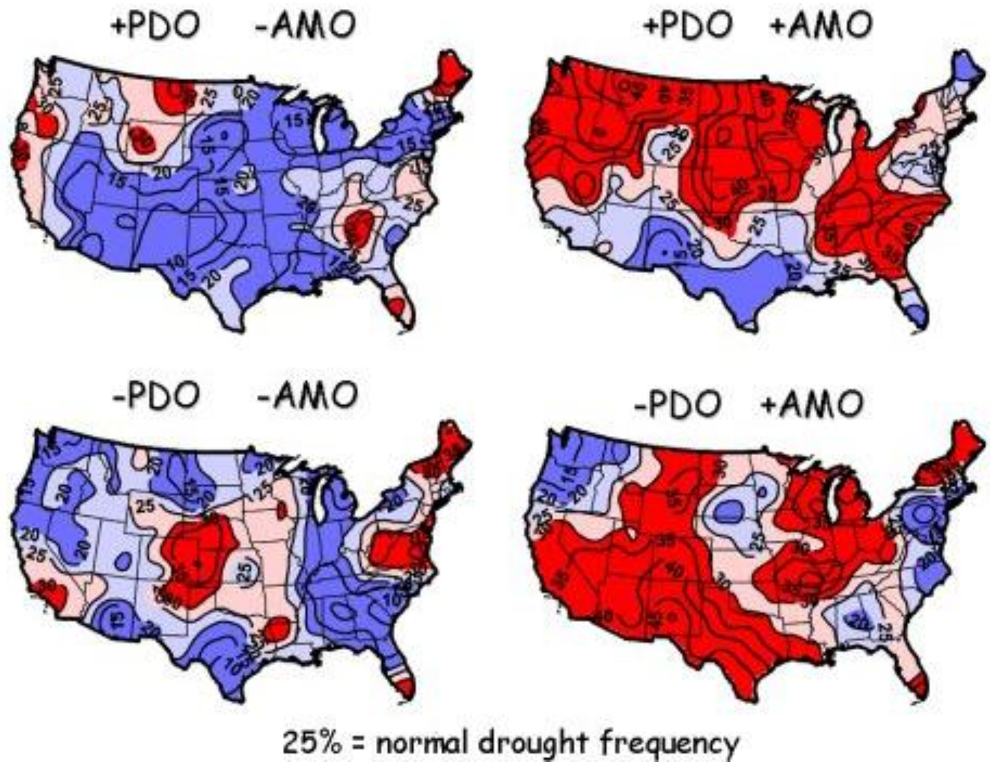

Figure 45. Areas of high (red >25%) and low (blue<25%) drought frequencies associated with complimentary modes of the PDO and AMO (McCabe *et al*. 2004).

values of the SOI, cold phases of ENSO) of the previous year lead to increased growth for pine trees in the current year, and vice versa. ENSO originates in the tropical Pacific Ocean, and contributes to the unusually wet and cold climate in the Southeast, while La Niña brings relatively drier conditions (Goddard *et al*. 2006, Seager *et al*. 2009). This is probably because the impacts on the southeastern U.S. are indirect. Research has shown that ENSO-associated wet and cold conditions in the previous year prolong the dormancy of trees, so that a previous El Niño would constrain the current year's growth. Conversely, a previously drier climate provided by La Niña would facilitate trees to break dormancy and grow faster. However, the ENSO signal is often vague in the southeastern U.S. and hard to detect (Mo *et al*. 2009).

In summary, the climate-tree growth relationship is relatively stronger between tree growth and the Atlantic Ocean-related oscillations such as NAO and AMO, than the Pacific Ocean-related oscillations such as PDO and ENSO. The major reason is the geographical location of the Southeast, where air masses from the Gulf of Mexico and the Atlantic Ocean are the primary influences on the regional climate and vegetation. Additionally, it is also necessary to consider the coupled effect of climate teleconnections on tree growth. For example, the drought frequency pattern of the U.S. is largely determined by a combination of AMO and PDO (McCabe *et al*. 2004). In addition, the impact of one climate oscillation on tree growth may be masked or weakened by the influence of another oscillation, which might cause a misinterpretation of tree growth responses. However, in my opinion, these uncertainties are inevitable. For example, studies suggest that AMO could regulate the strength of El Niño/La Niña effects on weather year round (Enfield *et al*. 2001), while accumulated ENSO effects could be the direct forcing of PDO (Newman *et al*. 2003). Although effects of these climate oscillations are broadly observed, the mechanisms behind the phenomena are still not fully understood.

6.2.4 Temporal Stationarity of Responses to NAO, AMO, PDO, and ENSO

Results showed that the relationship between large-scale climate fluctuations and tree growth also changes over time. Temporal shifts of NAO, AMO, PDO, and ENSO have different patterns from those of temperature, precipitation, and PDSI. Climate oscillations are defined with different time scales of phases and have different geographical ranges of influences, and thus they may not share common major response shifts over time. Although these four climate indices had different analysis periods, they all demonstrated the complexity and uncertainty of their relationships with tree growth.

In my study, NAO has the most uncertain pattern of climate-tree growth relationship. Negative and positive associations occurred irregularly in any month of the year along the timeline. The winter temperature signal strengthened in the latter half of the 20th century, while positive correlations between winter NAO (January and February) and growth also occurred since ca. 1950. This phenomenon is most likely related to the winter feature of the NAO. Although they are present throughout the year, fluctuations in the NAO are most pronounced during winter months (Rogers 1984, Hurrell and van Loon 1997). Therefore, due to the greatest amplitude of NAO phases in this season, tree growth in the southeastern U.S. responds accordingly, along with increased sensitivity to winter temperature in the mountain sites.

Results of the moving interval analysis between growth and AMO indices showed well-patterned temporal characteristics. An appearance of significant association with AMO indices was shown since the 1930s, but moving correlations were negative at Hope Mills, while positive at Gold Mine Trail. Also, at these two sites, the strong association was more interannual rather than across individual months. Gray *et al*. (2004) pointed that the AMO shifted from a cool phase to a warm phase during the 1930s through the 1960s. Warm phases bring decreased precipitation to the southeastern U.S, which probably cause decreased growth of trees. Thus, a negative relationship would be expected. During the warm phase of AMO in 1930–1960, the tree growth was negatively related to summer AMO at Linville Mountain. During the cool phase of the AMO in 1900–1925, yellow pine growth at Gold Mine Trail was negatively correlated with summer and fall AMO indices. But the significant correlations between the Linville Mountain chronology and previous May–December AMO were positive since the 1960s, the beginning of a cool AMO phase. Therefore, the relationship between AMO and growth is not consistently positive or negative over time, but the coincidence of significant response to different AMO phases and the intra-annual consistency of the significance were still noteworthy for the southeastern region.

The PDO typically refers to the wintertime climate fluctuation over the North Pacific on inter-decadal time-scales (Mantua *et al*. 1997). It was not expected to have strong associations with trees from the southeastern U.S. It holds true in the Coastal Plain site, but results of the moving interval analysis in the mountain sites suggested that PDO indices were more or less significantly negatively correlated with tree growth. Current summer and November PDO indices were significant to growth at the western southern Appalachian Mountains. The negative association with wintertime PDO indices from the 1940s to 1990s existed at both mountain sites, and may be related to striking winter features (e.g. SST, SLP, surface wind stress, and others) of the PDO. Decades with negative relationships, however, did not coincide with either a warm or cool phase of the PDO, probably because PDO impacts are indirect in the Southeast and not independent of other climate fluctuations.

ENSO is also a climate phenomenon centered in the Pacific, but it links worldwide with the anomalous climate pattern (Kiladis and Mo 1998). Except for the Gold Mine Trail site, moving correlation analysis showed consistently positive relationships over the analysis period (1951–2003) at Hope Mills and Linville Mountain. Despite the shortest study period, the ENSO-tree growth relationship has the highest level of temporal stationarity among these four climate oscillations.

Several points on the temporal non-stationarity of tree growth responses to climate oscillations may help elucidate this complexity. First, large-scale climate oscillations operate on local ecological systems in a different manner from local climate patterns. Climate oscillation indices are always derived from various calculations of SST, SLP, or principal components of several factors on the oceans, while divisional climate variables such as temperature, precipitation, or PDSI are assembled from local weather stations. Trees are more likely responsive to local climate variations rather than large-scale fluctuations. In other words, impacts of climate oscillations on trees operate through local climate features. Therefore, the relationship between climate oscillations and growth is not that straightforward compared to relationships between local climate variables and growth. Second, it is important to realize the interaction between climate fluctuations. Their effects are not independent from each other on an ecosystem. An example is the simultaneous occurrence of AMO and PDO, which contributes to drought frequency in the U.S. (McCabe *et al*. 2004). Also, given their different time scales, at different phases of a certain climate oscillation, the accompanying fluctuation that occurred might be different, which causes the uncertainty and non-stationarity of large-scale effects over time. The interaction between climate factors is nonlinear, and tree growth also responds to climate in a nonlinear manner (Biondi 1997, Ni *et al.* 2002). Either of the two nonlinear relationships may induce unexpected effects, and perhaps, in most cases, it is not easy to determine the "best" climate index to which trees respond.

A third explanation would be the lack of truly stationary, periodic behavior in the atmosphere (Stenseth *et al*. 2003). Non-stationarity is in the nature of the climate system, and the influence of climate patterns do vary over time. Trees may accordingly or selectively respond to the most significant climate influence. Many dendroclimatic studies revealed this temporal non-stantionarity of climate-tree growth relationship in different regions around the world (Solberg *et al*. 2002, Carrer and Urbinati 2006, Hilasvuori *et al*. 2009, Shi *et al*. 2010). Finally, tree growth response to climate also largely depends on geographical location. Despite the fact that the effects of climate oscillations are geographically anchored to some particular regions, the oceanic-atmospheric teleconnection influence on local ecosystems is also based on other factors, such as high mountains and land-sea boundaries.

6.3 Coastal-Inland Gradient Changes of Responses to Climate

The three study sites were located along a longitudinal transect in the southeastern U.S. They represent the Coastal Plain, the eastern side, and the western side of the southern Appalachians respectively. I proposed to use this small tree-ring network to examine whether the influence of large-scale climate oscillations on tree growth has a decreasing trend of magnitude from coastal to interior locations. The idea started with the basic but essential knowledge of the dynamic unity among land, sea, and air. Spatial relationships between land and sea profoundly affect the operations of atmospheric, oceanic, and terrestrial processes. Because more than 70% of the Earth's surface is oceanic, the earth's atmosphere is directly influenced by the various states of the sea. This also explains why the climate oscillations are all dominant climate patterns in the ocean area, but affect terrestrial weather and climate variability. Large-scale climate fluctuations accompany abnormal exchanges of energy and matter among sea, air, and land. Terrestrial systems distributed between oceans interact with the sea and atmosphere, but how ecosystems on land respond and modulate the large-scale climate controls differs from region to region and also depends on other factors, such as human influence. Studying tree growth responses to climate along ecological gradients is important for understanding spatial characteristics of climate influences. Many researchers have demonstrated that limiting factors for tree growth vary among different positions along a geographical transect.

In the analysis of the relationship between divisional climate variables and tree growth, winter temperature and summer drought conditions were the most significant climate signals, but they showed gradient characteristics of response strength among the three sites. Winter temperature signal was apparent in the most inland site (Gold Mine Trail), while its strength was reduced in the middle site (Linville Mountains), and disappeared at the coastal site (Hope Mills). In contrast, the response to drought (PDSI) gradually strengthened from the most inland site to the coastal site. These behaviors of climate response may suggest that, in the Southeast, moisture is more important to trees in the Coastal Plain area than to trees growing west of the southern Appalachians. After ca. 1950–1960, a strengthened winter temperature signal became increasingly important at the two mountain sites, while the signal did not appear at the Coastal Plain site. Identification of limiting climate factors along such geographical transects may be helpful to delineate the range of a certain climate response. In addition, gradient response features of climate variables may help explain the gradient response features of large-scale climate fluctuations.

Coinciding with the significant winter temperature signal at Gold Mine Trail, the winter NAO signal was also the strongest at this site, likely because NAO is most pronounced during winter. Considering the geographical locations of climate oscillations, the NAO was expected to exhibit the strongest gradient characteristics along the transect. Based on the pattern of significant periods in moving correlation analysis results, the coastal site indeed exhibited the most signals among three sites, but no stationary NAO signal was found or changed in a gradient trend along the transect.

A negative relationship between PDO and growth showed a gradient feature from coastal to inland locations. The 1900–1950 summer PDO and 1940–2000 winter PDO were two significant periods found in trees at the western southern Appalachians site, but only the 1940–2000 winter PDO signal existed at the middle site. No strong correlations were found at the coastal site. Because PDO is also a wintertime climate fluctuation, the two inland sites reflected these winter features rather than signals at other seasons. The decreasing strength of PDO signal from inland to coastal can be basically explained by the North Pacific location of the PDO, so its impacts on the southeastern U.S. ideally decrease from west to east on the continent, also from inland to coastal area.

Despite its global effects, the ENSO is a Pacific fluctuation like the PDO. However, it had no gradient features found in the trees at the three sites. No ENSO signal was found at the western southern Appalachians. The previous year's ENSO was consistently related to growth at the eastern southern Appalachians, but was inconsistent at the coastal site. I speculate that this spatial pattern of tree response to ENSO is attributed to the large mountain effect, which means the Appalachian Mountains interact with the abnormal atmospheric dynamics induced by the climate fluctuation and cause different influences on the two sides of the mountains. The eastern side of the mountains includes the Linville Mountain site and the Coastal Plain site, with a notable ENSO signal; the western side of the mountains has the Gold Mine Trail site, with no ENSO signal.

Although all three sites revealed a temporal shift in the AMO in the 1930s, spatial characteristics interestingly suggested a gradient change in the AMO-tree growth relationship.

During the warm phase of AMO in the 1930s–1960s, the relationship was positive from inland sites, while it was negative at the coastal site. Given the behaviors of the AMO, warm phases bring dry climate conditions and limit tree growth in the southeastern U.S, as shown at the coastal site. The positive relationships after the 1930s until the 2000s at inland sites can be partly explained by their non-sensitivity to precipitation and drought. When winter temperature became the dominant limiting factor in the southern Appalachians, it may be possible that cool AMOs (negative index values) indirectly coincide with reduced tree growth. AMO signals found in trees were strongest in the western southern Appalachians, and less strong in the eastern southern Appalachians and the Coastal Plain.

Other factors may have influenced the gradient features of climate responses. Most importantly, climate response by trees is greatly dependent on the geographical location, both at a broad spatial scale and in terms of microenvironment. In the southeastern U.S, the western Atlantic Ocean and the southern Appalachian Mountains are the two major physical features that determine the fundamental pattern of regional climate. Air masses from the Atlantic Ocean bring warm and moist climate to the coastal area in the Southeast, as do subtropical air masses from the Gulf of Mexico (Figure 46). More inland, a gradient of continentality is present and enhanced by the southern Appalachian Mountains, which also create local montane climates. As a result, climate west of the southern Appalachians is rather more continental. These land-sea interactions and high mountain effects modulate atmospheric processes, and thus influence the gradient trends in climate responses.

The local physical environment sometimes has a more important influence on determining tree growth patterns. On one side, climate operates mechanistically on ecological systems through local weather variations (Stenseth *et al*. 2003). On the other side,

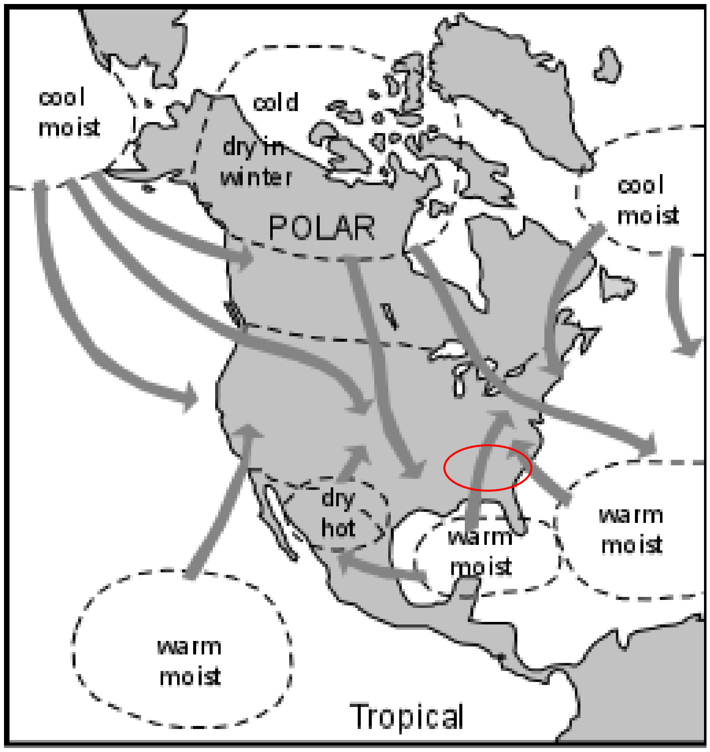

Figure 46. General air circulation pattern in North America (Eagleman, 1983). The red circle indicates the study region.

other factors on a local scale, such as human population density, human disturbances, competition among trees, forest self-maintenance, and extreme weather conditions, may also play a role in tree growth. Furthermore, trees have their own physiological growth responses. For example, under drought conditions, a tree controls its annual growth by allocating more energy to its roots to obtain stored water from the ground, or it can reduce leaf amount to decrease photosynthesic activity which requires water. These biological feedback responses to environmentally-driven conditions are the internal mechanism of trees, and they are different among species. This aspect of environmental effects is hypothesized to be a linear relationship between climate and tree growth in most dendrochronological studies. Though it is not a major problem in dendroclimatic study, disparity among tree species may still be a potential drawback.

The use of a tree-ring network to study climate oscillations has advantages in terms of examining spatial characteristics of tree growth responses to large-scale climate patterns. Unlike divisional climate variables, the atmospheric-oceanic teleconnections represent broad-scale climate conditions, and provide a “package of weather” through which climate affects ecosystems. Climate indices reduce complex space and time variability into simple measures, and they may be ecologically important by themselves (Stenseth *et al*. 2003). In addition, trees often respond to a combination of interacting climate variables, and a given large-scale climatic index may be a better representation of climatic effects than single variables. In summary, results of correlation analysis between climate indices and tree growth preliminarily suggested associations with large-scale climates. Spatial characteristics from the three sites along a transect indicated the gradient or non-gradient changes of climate fluctuation effects in terms of magnitude, duration and frequency. To some degree, this dendroclimatic application makes the influence of climate fluctuations more apparent on ecological patterns and processes.

6.4 Regional Climate Oscillation-Growth Relationships

Pine growth in the small tree-ring network was related to oceanic-atmospheric teleconnections that affect the southeastern U.S. Climate patterns in the Atlantic Ocean were expected to have stronger effects in the study region and trees to be more responsive to NAO or AMO. Averaged ring width indices from three chronologies were used to examine the regional relationship between tree growth and climate oscillations. Correlation results showed that the AMO had no significant relationships with growth in the Southeast. Positive NAO values in winter (January and February) and summer (August and October) tend to bring above-average annual growth. The current year's PDO is negatively related to growth. El Niño events in the previous year induce below average growth, while a La Niña event in the previous year causes increased growth.

However, it is cursory to conclude that tree growth in the southeastern U.S. has such relationships with these climate oscillations in general. The reason is that three individual study sites may not be adequate to make a statistically convincing regional generalization. Results of the correlation analysis using the composite chronology can be easily interpreted from the results of individual chronologies. For example, the absence of the AMO signal in the composite chronology is probably because the negative relationship at the coastal site neutralized the positive relationship at the Gold Mine Trail site, while no significant relationship showed at Linville Mountain. Other climate oscillation signals in the composite chronology may also be explained through adding, subtracting, or neutralizing responses of individual chronologies. The results thus resemble mathematical calculations compromising each other, rather than a clear composite picture of geographical indications. Therefore, in order to reliably study regional climate responses by trees, a larger network consisting of more sites would be better to represent a region or larger geographical range.

CHAPTER 7

CONCLUSIONS

7.1 Major Conclusions

The main objective of this study was to explore patterns in climate-tree growth relationships, especially between large-scale climate oscillations and growth along a longitudinal transect in the southeastern U.S. A small tree-ring network consisted of sites from the Coastal Plain, and the eastern and western southern Appalachians. Temporal and spatial changes of tree growth responses to climate factors were the two themes in this dendroclimatological study. The examination of the temporal stationarity in climate signals is important for understanding the shift of tree growth responses through time and for evaluating the reliability of climate reconstructions. If any climate factors are found stable over time, that variable may be useful for climate reconstruction. Little research has been conducted to examine the spatial characteristics of climate responses along a longitudinal transect. Although tree sensitivity to climate fluctuations is low in the southeastern U.S, climate analyses still revealed significant patterns in climate-growth relationships along a longitudinal transect. This also indicated influences from regional landscapes and land-sea interactions on tree growth in the study area. Changes of the strength and stability of the relationships showed gradient features for some climate factors, depending on the geographical locations of the sites. This final chapter summarizes the major findings of my research. I also present the limitations of this study and suggest potential future improvements on such study, especially in the southeastern United States.

1. ***Tree-ring chronologies indicate extreme climatic events in history.***

Extreme climatic events such as droughts or very cold periods normally induce below-average growth of trees. In the common period of the three chronologies (1828–2003), extreme climate episodes coincided with low values of ring-width indices, while some well-known events do not show up in the chronologies. A colder and wetter climate in the 1830s–1840s caused reduced ring width at all sites. Constrained growth in the 1890s can be attributed to a severe short-term drought, but some global-scale studies also suggested colder-than-normal temperature in this decade. The effects of the famous Dust Bowl were not found in my chronologies. Severe continental drought in the 1950s exhibited a negative influence on tree growth at the coastal site, but no significant influence at the other two sites. The ring growth pattern after the 1990s matches the global temperature trend in recent decades.

2. ***Temperature, precipitation, and PDSI signals were not stable over time, and a shift in climate-growth relationships was notable at two sites in the mid-20^th^ century.***

Moving correlation analyses tested the temporal stationarity of climate response over the last century. Results showed that although some significant signals remained stable over decades, the climate-growth relationship still changed on a centennial time-scale. A common shift occurred around the 1950s at the Linville Mountain and Gold Mine Trail sites. Two features of this shift were: 1) previously strong precipitation signals weakened in the latter half of the 20^{th} century, while temperature signals strengthened at Gold Mine Trail and Linville Mountain; 2) a change of responses from growing season climate conditions to wintertime since the 1960s. This finding is consistent with the findings by Biermann (2009), who identified the mid-20^{th} century shift and the increasing importance of winter temperature.

The cause is unknown, however, and speculations include an AMO phase change, anthropogenic warming, and/or physiological changes of pines, among others (Biermann 2009).

3. ***Pine trees in the southeastern U.S. respond to multiple climatic factors. The strengths of winter temperature and summer drought conditions show gradient changes along this coastal-inland transect.***

Although pine growth at Gold Mine Trail only had a significant relationship with winter temperature, the Linville Mountain and Hope Mills sites showed associations with temperature, precipitation, and PDSI. Climate-growth relationships were not uniform across sites and they demonstrated gradient characteristics along the transect. The Gold Mine Trail chronology had the strongest relationships with winter temperature, but this signal was weaker in the Linville Mountain chronology. At Hope Mills, winter temperature was insignificant to pine growth. However, the Hope Mills chronology was the most moisture-sensitive during the entire year. The Linville Mountain chronology showed a PDSI signal only during summer, while the Gold Mine Trail chronology was not sensitive to drought conditions. Differences in climate response along this gradient were likely related to the geographical locations of the sites and their surrounding environment.

4. ***Four large-scale climate oscillations NAO, AMO, PDO, and ENSO showed different associations with tree growth at the three sites.***

Winter NAO was positively correlated with pine growth at the two more inland sites, Linville Mountain and Gold Mine Trail. Summer NAO tended to affect growth at all sites, but it was not as strong as the winter signal. Because NAO behavior is pronounced during winter, the concurrence of winter NAO and winter temperature signals may be related. The AMO was negatively correlated at the coastal site of Hope Mills, positive in the western Great Smoky Mountains, and showed no relationship with the Linville Mountain chronology. These patterns between AMO and tree growth may be highly dependent on their geographical locations. The PDO tended to be negatively related to growth at all sites. It least affected tree growth in the coastal area, but showed significance during winter and/or summer at the two inland sites. The ENSO had no significant effect at Gold Mine Trail, while ENSO in the previous year was positively correlated with growth for the other sites. Pacific Ocean temperature and pressure patterns (PDO and ENSO) were not expected to have strong influence on growth in the Southeast, but the presence of these signals suggested that interaction between climate oscillations may cause uncertainty in the relationship.

5. ***The strong associations between growth and NAO, AMO, PDO, and ENSO showed lack of stationarity over time, but in some cases the associations changed with phase changes of the oscillations.***

NAO responses by trees were the most unpatterned in the moving correlation results, and the frequent shifts did not match shifts of NAO phases. Tree responses to AMO were more likely in the form of annual characteristics at Hope Mills and Gold Mine Trail. Significant correlations starting around the 1930s appeared at all three sites, which coincided with the beginning of a warm phase of the AMO. During other phases of the AMO within the study period, such as the cool phases in 1900–1925 and 1960–1990, chronologies from different sites illustrated strong responses. This observation might suggest that tree growth in the southeastern U.S is responding to AMO along with its phases. The negative relationship between growth and PDO was not stationary over the last century. The winter PDO became increasingly significant towards the last two decades of the century at the two mountain sites. The overall influence of the PDO in the Southeast, however, was not strong. The previous year's ENSO signal was consistent over the 50 years analyzed at the Linville Mountain site. Less consistent but still significant correlations occurred between the Hope Mills chronology and ENSO. The Gold Mine Trail chronology had a very weak relationship with ENSO. This phenomenon may suggest different ENSO influences on the two sides of the southern Appalachians.

6. ***Analyzing relationships between growth and climate oscillations over moving intervals helped to identify possible causes of shifts in temperature, precipitation, and PDSI responses.***

Responses either to fundamental climatic variables or to climate oscillation indices were not stable over time. Similarities in shifts of these two types of climate-growth relationships may help us understand the mechanism of climate dynamics. Climate oscillations, as large-scale climate patterns, operate upon ecological systems through local, fundamental climate variation. Therefore, concurrent changes of climate oscillation responses may explain shifts in the temperature and precipitation responses. The major 1950s shift from a precipitation to temperature signal at the two inland sites may be related to the significant response to a phase change of the AMO in the 1960s. Also, the appearance of the winter temperature signal in the latter half of the 20th century can probably be attributed to the strong winter NAO response which occurred around the same time.

7. ***Along the longitudinal transect analyzed, spatial variations of tree growth responses to climate oscillations were obvious. Effects from high mountains and land-sea boundaries may primarily explain such response patterns in the southeastern U.S.***

Both divisional climatic variables and climate oscillations showed gradient characteristics of their response strength along the coastal-inland transect. The winter temperature signal exhibited a decreasing trend from the most inland site to the coastal site, while the response to drought gradually appeared and strengthened from inland sites to the coast. Therefore, in the southeastern U.S, moisture conditions may be more important to tree growth in the Coastal Plain area than west of the southern Appalachians, while winter temperature is the limiting factor in the mountain area or at higher elevations, especially after the 1950s. Although frequent shifts existed in the relationship between growth and the NAO, based on the number of signals and the duration of the signals, the coastal site exhibited the strongest response. AMO response was the strongest at the most inland site, and weakened east of the mountains. The significant response to the warm phase of the AMO in the 1930s–1960s was positive at the inland sites but negative at the coastal site. The decreasing strength of the PDO signal was shown from inland to coastal sites, probably due to the North Pacific location of the PDO. No gradient change of ENSO response was found from coastal to inland sites, but the disparity of its response between the eastern and western sides of the southern Appalachians may suggest the influence of large mountains. Factors that may contribute to the spatial gradient features of climate response include geographical locations of sites, microenvironments, dynamics of air circulations, land-sea interactions, high mountain effects, physiological growth responses of trees, and influence from humans.

8. ***Results of the tentative examination on the relationship between the composite chronology and climate oscillations were not reliable, so reconstructing any oscillation index in the past using this chronology may not be possible.***

The composite chronology was derived from the average indices of the three chronologies. Although significant relationships between this chronology and climate oscillations were shown, the results of the correlation analysis were not sufficient to support a regional generalization because of the small number of sample sites. The significant correlations more reflected the adding, subtracting, or neutralizing combinations of responses from individual chronologies. Therefore, to reconstruct the past climate oscillation index for the southeastern U.S, this composite chronology might not be useful.

7.2 Limitations of this Study and Suggestions for Future Research

The southeastern U.S. is in the temperate climate zone where multiple climatic parameters often control tree growth. The fact that climate response may vary with species and interactions with various climate factors could be major influences on climate-growth relationship analysis. These are problems that limit traditional dendroclimatic analyses. This study also assumed a linear relationship between tree growth and climate, but the nonlinearity problem and interactive relationships have to be acknowledged. In a future study, nonlinear methods, such as neural networks, can be applied to identify relationships between growth and climate and eliminate interactions among climatic variables. Also, nonlinear climate analysis is more suitable to determine a particularly clear climate signal for reconstructing past climate from tree rings. Furthermore, moving correlation analyses in this study suggested that none of the climate signals was stationary over time; thus, it is impossible to determine a “best” climate variable to reconstruct. In my opinion, in nature it is impossible to find a single climate variable which maintains the same significance to tree growth over hundreds of years. Therefore, a nonlinear model applied to the climate-tree growth system would also be an improved approach for reconstructions.

Blasing *et al*. (1981) pointed out that seasonal climate data usually have stronger relationships with tree growth than monthly data. Biologically, it would be better to use seasonal data to test climate responses by trees because sequential months with similar conditions affect the radial growth of trees significantly. In this study, all climatic variables were in the form of months while applying climate response analyses. Although significant months clustered to form a seasonal signal broadly in the results, climate analyses using seasonal temperature, precipitation, and PDSI might have stronger and clearer patterns of responses. For example, if using seasonal rather than monthly data, the degree of sensitivity to winter temperature at the two inland sites would be strengthened. Future analysis based on seasonalized data in the southeastern U.S. could be an improvement to reveal climate-tree growth relationships. Seasonlized data can also be used in the moving correlation and response function analyses to examine the shifts of seasonal climate signals over time. In addition, to better understand how climate oscillations affect tree growth through fundamental climatic factors, the seasonal characteristics of responses may be more important and helpful than the monthly characteristics.

One of the purposes of this study was to examine the relationships between climate oscillations and tree growth, but a limitation for such analyses is the length of climate oscillation data. Phases of these climate fluctuations have durations lasting from several years to many decades. The length of the period analyzed should be long enough to cover adequate phases of climate oscillations, so that findings about the relationship between tree growth and a particular phase of climate oscillation can be convincing. For example, tree growth at the three study sites turned out to be significantly associated with different phases of the AMO. But only a few phases were tested. If a longer sequence of the AMO index can be used, it would be critical to determine the relationship between AMO and tree growth in the southeastern U.S.

A study on regional climate-growth relationship has drawbacks when only three sites are used. Even though the sites spatially cross two southeastern states, the integration of their chronologies cannot represent the regional tree growth trend. The large distance from each other and the unique environment of each site are two main reasons for the failure of generalization. However, studying the effects of climate oscillations in the southeastern U.S. is still a necessary goal. For future research focused on the southeast region, adequate number of sample sites and good site selections with broad distribution should be considered at the beginning of the study, so that the result of a regional relationship between climate oscillations and tree growth may have robust reliability.

7.3 Concluding Remarks

The large-scale nature of climate systems is of importance to local ecosystems, and tractable climate factors such as long-term, multidecadal climate oscillations provide advantages to explore the relationship between the two. Tree-ring networks are a useful technique in dendroclimatology, and contribute greatly to the study on the large-scale spatial coherence of climate signals (Alverson *et al*. 2003). Effects of some certain climate oscillations are sufficiently shown in the southeastern United States. It seems promising to use tree-ring networks to study recurrent oceanic-atmospheric fluctuation patterns.

Furthermore, it is important to realize that the conformity of tree species used in a tree-ring network can reduce the danger of spurious relations between climatic factors and tree growth. Pine species are valuable and the most common species used for dendrochronological research. Considering the dwindling number of old, living pines in the Southeast, the fact that the three chronologies analyzed in this study were all from pine trees is an advantage. As a result, they all exhibited high-quality chronology characteristics. Due to the significant value of this environmental proxy source to benefit further research on the regional characteristics of the southeastern U.S, it is crucial to preserve living pine trees as well as dead trees often found in old-growth forests.

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APPENDIX

Linville Mountain COFECHA Output

```
[]
[]  P R O G R A M      C O F E C H A                                                                          Version 6.06P    27455
------------------------------------------------------------------------------------------------------------------------------------

 QUALITY CONTROL AND DATING CHECK OF TREE-RING MEASUREMENTS

 File of DATED series:   lm83.txt

 CONTENTS:

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

 RUN CONTROL OPTIONS SELECTED                             VALUE

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

 Time span of Master dating series is  1810 to  2008   199 years
 Continuous time span is               1810 to  2008   199 years
 Portion with two or more series is    1812 to  2008   197 years

 >> LMC002A     1975 absent in   1 of   75 series, but is not usually narrow: master index is  -.195
 >> LMC011B     1843 absent in   1 of   20 series, but is not usually narrow: master index is   .407

                                       ****************************************
                                       *C* Number of dated series        83 *C*
                                       *O* Master series 1810 2008  199 yrs *O*
                                       *F* Total rings in all series   8868 *F*
                                       *E* Total dated rings checked   8866 *E*
                                       *C* Series intercorrelation     .539 *C*
                                       *H* Average mean sensitivity    .274 *H*
                                       *A* Segments, possible problems   16 *A*
                                       *** Mean length of series      106.8 ***
                                       ****************************************
```

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

LMA001A	1 absent rings:	1932		
LMA002B	1 absent rings:	1902		
LMA004A	1 absent rings:	1979		
LMA006A	1 absent rings:	1932		
LMA041B	3 absent rings:	1845	1846	1847
LMC002A	1 absent rings:	1975		
LMC004B	1 absent rings:	1930		
LMC005B	1 absent rings:	1973		
LMC011B	1 absent rings:	1843		
	11 absent rings	.124%		

```
----------------------------------------------------------------------------------------------------------------------------------
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050 Ident     Seq Time-span  Yrs
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    : --------  --- ---- ----  ----
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  .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <====>    . LMB004A   48 1950 2008   59
  .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=====>    . LMB004B   49 1949 2008   60
  .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=====>    . LMB005A   50 1949 2008   60
  :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :
1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050
```

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PART 2:  TIME PLOT OF TREE-RING SERIES:                                                      17:36  Mon 01 Mar 2010  Page   3
-----------------------------------------------------------------------------------------------------------------------------------
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050 Ident    Seq Time-span  Yrs
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    : -------- --- ---- ---- ----
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <=====>    . LMB005B   51 1943 2008   66
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <=====>    . LMB006A   52 1945 2008   64
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <=====>    . LMB006B   53 1943 2008   66
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   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <=====>    . LMB007B   55 1947 2008   62
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <==============>    . LMB008A   56 1857 2008  152
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <==============>    . LMB008B   57 1857 2008  152
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   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <=======>    . LMC008A   74 1920 2008   89
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   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<========>    . LMC009A   77 1918 2008   91
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   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <===============>    . LMC011A   81 1846 2008  163
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<==================>    . LMC011B   82 1817 2008  192
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<======> .    .    .    . LMC011C   83 1817 1885   69
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050
```

Year	Value	No	Ab	Year	Value	No	Ab	Year	Value	No	Ab	Year	Value	No	Ab	Year	Value	No	Ab	Year	Value	No	Ab
				1850	.691	26		1900	-.683	30		1950	-.693	77		2000	1.141	71					
				1851	2.313	26		1901	.001	30		1951	-1.049	77		2001	.606	71					
				1852	-.918	26		1902	-1.075	30	1	1952	-1.109	77		2002	.211	70					
				1853	-.163	26		1903	.773	30		1953	.012	77		2003	-.019	70					
				1854	1.127	26		1904	.762	32		1954	-.301	77		2004	1.491	70					
				1855	.134	26		1905	.167	33		1955	1.485	78		2005	.532	70					
				1856	-.716	26		1906	1.395	35		1956	1.219	78		2006	-.513	70					
				1857	.653	28		1907	.392	35		1957	1.732	78		2007	-1.526	70					
				1858	.937	29		1908	1.555	36		1958	.239	78		2008	-.541	70					
				1859	-.180	31		1909	-.301	36		1959	-.087	78									
1810	-.025	1		1860	.496	31		1910	.201	36		1960	-1.394	78									
1811	1.626	1		1861	1.339	31		1911	-.037	39		1961	-1.277	78									
1812	1.539	2		1862	.193	31		1912	-.157	39		1962	-.805	78									
1813	.262	2		1863	-.500	31		1913	-2.464	40		1963	.722	78									
1814	1.368	2		1864	-.676	31		1914	-2.096	41		1964	-.934	78									
1815	1.441	3		1865	.070	31		1915	-.396	41		1965	-.086	78									
1816	-.224	3		1866	-1.888	31		1916	1.594	42		1966	-2.003	77									
1817	1.175	6		1867	.331	31		1917	-.144	42		1967	.729	77									
1818	-1.331	6		1868	.055	31		1918	.726	44		1968	1.336	77									
1819	.307	8		1869	-.935	32		1919	-.816	44		1969	.150	77									
1820	-2.132	8		1870	-1.302	33		1920	-.738	48		1970	-.430	77									
1821	-1.676	8		1871	-1.278	33		1921	.705	48		1971	-.179	76									
1822	-.147	9		1872	.135	33		1922	.765	48		1972	.041	76									
1823	-.782	9		1873	.066	33		1923	.971	48		1973	-.412	76	1								
1824	-1.488	9		1874	.339	33		1924	1.282	49		1974	1.105	75									
1825	.062	9		1875	.050	33		1925	-1.350	50		1975	-.195	75	1<<								
1826	-.132	9		1876	1.043	33		1926	.106	50		1976	.524	75									
1827	1.550	12		1877	-1.028	33		1927	1.003	51		1977	-.121	75									
1828	1.080	13		1878	.822	33		1928	.640	52		1978	-.892	75									
1829	.508	14		1879	-.059	33		1929	1.197	52		1979	-.706	75	1								
1830	-.419	16		1880	-.040	33		1930	-2.296	52	1	1980	.425	75									
1831	1.521	16		1881	-1.565	32		1931	-.178	52		1981	1.225	74									
1832	-.307	17		1882	2.036	32		1932	-1.483	52	2	1982	1.140	74									
1833	.329	17		1883	-1.346	32		1933	-.065	52		1983	-.728	74									
1834	.999	17		1884	1.387	32		1934	-.285	53		1984	-.317	73									
1835	.141	17		1885	-.530	32		1935	1.174	53		1985	.425	73									
1836	.265	18		1886	.492	31		1936	-1.759	54		1986	-1.660	73									
1837	-2.421	18		1887	.047	31		1937	.288	53		1987	-1.506	73									
1838	-.400	19		1888	1.058	31		1938	.020	54		1988	-1.382	73									
1839	.555	19		1889	2.056	31		1939	-.734	57		1989	.890	73									
1840	1.320	19		1890	1.319	31		1940	-.116	58		1990	1.680	73									
1841	.414	20		1891	-1.654	31		1941	-.490	59		1991	1.929	72									
1842	.216	20		1892	-1.323	31		1942	-.075	59		1992	-.553	72									

1843	.407	20	1<<	1893	-.520	31	1943	.308	64	1993	-.209	72
1844	.110	21		1894	.078	31	1944	-.674	64	1994	-1.087	71
1845	-2.152	22	1	1895	-.928	31	1945	.421	65	1995	-.776	71
1846	-.762	25	1	1896	-1.519	31	1946	.093	68	1996	-.438	71
1847	-1.014	25	1	1897	.120	30	1947	.893	70	1997	1.124	71
1848	-.722	25		1898	.815	30	1948	1.519	71	1998	-1.056	71
1849	-.442	25		1899	-.594	29	1949	.800	75	1999	.372	71

```
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   Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value  Year Rel value
                   1850--------C   1900--c         1950--c         2000---------E
                   1851----------I 1901-----@      1951-d          2001-------B
                   1852--d         1902-d          1952-d          2002------A
                   1853----a       1903--------C   1953-----@      2003-----@
                   1854---------E  1904--------C   1954---a        2004----------F
                   1855------A     1905------A     1955----------F 2005-------B
                   1856--c         1906----------F 1956---------E  2006---b
                   1857-------C    1907-------B    1957----------G 2007f
                   1858--------D   1908----------F 1958------A     2008---b
                   1859----a       1909---a        1959----@
   1810-----@      1860-------B    1910------A     1960f
   1811----------G 1861---------E  1911-----@      1961-e
   1812----------F 1862------A     1912----a       1962--c
   1813------A     1863---b        1913j           1963--------C
   1814---------E  1864--c         1914h           1964-d
   1815----------F 1865-----@      1915---b        1965----@
   1816----a       1866h           1916----------F 1966h
   1817---------E  1867------A     1917----a       1967--------C
   1818-e          1868-----@      1918--------C   1968---------E
   1819------A     1869-d          1919--c         1969------A
   1820i           1870-e          1920--c         1970---b
   1821g           1871-e          1921--------C   1971----a
   1822----a       1872------A     1922--------C   1972-----@
   1823--c         1873-----@      1923--------D   1973---b
   1824f           1874------A     1924---------E  1974---------D
   1825-----@      1875-----@      1925-e          1975----a
   1826----a       1876---------D  1926-----@      1976-------B
   1827----------F 1877-d          1927--------D   1977----@
   1828---------D  1878--------C   1928-------C    1978--d
   1829-------B    1879----@       1929---------E  1979--c
   1830---b        1880-----@      1930i           1980-------B
   1831----------F 1881f           1931----a       1981---------E
   1832---a        1882----------H 1932f           1982---------E
   1833------A     1883-e          1933----@       1983--c
   1834--------D   1884----------F 1934----a       1984---a
   1835------A     1885---b        1935---------E  1985-------B
   1836------A     1886-------B    1936g           1986g
   1837j           1887-----@      1937------A     1987f
   1838---b        1888---------D  1938-----@      1988-f
   1839-------B    1889----------H 1939--c         1989--------D
   1840---------E  1890---------E  1940----@       1990----------G
   1841-------B    1891g           1941---b        1991----------H
   1842------A     1892-e          1942----@       1992---b
   1843-------B    1893---b        1943------A     1993----a
   1844-----@      1894-----@      1944--c         1994-d
   1845i           1895-d          1945-------B    1995--c
   1846--c         1896f           1946-----@      1996---b
   1847-d          1897-----@      1947--------D   1997---------D
```

1848--c	1898--------C	1948----------F	1998-d
1849---b	1899--b	1949--------C	1999-------A

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

Seq	Series	Time_span	1800 1849	1825 1874	1850 1899	1875 1924	1900 1949	1925 1974	1950 1999	1975 2024
1	LMA001A	1911 2008					.44	.51	.35	.33A
2	LMA001B	1913 2008					.40	.45	.48	.56
3	LMA002A	1858 2008			.46	.63	.64	.51	.32A	.33
4	LMA002B	1819 2008	.37	.36	.52	.74	.66	.59	.59	.56
5	LMA002C	1819 1898	.45	.40	.65					
6	LMA003A	1846 2008		.66	.64	.65	.67	.59	.58	.69
7	LMA003B	1817 2008	.45	.54	.52	.50	.32A	.35	.58	.57
8	LMA004A	1841 2008		.69	.61	.49	.47	.61	.64	.71
9	LMA004B	1815 2008	.39	.43	.50	.53	.55	.54	.64	.64
10	LMA006A	1846 2008		.55	.55	.67	.50	.44	.60	.59
11	LMA006B	1850 2008			.59	.80	.68	.56	.62	.63
12	LMA007A	1844 2008		.44	.61	.57	.48	.49	.49	.48
13	LMA007B	1908 2008					.43	.62	.47	.42
14	LMA008A	1810 1965	.68	.57	.49	.57	.63	.60		
15	LMA008B	1812 1980	.72	.62	.54	.67	.73	.67	.69	
16	LMA009A	1830 2008		.16B	.64	.71	.53	.60	.64	.64
17	LMA009B	1827 2008		.45	.56	.69	.65	.64	.65	.66
18	LMA010A	1822 2008	.44	.55	.64	.65	.69	.66	.59	.54
19	LMA010B	1827 2008		.66	.65	.60	.52	.59	.66	.62
20	LMA010C	1827 1896		.44	.61					
21	LMA011A	1943 2008						.55	.54	.58
22	LMA011B	1948 2008						.64	.65	.67
23	LMA012A	1938 2008						.30A	.40	.40
24	LMA012B	1941 2008						.52	.55	.56
25	LMA014A	1939 2008						.47	.62	.60
26	LMA014B	1943 2008						.41	.39	.36
27	LMA015A	1870 2008			.66	.70	.63	.55	.56	.62
28	LMA015B	1845 2008		.58	.63	.65	.53	.53	.64	.66
29	LMA015C	1836 2008		.57	.59	.79	.70	.56	.56	.49
30	LMA017A	1906 2008					.54	.61	.59	.56
31	LMA017B	1906 2008					.61	.59	.64	.55
32	LMA019A	1832 1993		.57	.59	.45	.46	.43	.30A	
33	LMA019B	1905 2008					.53	.39	.32A	.30A
34	LMA019C	1830 2008		.73	.70	.64	.64	.53	.42	.39
35	LMA019D	1828 1880		.66	.67					
36	LMA021A	1939 2008						.25B	.40	.35
37	LMA021B	1939 2008						.44	.56	.58
38	LMA027A	1946 2008						.47	.48	.45
39	LMA027B	1940 2008						.55	.58	.45
40	LMA027C	1946 1990						.65		
41	LMA041B	1829 2008		.33	.54	.79	.64	.45	.55	.48
42	LMB001A	1943 2008						.33	.32A	.40
43	LMB001B	1949 2008						.60	.60	.66

44	LMB002A	1946	2008						.59	.58	.54
45	LMB002B	1950	2008							.55	.53
46	LMB003A	1955	2008							.49	.42
47	LMB003B	1947	2001						.63	.61	.62
48	LMB004A	1950	2008							.42	.46
49	LMB004B	1949	2008						.70	.70	.51
50	LMB005A	1949	2008						.58	.60	.62
51	LMB005B	1943	2008						.50	.58	.51
52	LMB006A	1945	2008						.51	.56	.56
53	LMB006B	1943	2008						.43	.58	.52
54	LMB007A	1936	2008						.47	.53	.54
55	LMB007B	1947	2008						.55	.59	.63
56	LMB008A	1857	2008			.46	.67	.58	.56	.55	.53
57	LMB008B	1857	2008			.30B	.48	.50	.55	.49	.48
58	LMB011A	1838	2008		.42	.31B	.51	.44	.29A	.54	.69
59	LMC001A	1900	2008					.39	.45	.53	.40
60	LMC001B	1914	2008					.58	.59	.61	.53
61	LMC002A	1916	2008					.70	.65	.56	.57
62	LMC002B	1904	2008					.53	.66	.53	.41
63	LMC003A	1949	2008						.58	.58	.56
64	LMC003B	1924	2008					.43	.43	.34	.30A
65	LMC004A	1927	2008						.64	.64	.44
66	LMC004B	1918	2008					.66	.62	.66	.59
67	LMC005A	1859	1983			.68	.78	.73	.60	.47	
68	LMC005B	1869	1973			.81	.80	.63	.52		
69	LMC005C	1859	1936			.59	.73	.64			
70	LMC006A	1911	2008					.70	.70	.54	.53
71	LMC006B	1904	2008					.42	.62	.48	.52
72	LMC007A	1934	2008						.57	.47	.44
73	LMC007B	1928	2008						.62	.67	.68
74	LMC008A	1920	2008					.56	.57	.45	.34
75	LMC008B	1925	2008						.60	.42	.40
76	LMC008C	1920	1970					.64	.64		
77	LMC009A	1918	2008					.69	.66	.54	.52
78	LMC009B	1911	2008					.72	.77	.52	.53
79	LMC010A	1920	2008					.77	.75	.67	.68
80	LMC010B	1920	2008					.70	.66	.54	.57
81	LMC011A	1846	2008		.60	.60	.63	.47	.32A	.52	.59
82	LMC011B	1817	2008	.23B	.54	.58	.63	.72	.63	.61	.62
83	LMC011C	1817	1885	.48	.64	.67					
Av segment correlation				.47	.53	.58	.64	.58	.55	.54	.53

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

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

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

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

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

 [D] Absent rings (zero values)

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

 LMA001A   1911 to  2008      98 years                                                                                Series   1

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
     --------- ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
     1959 2008    0   .20  .22  .08  .05 -.14 -.03 -.06 -.18 -.15  .07  .33*   -    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .391) is:
       Lower   1986> -.028   1975> -.024   1917> -.016   1913> -.015   1929< -.012   1976< -.011  Higher   1932  .020   1955  .014
     1959 to 2008 segment:
       Lower   1986> -.067   1975> -.060   1976< -.027   1980< -.024   1983> -.019   1998> -.018  Higher   1991  .037   1960  .036

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1932   -1.483      52       2

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

 LMA001B   1913 to  2008      96 years                                                                                Series   2

 [B] Entire series, effect on correlation (  .460) is:
       Lower   1932< -.026   1929< -.018   1957< -.016   1930> -.014   1977< -.014   1917> -.012  Higher   1913  .018   2007  .013

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1932 -4.7 SD
=================================================================================================================================

 LMA002A   1858 to  2008     151 years                                                                                Series   3

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
     --------- ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
     1950 1999    0   .16  .10  .23 -.06  .04 -.19 -.28 -.39 -.08 -.12  .32* .08  .20 -.09  .16 -.31  .13 -.23  .04  .01   -

 [B] Entire series, effect on correlation (  .471) is:
       Lower   1867< -.015   1868< -.015   1932> -.014   1987> -.014   1910< -.013   1974< -.013  Higher   1936  .029   1930  .022
```

```
    1950 to 1999 segment:
      Lower   1987> -.047   1974< -.036   1964> -.020   1970> -.018   1975> -.018   1973> -.015  Higher   1960  .042   1991  .035

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1868 -5.0 SD
=====================================================================================================================================

 LMA002B   1819 to  2008     190 years                                                                                    Series   4

 [B] Entire series, effect on correlation (  .530) is:
      Lower   1867< -.025   1833< -.011   1925> -.011   1845> -.010   1968< -.008   1866> -.008  Higher   1930  .014   1882  .011

 [C] Year-to-year changes diverging by over 4.0 std deviations:
      1866 1867  -4.7 SD

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1902   -1.075      30       1

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
      1852 -4.5 SD;    1869 -5.3 SD
=====================================================================================================================================

 LMA002C   1819 to  1898      80 years                                                                                    Series   5

 [B] Entire series, effect on correlation (  .559) is:
      Lower   1845> -.023   1868< -.020   1847> -.019   1881> -.015   1836< -.013   1837> -.012  Higher   1883  .034   1820  .034

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

 LMA003A   1846 to  2008     163 years                                                                                    Series   6

 [B] Entire series, effect on correlation (  .624) is:
      Lower   1952> -.012   1909> -.010   1930> -.010   1902> -.009   1956< -.008   1951> -.008  Higher   1913  .015   1866  .010

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1852 -4.6 SD
=====================================================================================================================================

 LMA003B   1817 to  2008     192 years                                                                                    Series   7

 [A] Segment   High   -10    -9    -8    -7    -6    -5    -4    -3    -2    -1    +0    +1    +2    +3    +4    +5    +6    +7    +8    +9   +10
   ---------   ----   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---
   1900 1949    0    .04 -.06  .12 -.17 -.10  .19  .17  .21 -.04 -.26  .32*-.10  .21  .09 -.07 -.35  .09 -.27  .19 -.16 -.04

 [B] Entire series, effect on correlation (  .469) is:
      Lower   1932> -.021   1818> -.014   1850< -.010   1852> -.009   1917< -.007   1933< -.006  Higher   1851  .015   1837  .011
    1900 to 1949 segment:
      Lower   1932> -.081   1933< -.022   1902> -.015   1900> -.014   1918< -.013   1935< -.012  Higher   1930  .043   1906  .041

 [C] Year-to-year changes diverging by over 4.0 std deviations:
      1819 1820  -4.4 SD
```

```
 [E] Outliers     4   3.0 SD above or -4.5 SD below mean for year
       1820 -6.3 SD;    1917 -4.6 SD;    1931 +3.0 SD;    1932 +3.7 SD
===================================================================================================================================

 LMA004A   1841 to  2008     168 years                                                                                    Series   8

 [B] Entire series, effect on correlation (  .581) is:
       Lower   1900< -.033   1899> -.017   1909> -.010   1903< -.010   1979< -.008   1952> -.007  Higher   1845  .015   1866  .011

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1979    -.706      75       1

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

 LMA004B   1815 to  2008     194 years                                                                                    Series   9

 [B] Entire series, effect on correlation (  .520) is:
       Lower   1839< -.015   1832> -.009   1820> -.007   1932> -.007   1860< -.006   1902> -.006  Higher   1913  .012   1966  .012

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1866 -5.6 SD
===================================================================================================================================

 LMA006A   1846 to  2008     163 years                                                                                    Series  10

 [B] Entire series, effect on correlation (  .550) is:
       Lower   1930> -.014   1860< -.013   1862< -.012   1979> -.011   1870> -.010   1852> -.006  Higher   1986  .013   1955  .008

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1932   -1.483      52       2

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

 LMA006B   1850 to  2008     159 years                                                                                    Series  11

 [B] Entire series, effect on correlation (  .633) is:
       Lower   1860< -.016   1856> -.011   1884< -.009   1930> -.008   1871> -.008   1970< -.008  Higher   1883  .014   1913  .008

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

 LMA007A   1844 to  2008     165 years                                                                                    Series  12

 [B] Entire series, effect on correlation (  .467) is:
       Lower   1943< -.060   1845> -.036   1980< -.024   1966> -.014   1877> -.010   1883> -.010  Higher   1930  .035   1852  .018

 [C] Year-to-year changes diverging by over 4.0 std deviations:
       1979 1980  -4.2 SD

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1944 -4.5 SD;    1980 -6.6 SD
```

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

 LMA007B   1908 to  2008     101 years                                                Series  13

 [B] Entire series, effect on correlation (  .418) is:
       Lower   1994> -.019   1991< -.019   1975< -.017   1948< -.016   1914> -.015   1977< -.011  Higher   1930  .026   1966  .020

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

 LMA008A   1810 to  1965     156 years                                                Series  14

 [*] Early part of series cannot be checked from 1810 to 1811 -- not matched by another series

 [B] Entire series, effect on correlation (  .600) is:
       Lower   1832> -.015   1930> -.012   1870> -.011   1877> -.011   1925> -.010   1878< -.010  Higher   1845  .019   1820  .018

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

 LMA008B   1812 to  1980     169 years                                                Series  15

 [B] Entire series, effect on correlation (  .654) is:
       Lower   1856< -.016   1866> -.014   1875< -.013   1969< -.011   1832> -.008   1973> -.007  Higher   1837  .018   1845  .013

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

 LMA009A   1830 to  2008     179 years                                                Series  16

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1830 1879   -4    .10 -.13 -.09  .06 -.02 -.26  .30* .18 -.01 -.19  .16|-.18 -.39  .13  .14  .04 -.13  .08 -.08 -.06 -.10

 [B] Entire series, effect on correlation (  .520) is:
       Lower   1845> -.031   1849< -.025   1837> -.025   1852> -.012   1963< -.009   1982< -.008  Higher   1930  .019   1883  .017
     1830 to 1879 segment:
       Lower   1845> -.078   1837> -.054   1849< -.033   1852> -.024   1869> -.019   1871> -.017  Higher   1831  .046   1832  .029

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1845 +3.0 SD
===================================================================================================

 LMA009B   1827 to  2008     182 years                                                Series  17

 [B] Entire series, effect on correlation (  .601) is:
       Lower   1849< -.022   1939> -.008   1898< -.008   1852> -.008   1869> -.007   1909> -.007  Higher   1883  .014   1913  .013

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

 LMA010A   1822 to  2008     187 years                                                Series  18

 [B] Entire series, effect on correlation (  .570) is:
       Lower   1822< -.020   1932> -.016   1824> -.013   1886< -.012   1837> -.012   1832> -.009  Higher   1883  .019   1845  .015
```

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

 LMA010B   1827 to  2008     182 years                                                    Series  19

 [B] Entire series, effect on correlation (  .608) is:
       Lower   1932> -.017   1829< -.010   1988> -.008   1896> -.008   1892> -.007   1930> -.007  Higher   1845  .014   1852  .011

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 LMA010C   1827 to  1896      70 years                                                    Series  20

 [B] Entire series, effect on correlation (  .506) is:
       Lower   1828< -.059   1837> -.041   1866> -.028   1827< -.020   1896> -.019   1878< -.015  Higher   1845  .055   1891  .027

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

 LMA011A   1943 to  2008      66 years                                                    Series  21

 [B] Entire series, effect on correlation (  .551) is:
       Lower   1966> -.020   1979> -.018   1968< -.016   1946< -.009   1994> -.008   1950< -.008  Higher   1991  .016   2004  .015

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

 LMA011B   1948 to  2008      61 years                                                    Series  22

 [B] Entire series, effect on correlation (  .664) is:
       Lower   1972< -.025   1959< -.017   1973> -.013   1955< -.011   1970> -.010   1978> -.010  Higher   1986  .030   1964  .012

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

 LMA012A   1938 to  2008      71 years                                                    Series  23

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1938 1987    0    .07  .11  .17  .20 -.02 -.25 -.07 -.15  .05 -.07  .30*-.17  .22 -.23  .15  .02  .00 -.09  .00 -.18  .06

 [B] Entire series, effect on correlation (  .371) is:
       Lower   1960> -.030   1946< -.028   1973< -.026   1983> -.021   1993< -.015   1954> -.012  Higher   2007  .026   1998  .021
     1938 to 1987 segment:
       Lower   1960> -.042   1946< -.035   1983> -.028   1973< -.024   1954> -.015   1944> -.014  Higher   1986  .024   1957  .022

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

 LMA012B   1941 to  2008      68 years                                                    Series  24

 [B] Entire series, effect on correlation (  .556) is:
       Lower   1976< -.029   1972< -.022   1975> -.019   1979> -.014   1941> -.013   1960> -.013  Higher   1966  .047   1957  .018

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 LMA014A   1939 to  2008      70 years                                                                    Series  25

 [B] Entire series, effect on correlation (  .546) is:
       Lower   1966> -.033   1964> -.024   1939< -.021   1949< -.017   1944> -.016   1971< -.015  Higher   2007  .021   1955  .015

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

 LMA014B   1943 to  2008      66 years                                                                    Series  26

 [B] Entire series, effect on correlation (  .274) is:
       Lower   1949< -.062   1999< -.058   1953< -.032   1956< -.019   1964> -.017   2007> -.017  Higher   1986  .030   1955  .029

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 LMA015A   1870 to  2008     139 years                                                                    Series  27

 [B] Entire series, effect on correlation (  .615) is:
       Lower   1921< -.014   1876< -.014   1902> -.014   1966> -.013   1950> -.012   1870> -.009  Higher   1891  .018   1930  .011

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

 LMA015B   1845 to  2008     164 years                                                                    Series  28

 [B] Entire series, effect on correlation (  .562) is:
       Lower   1852> -.017   1932> -.017   1845> -.016   1937< -.012   1905< -.010   1906< -.008  Higher   1891  .017   1913  .013

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 LMA015C   1836 to  2008     173 years                                                                    Series  29

 [B] Entire series, effect on correlation (  .598) is:
       Lower   1856< -.018   1857< -.014   1852> -.012   2007> -.011   1869> -.010   1966> -.010  Higher   1913  .011   1866  .011

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

 LMA017A   1906 to  2008     103 years                                                                    Series  30

 [B] Entire series, effect on correlation (  .555) is:
       Lower   1916< -.016   1906< -.014   1929< -.014   1917> -.013   1963< -.012   1914< -.012  Higher   1913  .023   1930  .018

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

 LMA017B   1906 to  2008     103 years                                                                    Series  31

 [B] Entire series, effect on correlation (  .590) is:
       Lower   2006< -.021   1981< -.021   1939> -.016   1936> -.015   2007> -.012   1920> -.010  Higher   1913  .023   1930  .022

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

 LMA019A   1832 to  1993     162 years                                                                    Series  32
```

```
[A] Segment    High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1944 1993    0    .23  .17 -.09  .06 -.20 -.17  .02 -.21 -.09  .29  .30* .24 -.14 -.06 -.12  .06  .02 -.17 -.07 -.07  .22

[B] Entire series, effect on correlation ( .472) is:
      Lower   1986> -.021   1963< -.019   1875< -.016   1914> -.013   1906< -.012   1966> -.009  Higher   1837  .017   1866  .017
    1944 to 1993 segment:
      Lower   1986> -.076   1963< -.060   1966> -.030   1982< -.026   1952> -.022   1948< -.019  Higher   1960  .035   1987  .032

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

LMA019B   1905 to  2008     104 years                                                                                 Series  33

[A] Segment    High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1950 1999    0    .02  .21 -.16  .19 -.21 -.28  .16 -.01 -.04  .00  .32*-.17  .14 -.12  .02 -.09  .06 -.14 -.06 -.11    -
    1959 2008    0   -.09  .17 -.11  .15 -.26 -.19  .19  .02 -.08 -.03  .30*   -    -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation ( .409) is:
      Lower   1973< -.052   1963< -.018   1999< -.016   1982< -.013   1952> -.012   1990< -.012  Higher   1930  .021   1916  .018
    1950 to 1999 segment:
      Lower   1973< -.067   1963< -.032   1999< -.029   1982< -.023   1952> -.022   1990< -.022  Higher   1998  .037   1957  .026
    1959 to 2008 segment:
      Lower   1973< -.056   1963< -.031   1999< -.028   1982< -.022   1983> -.021   1990< -.021  Higher   1998  .038   1989  .025

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1973 -5.3 SD
=================================================================================================================================

LMA019C   1830 to  2008     179 years                                                                                 Series  34

[B] Entire series, effect on correlation ( .589) is:
      Lower   1990< -.017   1973< -.013   1983> -.011   1904< -.008   1881> -.008   1963< -.007  Higher   1837  .012   1882  .012

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

LMA019D   1828 to  1880      53 years                                                                                 Series  35

[B] Entire series, effect on correlation ( .654) is:
      Lower   1845> -.025   1829< -.021   1877> -.020   1838< -.018   1832> -.013   1842< -.011  Higher   1837  .074   1866  .027

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

LMA021A   1939 to  2008      70 years                                                                                 Series  36

[A] Segment    High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1939 1988   -2    .04  .02  .11  .01 -.02 -.16  .13 -.19  .32*-.20  .25| .05  .11 -.12  .01 -.19 -.30  .05  .09  .23  .18

[B] Entire series, effect on correlation ( .385) is:
      Lower   1968< -.152   2000< -.034   1961> -.024   1943< -.019   1964> -.017   1949< -.011  Higher   2007  .023   1998  .019
```

```
    1939 to 1988 segment:
      Lower   1968< -.199   1961> -.029   1943< -.023   1964> -.021   1949< -.014   1944> -.012  Higher   1966  .032   1957  .031

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

 LMA021B   1939 to  2008      70 years                                                                                    Series  37

 [B] Entire series, effect on correlation (  .559) is:
      Lower   1966> -.069   1968< -.034   1961> -.023   1946> -.019   1976< -.018   1973> -.013  Higher   1986  .021   1964  .018

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
      1946 +3.1 SD;    1966 +3.0 SD
=====================================================================================================================================

 LMA027A   1946 to  2008      63 years                                                                                    Series  38

 [B] Entire series, effect on correlation (  .456) is:
      Lower   1992> -.038   2003< -.019   1949< -.015   1995> -.013   2001< -.013   1969> -.013  Higher   1986  .032   2004  .025

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

 LMA027B   1940 to  2008      69 years                                                                                    Series  39

 [B] Entire series, effect on correlation (  .449) is:
      Lower   2000< -.057   1965< -.021   1992> -.020   2003< -.018   1948< -.015   1982< -.014  Higher   1966  .060   1974  .016

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

 LMA027C   1946 to  1990      45 years                                                                                    Series  40

 [B] Entire series, effect on correlation (  .646) is:
      Lower   1963< -.040   1957< -.040   1978> -.028   1950> -.019   1975> -.018   1958> -.009  Higher   1986  .059   1966  .050

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

 LMA041B   1829 to  2008     180 years                                                                                    Series  41

 [B] Entire series, effect on correlation (  .549) is:
      Lower   1837> -.022   1982< -.017   1933< -.013   1930> -.012   1866> -.011   1966> -.011  Higher   1845  .025   1913  .016

 [D]    3 Absent rings:  Year   Master  N series Absent
                         1845   -2.152      22       1
                         1846    -.762      25       1
                         1847   -1.014      25       1

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

 LMB001A   1943 to  2008      66 years                                                                                    Series  42

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
```

```
   1950 1999    0   -.18 -.18  .10 -.02  .10 -.10 -.16 -.28  .09 -.10  .32*-.01  .11 -.39  .23 -.20  .30 -.18  .13  .00    -

 [B] Entire series, effect on correlation (  .339) is:
       Lower   1982< -.038   1998> -.028   1999< -.017   1950> -.012   1955< -.011   1979> -.011  Higher   1960  .036   2004  .019
     1950 to 1999 segment:
       Lower   1982< -.045   1998> -.034   1999< -.020   1950> -.014   1966> -.014   1979> -.012  Higher   1960  .042   1968  .025

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

 LMB001B   1949 to  2008      60 years                                                                                    Series  43

 [B] Entire series, effect on correlation (  .602) is:
       Lower   1982< -.023   1952< -.018   1985< -.017   1989< -.017   1951> -.016   1950> -.014  Higher   1998  .025   2007  .021

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

 LMB002A   1946 to  2008      63 years                                                                                    Series  44

 [B] Entire series, effect on correlation (  .576) is:
       Lower   2000< -.031   1969< -.029   1973> -.019   1961> -.015   1976< -.014   1979> -.012  Higher   1964  .015   1957  .015

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

 LMB002B   1950 to  2008      59 years                                                                                    Series  45

 [B] Entire series, effect on correlation (  .562) is:
       Lower   1967< -.023   1979> -.019   1987> -.013   1999< -.012   1991< -.012   1969< -.012  Higher   1998  .025   1957  .020

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

 LMB003A   1955 to  2008      54 years                                                                                    Series  46

 [B] Entire series, effect on correlation (  .455) is:
       Lower   1963< -.036   1975< -.035   2000< -.034   2007> -.031   1960> -.018   1961> -.016  Higher   1966  .049   1986  .022

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

 LMB003B   1947 to  2001      55 years                                                                                    Series  47

 [B] Entire series, effect on correlation (  .632) is:
       Lower   1994< -.046   1998> -.014   1989< -.011   1977> -.011   1969> -.011   1986> -.010  Higher   1966  .026   1964  .016

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

 LMB004A   1950 to  2008      59 years                                                                                    Series  48

 [B] Entire series, effect on correlation (  .470) is:
       Lower   1968< -.075   1966> -.054   1988> -.029   1985< -.028   1950> -.021   1964> -.019  Higher   1986  .033   2007  .031

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```
 LMB004B   1949 to  2008      60 years                                                                                    Series  49

 [B] Entire series, effect on correlation (  .547) is:
       Lower   2005< -.105   2007> -.045   1967< -.027   1988> -.010   1964> -.010   1977> -.009  Higher   1986  .039   1957  .016

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

 LMB005A   1949 to  2008      60 years                                                                                    Series  50

 [B] Entire series, effect on correlation (  .567) is:
       Lower   1956< -.025   1979> -.023   1951> -.016   1969> -.015   1984< -.013   1976< -.012  Higher   1966  .028   1960  .021

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

 LMB005B   1943 to  2008      66 years                                                                                    Series  51

 [B] Entire series, effect on correlation (  .476) is:
       Lower   1946< -.032   2007> -.029   1943< -.021   1968< -.017   2006< -.016   1964> -.014  Higher   1966  .038   1992  .023

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

 LMB006A   1945 to  2008      64 years                                                                                    Series  52

 [B] Entire series, effect on correlation (  .508) is:
       Lower   1974< -.031   1960> -.029   1949< -.029   2006> -.020   1947< -.020   1970> -.011  Higher   2007  .029   1991  .019

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

 LMB006B   1943 to  2008      66 years                                                                                    Series  53

 [B] Entire series, effect on correlation (  .426) is:
       Lower   1947< -.086   2004< -.035   1960> -.032   1944> -.012   1969> -.010   1986> -.010  Higher   2007  .036   1992  .027

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

 LMB007A   1936 to  2008      73 years                                                                                    Series  54

 [B] Entire series, effect on correlation (  .516) is:
       Lower   1952< -.032   1967< -.028   2001< -.021   1941> -.017   1960> -.016   1976< -.014  Higher   1936  .041   1966  .040

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

 LMB007B   1947 to  2008      62 years                                                                                    Series  55

 [B] Entire series, effect on correlation (  .558) is:
       Lower   1967< -.031   1949< -.029   1998> -.023   1953< -.022   1951> -.019   1987> -.018  Higher   1966  .050   1986  .047

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

 LMB008A   1857 to  2008     152 years                                                                                    Series  56
```

```
[B] Entire series, effect on correlation (  .516) is:
      Lower   1866> -.020   1934< -.017   1861< -.017   1858< -.009   1994> -.009   1985< -.009  Higher   1883  .028   1913  .022

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1934 -4.8 SD
==================================================================================================================================

LMB008B   1857 to  2008     152 years                                                                                  Series  57

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    --------- ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1857 1906    8    .05 -.02  .07  .09  .25 -.31  .12  .12  .13 -.35  .30|-.16 -.07 -.21  .20 -.17 -.06 -.22  .45*-.11  .14

[B] Entire series, effect on correlation (  .417) is:
      Lower   1866> -.019   1873< -.019   1930> -.018   1861< -.018   1887< -.013   1997< -.010  Higher   1883  .036   1936  .025
    1857 to 1906 segment:
      Lower   1866> -.051   1861< -.039   1873< -.036   1896> -.027   1887< -.023   1885> -.021  Higher   1883  .124   1877  .035

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

LMB011A   1838 to  2008     171 years                                                                                  Series  58

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    --------- ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1850 1899    4   -.08 -.01 -.10  .02 -.17 -.08  .28 -.02 -.08  .05  .31|-.13  .11 -.13  .43*-.18  .03 -.05 -.06 -.22  .33
   - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   1925 1974    0   -.17 -.11 -.11 -.17  .02  .08  .19  .05 -.11  .03  .29*-.01  .12 -.06  .05  .08  .21 -.08  .16 -.07 -.06

[B] Entire series, effect on correlation (  .465) is:
      Lower   1867< -.052   1955< -.021   1904< -.014   1930> -.012   1891> -.011   1883> -.010  Higher   1845  .026   1986  .018
    1850 to 1899 segment:
      Lower   1867< -.166   1885> -.021   1891> -.020   1883> -.015   1876< -.015   1899> -.011  Higher   1881  .040   1882  .035
    1925 to 1974 segment:
      Lower   1955< -.085   1965< -.031   1930> -.029   1937< -.022   1929< -.018   1958< -.014  Higher   1936  .046   1964  .035

[C] Year-to-year changes diverging by over 4.0 std deviations:
      1866 1867  -5.1 SD

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

LMC001A   1900 to  2008     109 years                                                                                  Series  59

[B] Entire series, effect on correlation (  .412) is:
      Lower   1918< -.038   2000< -.025   1900< -.022   1974< -.020   1927< -.016   1947< -.012  Higher   1930  .072   1986  .025

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LMC001B   1914 to  2008      95 years                                                                                  Series  60

[B] Entire series, effect on correlation (  .554) is:
      Lower   1920< -.025   1942< -.020   2008< -.017   1970< -.011   1988> -.010   2007> -.009  Higher   1930  .038   1986  .029
```

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 LMC002A   1916 to  2008      93 years                                                    Series  61

 [B] Entire series, effect on correlation (  .582) is:
       Lower   1975< -.083   1926< -.016   1960> -.014   1983> -.012   1997< -.009   1980< -.008  Higher   1986  .017   1936  .016

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1975    -.195      75       1  >> WARNING:  Ring is not usually narrow

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1975 -6.3 SD
====================================================================================================

 LMC002B   1904 to  2008     105 years                                                    Series  62

 [B] Entire series, effect on correlation (  .489) is:
       Lower   2003< -.041   1940< -.017   1983> -.013   1913> -.012   1911< -.012   1980< -.011  Higher   1930  .029   1925  .022

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 LMC003A   1949 to  2008      60 years                                                    Series  63

 [B] Entire series, effect on correlation (  .574) is:
       Lower   1977< -.061   1960> -.040   1994> -.028   2001< -.017   1992> -.013   1989< -.011  Higher   1986  .052   1998  .021

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 LMC003B   1924 to  2008      85 years                                                    Series  64

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1959 2008    0   -.09  .16  .13  .11 -.29 -.22 -.16  .07 -.03  .15  .30*   -    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .423) is:
       Lower   1962< -.033   1966> -.029   1992> -.022   2007> -.018   1956< -.015   1940< -.013  Higher   1936  .027   1930  .024
     1959 to 2008 segment:
       Lower   1966> -.049   1992> -.036   2007> -.031   1962< -.030   1999< -.018   1987> -.016  Higher   1986  .037   1990  .033

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 LMC004A   1927 to  2008      82 years                                                    Series  65

 [B] Entire series, effect on correlation (  .520) is:
       Lower   2006< -.064   2007> -.035   2000< -.014   1935< -.012   1983> -.011   1979> -.010  Higher   1930  .043   2004  .014

 [C] Year-to-year changes diverging by over 4.0 std deviations:
       2006 2007   5.5 SD

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
```

```
      2006 -6.3 SD
=====================================================================================================================================

 LMC004B   1918 to  2008      91 years                                                                                  Series  66

 [B] Entire series, effect on correlation (  .660) is:
       Lower   2006< -.023   1947< -.016   1979> -.012   2007> -.011   1957< -.010   1977< -.009  Higher   1930  .059   1992  .007

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1930   -2.296      52       1

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 LMC005A   1859 to  1983     125 years                                                                                  Series  67

 [B] Entire series, effect on correlation (  .622) is:
       Lower   1965< -.019   1949< -.012   1881> -.012   1983> -.011   1960> -.010   1974< -.009  Higher   1930  .025   1883  .023

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 LMC005B   1869 to  1973     105 years                                                                                  Series  68

 [B] Entire series, effect on correlation (  .654) is:
       Lower   1931< -.023   1936> -.021   1923< -.012   1939> -.012   1960> -.009   1957< -.009  Higher   1930  .040   1891  .020

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1973    -.412      76       1
  >> WARNING:  Last ring in series is ABSENT

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 LMC005C   1859 to  1936      78 years                                                                                  Series  69

 [B] Entire series, effect on correlation (  .591) is:
       Lower   1936> -.051   1870< -.027   1866> -.026   1869> -.012   1931< -.011   1923< -.010  Higher   1930  .041   1891  .029

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 LMC006A   1911 to  2008      98 years                                                                                  Series  70

 [B] Entire series, effect on correlation (  .627) is:
       Lower   1913> -.022   1975> -.018   1932> -.017   1950> -.016   1983> -.014   1947< -.012  Higher   1930  .053   1936  .027

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 LMC006B   1904 to  2008     105 years                                                                                  Series  71

 [B] Entire series, effect on correlation (  .470) is:
       Lower   1907< -.046   1913> -.044   1986> -.017   1978< -.015   1938< -.014   1908< -.012  Higher   1930  .037   1991  .011

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
```

```
      1913 +3.1 SD
==========================================================================================================================

 LMC007A   1934 to  2008      75 years                                                                        Series  72

 [B] Entire series, effect on correlation (  .492) is:
      Lower   1999< -.111   1948< -.041   1986> -.035   1977> -.014   1960> -.013   1998> -.010  Higher   1936  .036   1991  .021

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

 LMC007B   1928 to  2008      81 years                                                                        Series  73

 [B] Entire series, effect on correlation (  .639) is:
      Lower   1935< -.031   1955< -.018   1934> -.014   2006> -.012   1939< -.012   1977> -.012  Higher   1930  .061   1966  .020

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

 LMC008A   1920 to  2008      89 years                                                                        Series  74

 [B] Entire series, effect on correlation (  .445) is:
      Lower   2000< -.030   1947< -.020   1992> -.016   1960> -.016   1986> -.011   1979< -.010  Higher   1925  .033   1936  .025

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 LMC008B   1925 to  2008      84 years                                                                        Series  75

 [B] Entire series, effect on correlation (  .505) is:
      Lower   1979< -.053   1960> -.018   1997< -.015   1973< -.015   1992> -.011   1947< -.011  Higher   1936  .044   1930  .020

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

 LMC008C   1920 to  1970      51 years                                                                        Series  76

 [B] Entire series, effect on correlation (  .643) is:
      Lower   1930> -.126   1960> -.028   1955< -.011   1964> -.010   1969> -.005   1945< -.005  Higher   1936  .054   1966  .035

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 LMC009A   1918 to  2008      91 years                                                                        Series  77

 [B] Entire series, effect on correlation (  .645) is:
      Lower   1966> -.019   1974< -.016   2001< -.011   2005> -.010   1950> -.010   1918< -.009  Higher   1930  .060   1932  .012

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 LMC009B   1911 to  2008      98 years                                                                        Series  78

 [B] Entire series, effect on correlation (  .639) is:
      Lower   1954< -.021   2006> -.018   1913> -.016   1986> -.015   1975> -.014   1988> -.008  Higher   1930  .052   1936  .021

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 LMC010A   1920 to  2008      89 years                                                                                    Series  79

 [B] Entire series, effect on correlation (  .723) is:
       Lower   1975> -.012   1944< -.012   1969< -.012   1951> -.008   1993< -.008   1952> -.007  Higher   1930  .022   1966  .016

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 LMC010B   1920 to  2008      89 years                                                                                    Series  80

 [B] Entire series, effect on correlation (  .660) is:
       Lower   1964> -.018   1961> -.017   1952> -.010   1986> -.009   1962> -.009   1948< -.009  Higher   1930  .035   1936  .029

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 LMC011A   1846 to  2008     163 years                                                                                    Series  81

 [A] Segment   High   -10    -9    -8    -7    -6    -5    -4    -3    -2    -1    +0    +1    +2    +3    +4    +5    +6    +7    +8    +9   +10
    ---------  ----   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---
    1925 1974    0    .28 -.27 -.02 -.08  .15 -.08 -.07 -.16  .00 -.10  .32*-.12  .06 -.28  .08  .02  .29  .10  .10  .07 -.10

 [B] Entire series, effect on correlation (  .516) is:
       Lower   1941> -.022   1920< -.013   1956< -.011   1957< -.011   1891> -.011   1899> -.010  Higher   1883  .018   1913  .016
     1925 to 1974 segment:
       Lower   1941> -.069   1956< -.036   1957< -.034   1966> -.022   1942< -.022   1935< -.015  Higher   1960  .041   1930  .037

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1941 +3.7 SD
====================================================================================================================================

 LMC011B   1817 to  2008     192 years                                                                                    Series  82

 [A] Segment   High   -10    -9    -8    -7    -6    -5    -4    -3    -2    -1    +0    +1    +2    +3    +4    +5    +6    +7    +8    +9   +10
    ---------  ----   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---   ---
    1817 1866    2      -     -     - -.15 -.12 -.19 -.27  .15 -.26  .18  .23| .19  .25*-.01 -.05  .15 -.05  .13 -.12 -.12  .15

 [B] Entire series, effect on correlation (  .506) is:
       Lower   1819< -.056   1820> -.038   1843< -.020   1852> -.013   1895> -.010   1908< -.006  Higher   1930  .027   1837  .015
     1817 to 1866 segment:
       Lower   1819< -.160   1820> -.094   1843< -.048   1852> -.028   1830> -.010   1835< -.010  Higher   1837  .087   1845  .050

 [C] Year-to-year changes diverging by over 4.0 std deviations:
       1818 1819  -5.1 SD    1819 1820   6.9 SD

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1843     .407      20       1  >> WARNING:  Ring is not usually narrow

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1819 -6.1 SD
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LMC011C   1817 to  1885      69 years                                                                                    Series  83

 [B] Entire series, effect on correlation (  .504) is:
       Lower   1820> -.061   1824< -.031   1835< -.018   1885> -.015   1852> -.012   1832> -.011  Higher   1837  .060   1851  .024

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							//-------- Unfiltered			--------\\	//---- Filtered		-----\\		
Seq	Series	Interval	No. Years	No. Segmt	No. Flags	Corr with Master	Mean msmt	Max msmt	Std dev	Auto corr	Mean sens	Max value	Std dev	Auto corr	AR ()
1	LMA001A	1911 2008	98	4	1	.391	1.63	3.06	.572	.736	.220	2.55	.343	-.012	1
2	LMA001B	1913 2008	96	4	0	.460	1.74	3.06	.609	.802	.194	2.36	.310	-.008	1
3	LMA002A	1858 2008	151	6	1	.471	1.41	4.07	.772	.774	.273	2.67	.438	-.055	1
4	LMA002B	1819 2008	190	8	0	.530	1.02	2.67	.475	.632	.295	2.56	.319	-.028	1
5	LMA002C	1819 1898	80	3	0	.559	1.29	2.66	.606	.614	.334	2.59	.436	-.014	1
6	LMA003A	1846 2008	163	7	0	.624	1.19	3.10	.573	.623	.329	2.55	.368	-.026	1
7	LMA003B	1817 2008	192	8	1	.469	1.03	6.17	.832	.459	.347	2.83	.305	-.015	1
8	LMA004A	1841 2008	168	7	0	.581	.90	2.68	.468	.708	.326	2.67	.408	-.042	1
9	LMA004B	1815 2008	194	8	0	.520	1.13	5.59	.988	.873	.292	2.62	.357	-.019	1
10	LMA006A	1846 2008	163	7	0	.550	.65	2.53	.463	.899	.266	2.67	.393	-.010	1
11	LMA006B	1850 2008	159	6	0	.633	.95	2.58	.491	.799	.269	2.60	.416	-.030	1
12	LMA007A	1844 2008	165	7	0	.467	.69	1.93	.344	.748	.263	2.70	.363	.020	1
13	LMA007B	1908 2008	101	4	0	.418	1.60	3.86	.766	.771	.264	2.64	.429	-.066	1
14	LMA008A	1810 1965	156	6	0	.600	.84	6.00	1.047	.932	.294	2.69	.492	-.017	1
15	LMA008B	1812 1980	169	7	0	.654	1.21	7.87	1.273	.902	.303	2.76	.498	-.008	1
16	LMA009A	1830 2008	179	7	1	.520	.93	3.97	.681	.936	.199	2.69	.460	-.021	1
17	LMA009B	1827 2008	182	7	0	.601	1.13	10.81	1.250	.906	.222	2.81	.508	-.003	1
18	LMA010A	1822 2008	187	8	0	.570	1.33	3.61	.787	.885	.240	2.63	.368	-.017	1
19	LMA010B	1827 2008	182	7	0	.608	.93	3.42	.553	.852	.262	2.79	.395	-.047	1
20	LMA010C	1827 1896	70	2	0	.506	2.16	4.05	.903	.800	.215	2.51	.466	.003	1
21	LMA011A	1943 2008	66	3	0	.551	2.32	3.75	.666	.634	.194	2.57	.539	.075	1
22	LMA011B	1948 2008	61	3	0	.664	2.01	4.97	.726	.738	.195	2.56	.623	.088	1
23	LMA012A	1938 2008	71	3	1	.371	2.46	3.39	.502	.495	.180	2.53	.453	.003	1
24	LMA012B	1941 2008	68	3	0	.556	2.57	4.49	.627	.717	.144	2.59	.443	-.029	1
25	LMA014A	1939 2008	70	3	0	.546	2.19	8.00	1.864	.914	.272	2.71	.497	.018	2
26	LMA014B	1943 2008	66	3	0	.274	2.54	7.25	1.428	.791	.275	2.67	.544	.015	3
27	LMA015A	1870 2008	139	6	0	.615	.93	2.85	.496	.736	.258	2.77	.500	-.045	2
28	LMA015B	1845 2008	164	7	0	.562	1.03	1.93	.354	.536	.270	2.72	.455	.009	1
29	LMA015C	1836 2008	173	7	0	.598	.94	2.93	.448	.663	.252	2.79	.456	.025	1
30	LMA017A	1906 2008	103	4	0	.555	1.73	4.54	.817	.759	.266	2.58	.423	.093	1
31	LMA017B	1906 2008	103	4	0	.590	1.65	4.50	.787	.716	.281	2.64	.483	.055	1
32	LMA019A	1832 1993	162	6	1	.472	.99	3.76	.603	.841	.243	2.96	.542	-.024	1
33	LMA019B	1905 2008	104	4	2	.409	.73	1.86	.461	.846	.268	2.56	.354	-.028	1
34	LMA019C	1830 2008	179	7	0	.589	.84	2.76	.593	.893	.233	2.67	.323	-.007	1
35	LMA019D	1828 1880	53	2	0	.654	1.37	2.77	.684	.877	.201	2.41	.432	.043	1
36	LMA021A	1939 2008	70	3	1	.385	2.44	3.90	.652	.707	.160	2.49	.464	-.110	1
37	LMA021B	1939 2008	70	3	0	.559	2.21	4.59	.640	.602	.193	2.95	.581	-.023	1
38	LMA027A	1946 2008	63	3	0	.456	1.87	4.71	.739	.732	.222	2.72	.531	-.034	1
39	LMA027B	1940 2008	69	3	0	.449	1.70	4.72	.945	.905	.223	2.66	.525	.015	2
40	LMA027C	1946 1990	45	1	0	.646	1.97	4.99	1.011	.878	.231	2.75	.556	.046	3
41	LMA041B	1829 2008	180	7	0	.549	1.17	4.99	.821	.891	.252	2.63	.410	.037	1
42	LMB001A	1943 2008	66	3	1	.339	1.75	6.87	1.640	.942	.323	2.59	.490	-.106	2
43	LMB001B	1949 2008	60	3	0	.602	1.63	6.60	1.162	.797	.378	2.69	.539	-.063	2
44	LMB002A	1946 2008	63	3	0	.576	1.92	4.67	.916	.742	.303	2.67	.561	-.068	1
45	LMB002B	1950 2008	59	2	0	.562	2.08	4.15	.722	.673	.229	2.57	.444	-.088	2

						Corr	//-------- Unfiltered --------\\					//---- Filtered -----\\			
			No.	No.	No.	with	Mean	Max	Std	Auto	Mean	Max	Std	Auto	AR
Seq	Series	Interval	Years	Segmt	Flags	Master	msmt	msmt	dev	corr	sens	value	dev	corr	()
46	LMB003A	1955 2008	54	2	0	.455	1.82	3.33	.630	.539	.265	2.44	.449	-.063	3
47	LMB003B	1947 2001	55	3	0	.632	1.49	5.71	1.070	.901	.261	2.52	.460	-.022	1
48	LMB004A	1950 2008	59	2	0	.470	2.62	5.20	1.007	.642	.257	2.79	.578	.076	1
49	LMB004B	1949 2008	60	3	0	.547	2.19	4.22	.744	.564	.270	2.48	.472	.030	3
50	LMB005A	1949 2008	60	3	0	.567	2.53	5.08	1.136	.849	.213	2.68	.582	-.073	1
51	LMB005B	1943 2008	66	3	0	.476	2.35	4.91	1.391	.919	.202	2.73	.557	-.025	1
52	LMB006A	1945 2008	64	3	0	.508	2.50	4.42	.942	.528	.282	2.63	.514	-.095	3
53	LMB006B	1943 2008	66	3	0	.426	3.13	5.51	.855	.440	.206	2.63	.574	-.054	1
54	LMB007A	1936 2008	73	3	0	.516	2.17	4.39	.984	.843	.214	2.60	.421	-.005	1
55	LMB007B	1947 2008	62	3	0	.558	2.64	5.78	1.060	.800	.213	2.56	.526	.009	1
56	LMB008A	1857 2008	152	6	0	.516	.83	3.19	.532	.698	.379	2.85	.507	.002	1
57	LMB008B	1857 2008	152	6	1	.417	.79	2.66	.508	.748	.396	2.82	.493	.001	3
58	LMB011A	1838 2008	171	7	2	.465	.94	2.73	.595	.893	.248	2.77	.434	-.005	2
59	LMC001A	1900 2008	109	4	0	.412	1.73	5.96	1.480	.886	.304	2.69	.458	-.001	5
60	LMC001B	1914 2008	95	4	0	.554	.78	2.13	.442	.813	.339	2.65	.526	-.024	2
61	LMC002A	1916 2008	93	4	0	.582	1.43	5.05	1.109	.892	.324	2.47	.337	-.088	1
62	LMC002B	1904 2008	105	4	0	.489	1.54	5.53	1.054	.885	.259	2.67	.473	.002	1
63	LMC003A	1949 2008	60	3	0	.574	1.66	3.10	.485	.675	.193	2.62	.528	-.012	2
64	LMC003B	1924 2008	85	4	1	.423	1.35	3.50	.527	.538	.274	2.64	.460	-.021	1
65	LMC004A	1927 2008	82	3	0	.520	2.11	4.86	1.095	.641	.335	2.48	.397	-.014	2
66	LMC004B	1918 2008	91	4	0	.660	1.64	3.43	.754	.664	.307	2.38	.347	-.058	3
67	LMC005A	1859 1983	125	5	0	.622	1.05	2.58	.594	.694	.345	2.69	.555	.034	1
68	LMC005B	1869 1973	105	4	0	.654	1.12	2.80	.633	.711	.334	2.76	.407	.067	1
69	LMC005C	1859 1936	78	3	0	.591	1.45	2.97	.605	.572	.330	2.65	.476	.076	1
70	LMC006A	1911 2008	98	4	0	.627	1.94	3.86	.867	.822	.215	2.59	.452	-.025	1
71	LMC006B	1904 2008	105	4	0	.470	1.64	4.27	.909	.819	.255	2.54	.460	.000	1
72	LMC007A	1934 2008	75	3	0	.492	1.43	4.01	.916	.891	.252	2.71	.474	-.033	1
73	LMC007B	1928 2008	81	3	0	.639	1.63	3.83	.917	.823	.244	2.72	.506	-.083	2
74	LMC008A	1920 2008	89	4	0	.445	1.58	2.83	.449	.534	.212	2.65	.398	-.047	1
75	LMC008B	1925 2008	84	3	0	.505	1.42	3.22	.470	.596	.244	2.52	.427	.015	1
76	LMC008C	1920 1970	51	2	0	.643	1.83	2.61	.383	.313	.200	2.60	.524	-.111	1
77	LMC009A	1918 2008	91	4	0	.645	1.48	2.71	.488	.484	.268	2.54	.400	-.018	1
78	LMC009B	1911 2008	98	4	0	.639	1.47	4.77	.622	.465	.280	2.55	.428	-.008	1
79	LMC010A	1920 2008	89	4	0	.723	1.80	5.53	1.033	.814	.278	2.53	.475	-.039	1
80	LMC010B	1920 2008	89	4	0	.660	1.83	4.66	.870	.741	.261	2.55	.436	-.072	1
81	LMC011A	1846 2008	163	7	1	.516	1.17	9.86	.885	.147	.410	3.27	.529	-.007	1
82	LMC011B	1817 2008	192	8	1	.506	.83	2.54	.500	.626	.407	2.59	.476	-.021	1
83	LMC011C	1817 1885	69	3	0	.504	.93	2.59	.575	.699	.368	2.72	.525	-.070	1
Total or mean:			8868	365	16	.539	1.38	10.81	.747	.740	.274	3.27	.448	-.014	

- = [COFECHA LM83 COF] = -

VITA

Yanan Li comes from China. She grew up in Urumqi, Xinjiang Uyghur Autonomous Region, and then spent her undergraduate years in Beijing Normal University, Beijing. In 2008, she obtained her Bachelor of Sciences in Geosciences major. She was first introduced to tree-ring science in her undergraduate research, and published a paper titled "*Precipitation in February–May Reconstructed from Tree-Ring since ca.1895 in Xiaowutai Mountains, China*" as the second author. Her undergraduate thesis is about "*A Test on the Measuring Ability of LIGNOSTATION Wood Surface Scanner*". In fall 2008, Yanan was enrolled in the master's program of the University of Tennessee at Knoxville. In the Department of Geography, she continued focusing on dendrochronology, but expanded also to biogeography and climate change. In her 2.5 years in the department, she served as a Graduate Teaching Assistant for World Regional Geography, Cultural Geography, and Natural Hazards. In summer 2009, she participated in the summer school of dendroclimatology, held by the Laboratory of Tree-Ring Research at the University of Arizona. She is a nature-loving person, and she took part in considerable field work during the master's program, including the Great Smoky Mountains, Tipton-Haynes State Historic Site, El Malpais National Monument, Cibola National Forest, Pisgah National Forest, and Tian Shan in China. She is a member of the Association of American Geographers (AAG), and presented at AAG annual meetings. She received her Master of Science degree in Geography from the University of Tennessee in January 2011. After graduation, Yanan seeks to have an internship for half of a year, and then plans to work toward a doctoral degree in Geography.