TREE-RING RECONSTRUCTED RAINFALL OVER THE SOUTHEASTERN U.S.A. DURING THE MEDIEVAL WARM PERIOD AND LITTLE ICE AGE

DAVID W. STAHLE and MALCOLM K. CLEAVELAND
Tree-Ring Laboratory, University of Arkansas, Fayetteville, AR 72701, U.S.A.

Abstract. A 1053-year reconstruction of spring rainfall (March-June) was developed for the southeastern United States, based on three tree-ring reconstructions of statewide rainfall from North Carolina, South Carolina, and Georgia. This regional reconstruction is highly correlated with the instrumental record of spring rainfall ($r = +0.80$; 1887–1982), and accurately reproduces the decade-scale departures in spring rainfall amount and variance witnessed over the Southeast during the past century. No large-magnitude centuries-long trends in spring rainfall amounts were reconstructed over the past 1053 years, but large changes in the interannual variability of spring rainfall were reconstructed during portions of the Medieval Warm Period (MWP), Little Ice Age (LIA), and the 20th century. Dry conditions persisted at the end of the 12th century, but appear to have been exceeded by a reconstructed drought in the mid-18th century. High interannual variability, including five extremely wet years were reconstructed for a 20-yr period during the late 16th and early 17th centuries, and may reflect amplified atmospheric circulation over eastern North America during what appears to have been one of the most widespread cold episodes of the Little Ice Age.

1. Introduction

The Medieval Warm Period (MWP) and Little Ice Age (LIA) have received increased scrutiny as possible examples of centuries-long, global-scale climate anomalies caused by natural factors internal and/or external to the climate system (e.g., Folland *et al.*, 1990; Bradley and Jones, 1992). The true scope and magnitude of these late Holocene climate episodes have become important issues relevant to the detection of anthropogenic influences on global climate. For example, some fraction of the observed rise in surface air temperature during the 20th century may represent a natural amelioration of the LIA (Folland *et al.*, 1990). Also, the regional climate and ecological changes during the MWP might provide useful examples of the environmental impacts that could attend CO_2 induced global warming. It is therefore important to document the nature of these climate episodes in all regions and all four seasons using as wide a range of climate variables as possible.

The MWP and LIA have been most clearly identified in a variety of historical and proxy climate sources from the temperate and arctic latitudes of western Europe and North America (e.g., LaMarche, 1974; Le Roy Ladurie, 1971; Williams and Wigley, 1983; Karlen, 1988; Chapman and Clow, 1991; Briffa *et al.*, 1992). The MWP dates from approximately A.D. 1000 to 1300 and included retreating glaciers (Grove, 1988), above average growth in temperature sensitive trees of the western

Climatic Change **26:** 199–212, 1994.

United States and Scandinavia (LaMarche, 1974; Briffa *et al.*, 1992), and Norse settlement of Greenland (Lamb, 1977). The LIA dates from approximately A.D. 1550 to 1850 and included roughly synchronous glacial advances in Europe and North America (e.g., Williams and Wigley, 1983; Grove, 1988; Bradley and Jones, 1992), and a series of long, cold winters in western Europe (Lamb, 1977). Evidence for the larger, perhaps global-scale extent of these late Holocene climatic episodes has been reported from Russia (Graybill and Shiyatov, 1992), China (Fu, 1990), Tasmania (Cook *et al.*, 1991), and South America (e.g., Thompson *et al.*, 1986; Villalba, 1990). However, scrutiny of a diverse body of climate evidence covering the last 500 yr led Jones and Bradley (1992) to conclude that the nature and timing of regional climate anomalies was quite variable during this period, and the consistent worldwide climatic conditions suggested by the term Little Ice Age might misrepresent the data. Examination of the proxy data reviewed by Williams and Wigley (1983) suggests that regional variability in reconstructed climates may cast similar doubts over the general use of the term Medieval Warm Period. There certainly has been considerable regional variability in seasonal and annually-averaged temperatures during the past century when hemispheric and globally-averaged temperature data have indicated a warming trend of approximately 0.5°C (e.g., Folland *et al.*, 1990).

Some of the clearest evidence for the LIA and MWP has been derived from glaciological and pollen data (e.g., Grove, 1988), but the temporal resolution and specific climatological implications of this evidence are often poorly constrained. Much of the evidence for the LIA and MWP is also based on proxies which are believed to be largely sensitive to variations in surface air temperature during the summer or winter season. Accurate high resolution paleoclimatic estimates of precipitation are generally less common, so the possible change in regional to global scale hydrological conditions during the MWP and LIA are not well documented, particularly during the transitional seasons of spring and fall. Dramatic, post-glacial changes in regional hydrology have occurred in regions such as North Africa (Folland *et al.*, 1990) and possibly over the southeastern U.S.A. (e.g., Frey, 1954; Whitehead, 1972), particularly during the mid-Holocene thermal maximum ca. 6000 B.P. The possibility that significant hydrological changes occurred during the MWP and LIA is therefore an important question, and can be addressed in some regions like the southeastern United States with high resolution tree-ring chronologies. In this paper, we develop a 1053-yr reconstruction of spring rainfall over the southeastern U.S.A., and then search for interannual to decadal anomalies in spring rainfall during the MWP, LIA, and other episodes over the past millennium.

2. Reconstruction of Spring Rainfall

Five rainfall-sensitive tree-ring chronologies 780 to 1614-yr long have been developed from baldcypress (*Taxodium distichum*) trees in North Carolina, South Carolina, and Georgia (Figure 1). These chronologies are well correlated with each

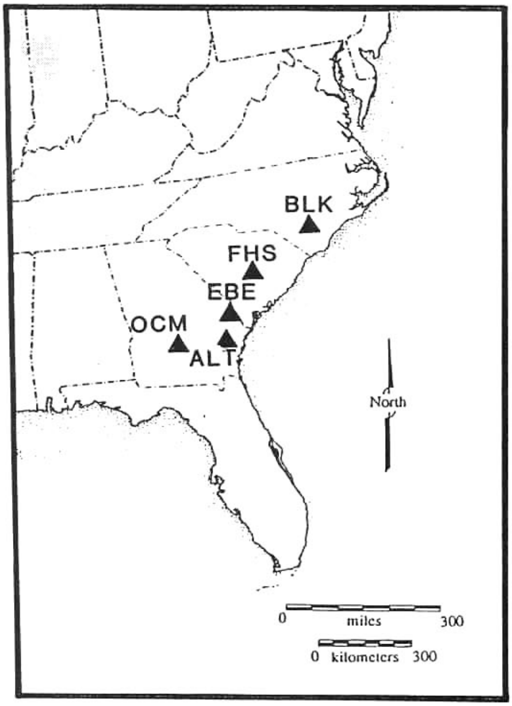

Fig. 1. The locations of the five tree-ring chronologies (triangles) used to develop the spring rainfall reconstruction for the 'Southeast' (i.e., averaged over North Carolina, South Carolina, and Georgia). BLK = Black River; FHS = Four Holes Swamp; EBE = Ebenezer Creek; ALT = Altamaha River; OCM = Ocmulgee River.

other and with monthly precipitation totals from March though June averaged on a statewide basis by Karl *et al.* (1983a, b, c). Variations in water level and water quality (particularly the dissolved oxygen concentration), which are both linked with rainfall amounts, are believed to be involved in the baldcypress growth response to spring rainfall (Stahle and Cleaveland, 1992). The radial growth of baldcypress is also inversely correlated with percentage possible sunshine and temperature during the growing season, but these influences are quite weak compared to the rainfall signal (e.g., Stahle *et al.*, 1991).

In a previous study, the five baldcypress chronologies were used to reconstruct spring rainfall amounts in each of North Carolina (April-June), South Carolina, and Georgia (both March to June; Stahle and Cleaveland, 1992). All five chronologies were considered for the calibration of spring rainfall in each state, and the best subsets of chronologies were selected (based on the F-statistics and explained variance computed in stepwise multiple regression analyses). The Black River chronology alone was used in a bivariate regression model to reconstruct April through June rainfall in North Carolina; the Four Holes Swamp and Ebenezer Creek chronologies were used in a multiple regression model to reconstruct March through June rainfall in South Carolina; and a regional average of the Altamaha and Ocmulgee River chronologies was used in bivariate regression to calibrate and reconstruct March through June rainfall in Georgia (Stahle and Cleaveland, 1992). Because the Ocmulgee chronology starts in A.D. 1206, the Altamaha-Ocmulgee average chronology is based only on Altamaha prior to 1206, and the variance of Altamaha before 1206 was reduced to match the variance of the Altamaha-Ocmulgee combination (1206–1985). The selected tree-ring predictor(s) explained highly significant fractions of the observed spring rainfall variance in each state (i.e., $R^2 = 0.54$; 0.58, and 0.68 based on the period 1887 (or 1892 in Georgia) to 1936 in North Carolina, South Carolina, and Georgia, respectively. The reconstructions of state-averaged rainfall derived from the tree-ring data in each state were also well verified when compared with instrumental state-averaged rainfall data available from 1937 to 1982 (Karl *et al.*, 1983 a, b, c), which were withheld from the calibration (Stahle and Cleaveland, 1992).

The three state ('Southeast') precipitation average in this study uses the three independent reconstructions of state-average precipitation for North and South Carolina and Georgia (Stahle and Cleaveland, 1992), all very well correlated over their 981-yr common period. We optimized the North Carolina tree-ring – climate relationship by reconstructing April-June rainfall, but March-June precipitation correlated better with growth in South Carolina and Georgia. All three reconstructions were square root transformed to adjust non-normal distributions. Because the three rainfall reconstructions covered two slightly different periods and had different means and variances, we normalized all three series before averaging (transformed to mean = 0.0, variance = 1.0), then normalized the resulting average from A.D. 933 to 1985 (Figures 2, 3, and 4).

This southeastern proxy rainfall series has uneven sample size through time, and its reliability certainly decreases with the absence of the Ocmulgee data before A.D. 1206 and especially with the absence of the South Carolina data before A.D. 1005. Nevertheless, the reconstruction from 1005 to 1206 is based on from 41 to 89 exactly dated ring-width series from four sites (representing 21 to 30 separate trees), and should represent major episodes of drought and wetness during this important part of the MWP with reasonable accuracy. The southeastern rainfall reconstruction during the LIA (A.D. 1600) is very well replicated, with 161 ring-width series from 97 separate trees at all five collection sites.

To test the accuracy of the southeastern spring rainfall reconstruction, we compared the reconstructed data with instrumental rainfall data during the period from 1887 to 1982 (Figure 2). The instrumental spring rainfall average for the 'Southeast' was developed in the same manner as the reconstructed average. April to June total rainfall in North Carolina, and March to June total rainfall in South Carolina and Georgia were first individually normalized, averaged together on an annual basis from 1887 to 1982, and the resulting average was then normalized. Note that the instrumental rainfall data for North and South Carolina both begin in 1887, but the data for Georgia begins in 1892 (Karl *et al.*, 1983a, b, c). Consequently, the

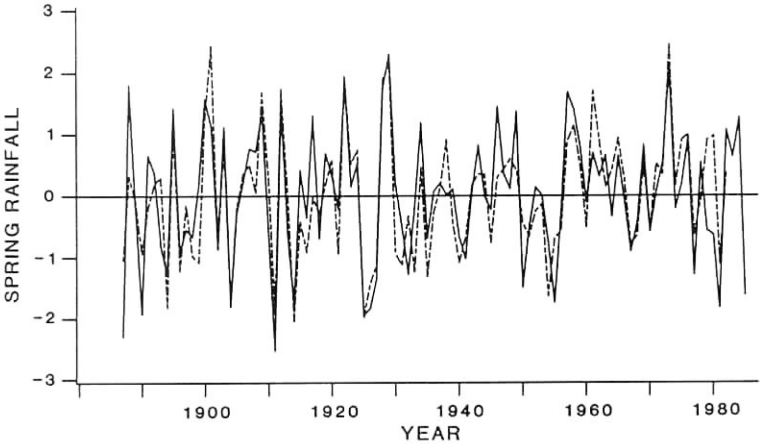

Fig. 2. Observed (dashed line) and reconstructed (solid line) spring rainfall (March-June) averaged and normalized for the southeastern United States from 1887 to 1982.

observed Southeast average is based on only two states from 1887 to 1891.

The reconstructed southeastern rainfall data are significantly correlated with the instrumental average at both the annual and decadal timescales (Figures 2 and 3). The Pearson correlation coefficient (r) computed for the full period of common data from 1887–1982 was +0.80 ($P < 0.0001$). However, the relationship between reconstructed and observed rainfall was higher during the first half of the common period (i.e., $r = +0.84$ for 1887 to 1936, while $r = +0.71$ for 1937 to 1982, see Figure 2). The reason for the lower correlation after 1936 is not entirely clear, but the period from 1887 to 1936 was characterized by higher variance in the tree-ring and rainfall data (e.g., Figures 5, 6), and the spatial coherence of spring rainfall departures over the Carolinas and Georgia appear to have declined after 1936 (Stahle and Cleaveland, 1992). There are also differences in the treatment of the instrumental rainfall data used to develop the state averages before and after 1931 (Karl *et al.*, 1983a, b, c), which are discussed further below. Nevertheless, the reconstructed rainfall data are strongly correlated with the instrumental data in both subperiods and overall, and these correlation results suggest that the reconstruction represents some 50 to 70% of the actual rainfall variance during 30 to 40-yr subperiods back to A.D. 1206, and somewhat less back to A.D. 1005.

The decade-scale fluctuations evident in the instrumental rainfall data are well replicated by the reconstructed data (Figure 2). This low-frequency coherence is illustrated in Figure 3 where the instrumental and reconstructed spring rainfall data from 1887 to 1982 were both filtered with a smoothing spline designed to emphasize variance in the 10-yr range. The decade-scale variations in observed and reconstructed rainfall data (Figure 3) represent 13.6 and 10.3% of the variance in the annual time series of spring rainfall from 1887 to 1982 (Figure 2), respectively.

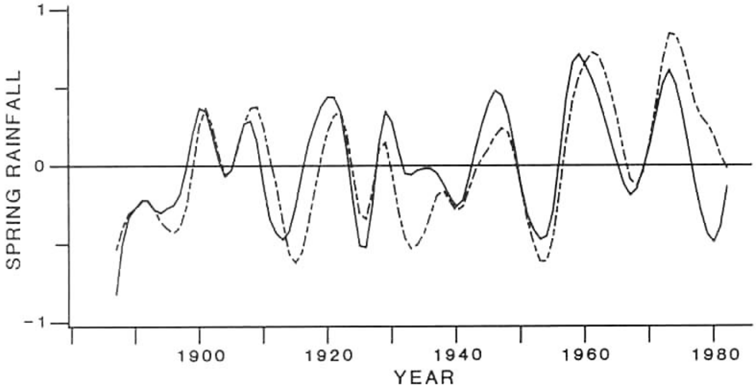

Fig. 3. The observed (dashed line) and reconstructed (solid line) spring rainfall for the three-state southeastern average (1887–1982) filtered with a smoothing spline designed to reduce 50% of the variance in a sine wave with a frequency of 10 yr (Cook and Peters, 1981). Note the agreement of decadal excursions between the observed and reconstructed series.

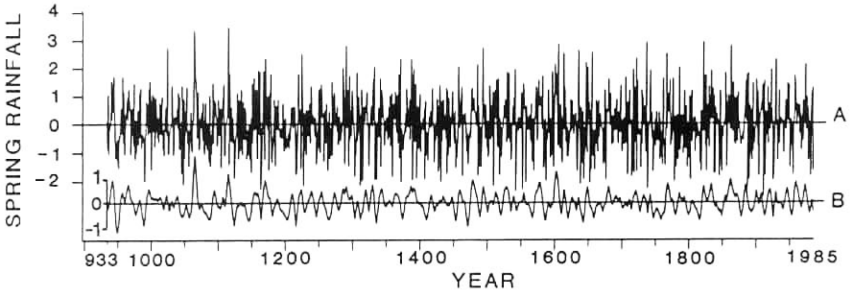

Fig. 4. (A) The normalized tree-ring reconstruction of southeastern spring rainfall (March-June) averaged over the Carolinas and Georgia from A.D. 933 to 1985; (B) The spline filtered version of the spring rainfall reconstruction emphasizing variations in the 10-yr frequency range.

The decadal variations in the reconstruction replicate the timing and magnitude of the low frequency variations in spring rainfall with good accuracy in most cases. The general upward trend instrumental in spring rainfall previously reported for the Carolinas and Georgia by Stahle and Cleaveland (1992) is reproduced by this tree-ring reconstruction, which suggests that the trend is not an artifact of precipitation measurement or data processing.

3. Analysis of Spring Rainfall during the Past Millennium

The spring rainfall reconstruction for the Southeast is plotted annually from A.D. 933 to 1985 in Figure 4a. This reconstruction is dominated by high frequency variance which is typical of the instrumental spring rainfall data available for the past century (Figure 2). There are no prominent century-scale trends in reconstructed spring rainfall which might reflect the regional influence of the Medieval

Warm Period or Little Ice Age in the southeastern United States. However, without specialized techniques (e.g., Cook *et al.*, 1990; Briffa *et al.*, 1992), tree-ring chronologies in general, and baldcypress chronologies in particular, are not ideal for detecting very long century-scale climate trends. The general necessity for removing age-related growth trends in tree-ring data limits the low-frequency climate signal in these data. The unique wetland adaptation of baldcypress further complicates the recovery of century-scale climate signal.

Baldcypress growth appears to be particularly sensitive to dissolved oxygen levels in swamp waters, and the fine root system of these trees tends to stratify in the well-oxygenated near surface waters (Stahle and Cleaveland, 1992). If the mean water level were to change permanently, baldcypress can, within limits, sprout new root hairs to follow persistent changes in the zone of well-oxygenated water. This root habit of baldcypress was dramatically illustrated at Reelfoot Lake, Tennessee, following the cataclysmic earthquakes of 1811–1812. These great earthquakes permanently raised the water level some 2 m to form Reelfoot Lake, and the baldcypress which survived responded with a phenomenal acceleration in growth which lasted for at least 10 yr. However, these trees also eventually formed a 'hanging buttress' and fine root system in the near surface waters, presumably to exploit the higher concentrations of dissolved oxygen (Stahle *et al.*, 1992). This vertical migration of the fine root system to exploit water level changes acts as a natural high-pass filter and appears capable of attenuating the registration of long-term rainfall trends in baldcypress tree-ring chronologies. The time involved in this physiological response has not been carefully quantified, but appears to have taken at least 30 yr following the formation of Reelfoot Lake. The apparent ability of baldcypress to adapt to long-term water-level changes is certainly antagonistic to the registration of possible century-scale rainfall trends and may diminish as well the registration of multi-decadal rainfall changes in baldcypress chronologies. Nevertheless, Figures 2 and 3 demonstrate that baldcypress ring-width chronologies are excellent proxies of interannual to decadal-scale climate variance.

The spring rainfall reconstruction was smoothed with a cubic spline to emphasize variance in the 10-yr range in Figure 4b, and the smoothed reconstruction indicates that the tendency for spring rainfall to oscillate between decades of relative drought and wetness as observed during the 20th century (Figure 3), has been prevalent over the past 1000 yr. The decadal variability in Figure 4b represents 12.3% of the variance in the rainfall reconstruction which is similar to the ratio represented by the 10-yr filter of the instrumental rainfall data. These decade-scale excursions in spring rainfall have important socioeconomic and environmental implications, but the frequency of wet or dry decades does not appear to have changed dramatically during the MWP, LIA, or at any other time during the past millennium.

To further examine spring rainfall variations over the past millennium and test for statistically significant changes in rainfall amounts or variance during the MWP, LIA, and other episodes, the rainfall reconstruction was arbitrarily subdi-

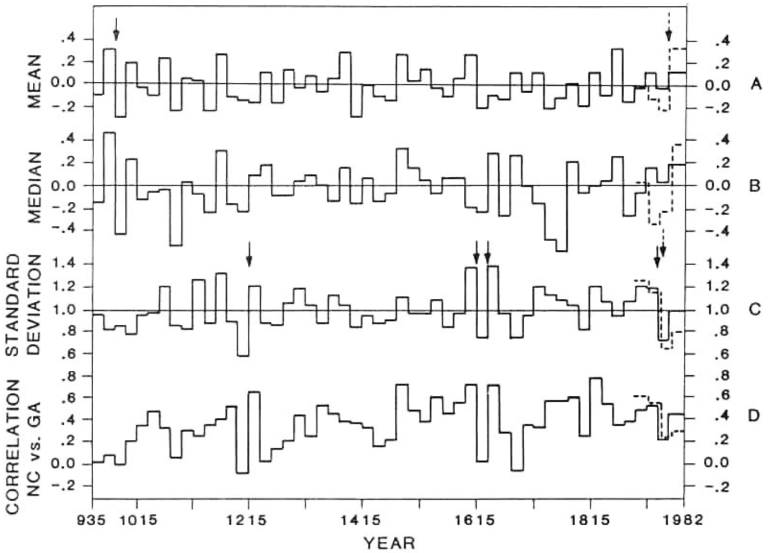

Fig. 5. The mean (A); median (B); and standard deviation (C) of spring rainfall over the southeastern United States computed for non-overlapping 20-yr subperiods from A.D. 935 to 1982 (solid lines). Statistically significant differences between adjacent 20-yr subperiods are indicated by arrows ($P \leq 0.05$). These statistics were also computed for the instrumental spring rainfall data during the same subperiods since 1895 (dashed line). The last subperiod includes 28 yr (i.e., 1955–1982); The correlation (D) between spring rainfall for North Carolina and Georgia for 20-yr subperiods [reconstructed series (solid line) from Stahle and Cleaveland (1992); instrumental data (dashed line)].

vided into non-overlapping 20-yr periods from A.D. 935 to 1982 (i.e., 935–954, 955–974...1935–1954, 1955–1982). For comparative purposes, the instrumental spring rainfall data for the Southeast were also subdivided into the same 20-yr subperiods from 1895–1982. In both cases, the last subperiod (1955–1982) included 28 yr (1955–1982). This testing scheme is certainly not exhaustive, but should be conservative. The arbitrary starting time (A.D. 935) and test interval length (20 yr) could fail to bracket the particular timing of a large excursion in the mean or variance, but it is unlikely that many significant changes in spring rainfall amount or variance would be detected if large excursions were not in the data. We only discuss the test results based on the 20-yr subperiods, but note that these analyses were repeated using 25, 30, and 35-yr subperiods. The results obtained with the longer subperiods closely resembled the 20-yr test interval results discussed below.

The mean, median, and standard deviation were computed for each 20-yr subperiod (Figure 5a, b, c), and differences between adjacent subperiods were tested for significance using *t*-tests, a non-parametric test between medians (SAS Institute, 1989), and Bartlett's test (Steele and Torrie, 1980), respectively. The time series plot of 20-yr means (Figure 5a) indicates that reconstructed spring rainfall was below average during much of the MWP (i.e., 9 of 15 subperiods from 975–1274), and was above average during portions of the LIA (i.e., 5 of 7 subperiods from 1475-1614). However, the spring rainfall means computed for each of these long time intervals are not statistically different from each other or from the long-term mean. Furthermore, when the means of adjacent 20-yr subperiods were tested for differences, only the change from 975–994 to 995–1014 was significant (Figure 5a). These data suggest that the MWP and LIA did not involve large-magnitude changes in spring rainfall amounts over the southeastern United States. However, the significant change in instrumentally-recorded rainfall from 1935–1954 to 1955–1982 ($P \leq 0.05$, Figure 5a) was not fully reproduced by the tree-ring reconstruction. This is further evidence that the tree-ring data are underestimating the magnitude and possibly the statistical significance of spring rainfall fluctuations over the past millennium.

The plot of median spring rainfall for the 20-yr subperiods largely conform with the 20-yr means, with the exception of the mid-18th century when 60 yr of below median rainfall were reconstructed. This 18th century drought era is evident in the smoothed reconstruction as the most prolonged period of below normal spring rainfall in the past 1000 yr (Figure 4b). This drought appears to have equalled or exceeded any dry episodes of comparable length during the MWP, and indicates that the time period normally associated with the LIA was certainly not uniformly wet (or dry) during spring and early summer over the southeastern United States.

Although no highly significant century-scale changes in spring rainfall amount have been reconstructed over the past 1000 years, there do appear to have been large changes in spring rainfall variance during the Medieval Warm Period, the 20th century, and most notably during the Little Ice Age (Figure 5c). Bartlett's test indicates that the standard deviation of reconstructed rainfall was significantly different ($P \leq 0.05$) between the following pairs of 20-yr subperiods: 1195–1214 and 1215–1234, 1595–1614 and 1615–1634, 1615–1634 and 1635–1654, and 1915–1934 and 1935–1954 (Figure 5c). Because 52 different 20-yr subperiods were tested, unequal variance might be observed between 2.6 subperiods simply by chance (assuming $P \leq 0.05$). The four periods of unequal variance may therefore suggest that spring rainfall is subject to statistically significant change over the southeastern United States.

The significant decline in spring rainfall variance observed in the instrumental record from 1915–1934 to 1935–1955 was matched by the reconstruction, and indicates that the tree-ring data are accurately reproducing decade-scale changes in rainfall variability. The tree-ring data also provide some reassurance that the variance changes evident in the instrumental rainfall data for the Southeast before and after 1931 are not artifacts of rainfall measurement or computation. The monthly precipitation data for the three states used to compile the Southeast average were based on areally-weighted climatic division data after 1931, but on equally-weighted station data prior to 1931 that were adjusted to 'more closely resemble' the state averages based on the divisional data (Karl *et al.*, 1983a, b, c). The faithful reproduction of the instrumentally-recorded changes in rainfall variance before and after 1931 by the tree-ring reconstruction (Figure 2), and by the three individual spring rainfall reconstructions for North Carolina, South Carolina, and Georgia (Stahle and Cleaveland, 1992) suggest that the variance changes in observed spring rainfall over the Southeast during the past century were largely real.

Spring rainfall variance peaked in the 17th century, which may represent the influence of unusual atmospheric circulation over the Southeast and much of the Northern Hemisphere during the Little Ice Age. Jones and Bradley (1992) suggest that the period from 1590 to 1610 was one of the few periods during the Little Ice Age when the paleoclimatic data they reviewed indicated synchronous cool conditions on a hemispheric to global scale. Southeastern spring rainfall is estimated to have been above average from 1595 to 1614, but also highly variable and with more dry years than wet years (Figures 5a, b, c). In fact, 5 of the 48 wettest years over the past millennium (i.e., in the upper 5th percentile) were reconstructed during this 20 year interval (1596, 1600, 1602, 1605, and 1613), which is over five times higher than the rate at which these wet extremes would occur if they were randomly distributed through time.

The interannual variability of reconstructed spring rainfall was also elevated during four 20-yr subperiods from the 11th to 13th centuries, and the increase from 1195–1214 to 1215–1234 was significant (Figure 5c). Whether these variance changes represent an effect of the Medieval Warm Period on spring rainfall over the Southeast is less clear due to the decline in sample size prior to A.D. 1206 associated with the loss of the Ocmulgee chronology.

The possibility that periods of high rainfall variability may reflect an amplified atmospheric circulation can be checked during the 20th century when both the observed and reconstructed rainfall data for the Southeast exhibit a significant change in variance. Spring rainfall declined considerably after the 1930's (Figure 5c), so the rainfall data were split into two long subperiods for this analysis (i.e., 1895–1930 and 1931–1982). The decline in rainfall variance between these two long subperiods is also significant for both the instrumental and reconstructed data ($P < 0.01$ and 0.05, respectively). Regional sea level pressure data and a circulation index related to the North Atlantic subtropical high were then used to investigate possible circulation changes between these two subperiods (Table I).

Sea level pressure data available from 1899 to 1980 were interpolated from station data to a $10^\circ \times 10^\circ$ latitude/longitude grid (Trenberth and Paolino, 1980), and we used the regional data for March through June at 30°N/90°W. Observed and reconstructed spring rainfall for the Southeast are significantly correlated with this regional sea level pressure series from 1899 to 1980 (Table I). However, this relationship is considerably stronger prior to 1931 (Table I), when the standard deviation of observed and reconstructed rainfall was highest (Figure 5c).

Anomalies in the zonal position of the North Atlantic subtropical high have been linked with observed and reconstructed spring rainfall over the Carolinas and Georgia (Stahle and Cleaveland, 1992). An index of the zonal movement of the

TABLE I: Correlation analyses between spring rainfall in the southeastern United States and atmospheric circulation data

	Regional Sea Level Pressure (grid point at 30° N–90° W)		
	1899–1930	1931–1980	1899–1980
Spring Rainfall			
Observed	–0.57***	–0.31**	–0.41***
Reconstructed	–0.52***	–0.27*	–0.35***
	Extended North Atlantic Ridge Index (June)		
	1895–1930	1931–1980	1895–1980
Spring Rainfall			
Observed	–0.31*	–0.24*	–0.26**
Reconstructed	–0.40**	–0.01	–0.19*

* $= P \leq 0.10$
** $= P \leq 0.05$
*** $= P \leq 0.01$

subtropical high into the eastern United States during summer has recently been developed by Heim *et al.* (1993), based on spatial anomalies in temperature and precipitation data. This Extended North Atlantic Ridge Index (or Ridge Index) is not available for spring, but the Ridge Index for June is nevertheless significantly correlated with observed and reconstructed rainfall totals for the spring season (i.e., March through June, Table I). This correlation between southeastern rainfall and the June Ridge Index is also highest during the early subperiod (1899–1930), particularly for the reconstructed data (Table I).

These correlation results suggest that spring rainfall over the Southeast was more strongly influenced by large-scale circulation during the early 20th century period of high rainfall variability, and this may also have been true during periods of high rainfall variability reconstructed for portions of the LIA and MWP (Figure 5c). These inferences are supported in part by analyses of the spatial homogeneity of spring rainfall over the Southeast, which appears to be highest during periods of greatest circulation influence. High interannual variability in the regional rainfall data usually reflects strong agreement among the three statewide rainfall series used to compute the regional average. Poor agreement among the three statewide series would tend to cancel individual state departures and thus reduce variance in the derived regional average. This is illustrated in Figure 5d by correlation analyses between the statewide spring rainfall data for North Carolina and Georgia, computed for the same 20-yr subperiods from A.D. 935 to 1982 for the reconstructed series (Stahle and Cleaveland, 1992), and from 1895 to 1982 for the instrumental series (Karl *et al.*, 1983a, b). The periods of strongest correlation between North Carolina and Georgia rainfall are usually also periods of highest variance in the regional rainfall average (Figure 5c, d).

The spatial homogeneity of observed and reconstructed spring rainfall from North Carolina to Gerogia was highest prior to the 1930's when regional sea level pressure and the Ridge Index were most strongly correlated with the southeastern spring rainfall data (Figure 5d, Table I). The decline in the correlation between North Carolina and Georgia rainfall after the 1930's (Figure 5d) is also evident in spring rainfall data for 11 individual weather stations located throughout the Carolinas and Georgia (Stahle and Cleaveland, 1992). One explanation for this apparent decline in the spatial homogeneity of spring rainfall over the Southeast after the 1930's might be a shift in the frequency of frontal as opposed to convective precipitation associated with a decrease in the influence of large-scale circulation during spring. These possibilities are important to the interpretation of reconstructed rainfall and could be tested with more detailed analyses of rainfall and circulation data for the Southeast.

4. Conclusions

The reconstructions of spring rainfall using baldcypress tree-ring chronologies indicate that the Medieval Warm Period and Little Ice Age were not vividly reflected in prolonged rainfall deficits or surpluses over the Carolinas and Georgia. There is weak evidence that dry conditions were more prevalent from ca. 1040 to 1275, and that wet conditions were prevalent from 1475 to 1620, but these differences are small and are not statistically significant. In fact, the most prolonged dry episode was reconstructed during the mid-18th century, at a time usually associated with the LIA. As presently formulated, these baldcypress tree-ring chronologies are not well suited for detecting possible century-scale excursions in spring rainfall amounts, but they do appear to be faithfully recording decade-scale changes. These reconstructed decade-scale variations in spring rainfall amount do not clearly identify MWP or LIA climate episodes over the Southeast.

The reconstructed data do, however, suggest that spring rainfall is subject to significant decadal changes in variance over the southeastern United States. Large and significant changes in spring rainfall variance were reconstructed during the 13th, 17th, and 20th centuries, and may represent the influence of unusual atmospheric circulation conditions during the MWP and LIA over the Southeast. The period from A.D. 1595 to 1614 is especially interesting because it appears to have been one of the most consistent and extensive cold episodes of the Little Ice Age, and the high mean, low median, and high variance of reconstructed rainfall indicate that a few extremely wet years were influential in the statistical properties of spring rainfall. These rainfall extremes suggest that large-scale atmospheric circulation over eastern North America may have been amplified during these particular years, and was perhaps responsible for climate anomalies elsewhere in the Northern Hemisphere during this notable episode of the Little Ice Age. Southeastern spring rainfall was more highly correlated with large-scale circulation indices during a period of high variability in the early 20th century, which lends some credence to these circulation inferences.

Acknowledgements

The research was supported by the National Science Foundation, Climate Dynamics Program, under grant number ATM-8914561. We thank Dr. Charles Wharton, Julie Moore, and Norman Brunswig for assistance in locating the old growth baldcypress stands sampled for this analysis, Dr. H.C. Fritts and G.R. Lofgren of the University of Arizona Laboratory of Tree-Ring Research for providing the gridded sea level pressure data, and Dr. R.R. Heim, Jr. for the Extended North Atlantic Ridge indices. We thank the landowners, particularly the National Audubon Society, the Nature Conservancy, Mr. Nelson Squires, and the Benjamin Cone estate, for permission to non-destructively sample the growth rings from these ancient forests.

References

Bradley, R. S. and Jones, P. D.: 1992, *Climate since A.D. 1500*, Routledge, London.

Briffa, K. R., Jones, P. D., Bartholin, T. S., Eckstein, D., Schweingruber, F. H., Karlen, W., Zetterberg, P., and Eronen, M.: 1992, 'Fennoscandian Summers from A.D. 500: Temperature Changes on Short and Long Timescale', *Clim. Dynam.* **7**, 111–119.

Chapman, D. S. and Clow, G. D.: 1991, 'Surface Temperature Histories Reconstructed from Borehole Temperatures: A Geothermal Contribution to the Study of Climate Change', *EOS* supplement. Oct. 29, 1991, pp. 69.

Cook, E. R. and Peters, K.: 1981, 'The Smoothing Spline: A New Approach to Standardizing Forest Interior Ring-Width Series for Dendroclimatic Studies', *Tree-Ring Bull* **41**, 45–53.

Cook, E. R., Briffa, K. R., Shiyatov, S. G., and Mazepa, V.: 1990, 'Tree-Ring Standardization and Growth Trends Estimation', in Cook, E. R. and Kairiukstis, L. A. (eds.), *Methods of Dendrochronology*, Kluwer, Dordrecht.

Cook, E. R., Bird, T., Peterson, M., Barbetti, M., Buckley, B., D'Arrigo, R., Francey, R., and Tans, P.: 1991, 'Climatic Change in Tasmania Inferred from a 1089-Year Tree-Ring Chronology of Huon Pine', *Science* **253**, 1266–1268.

Folland, C. K., Karl, T. R., and Vannikov, K. Ya.: 1990, 'Observed Climate Variations and Change', in Houghton, J. T., Jenkins, G. J., and Ephraums, J. J. (eds.), *Climate Change; the IPCC Scientific Assessment*, Cambridge University Press, pp. 194–238.

Frey, D. G.: 1954, 'Evidence for the Recent Enlargement of the "Bay" Lakes of North Carolina', *Ecology* **35**, 78–88.

Fu Congbin: 1990, 'Climatic Change in China from the Preinstrumental Period to the Last 100 Years', in Parker, D. W. (ed.), *Observed Climate Variations and Change: Contributions in Support of Section 7 of the 1990 IPCC Scientific Assessment*, Intergovernmental Panel on Climate Change, Geneva.

Graybill, D. A. and Shiyatov, S. G.: 1992, 'Dendroclimatic Evidence from the Northern Soviet Union', in Bradley, R. S. and Jones, P. D. (eds.), *Climate since A.D. 1500*, Routledge, London, pp. 393–414.

Grove, J. M.: 1988, *The Little Ice Age*, Methuen, London.

Heim, R. R., Jr., Brown, W. O., Owenby, J. R., and Garvin, C.: 1993, 'Circulation Indices for the Contiguous United States: 1895–1992', *Proceedings of the 17th Annual Climate Diagnostics Workshop*, U.S. Dept. of Commerce, Washington D.C.

Jones, P. D. and Bradley, R. S.: 1992, 'Climatic Variations over the Last 500 Years', in Bradley, R. S. and Jones, P. D. (eds.), *Climate since A.D. 1500*, Routledge, London, pp. 649–666.

Karl, T. R., Metcalf, L. K., Nicodemus, M. L., and Quayle, R. G.: 1983a, 'Statewide Average Climatic History, Georgia, 1892–1982', *Historical Climatology Series 6–1*, National Climatic Data Center, Asheville, North Carolina.

Karl, T. R., Metcalf, L. K., Nicodemus, M. L., and Quayle, R. G.: 1983b, 'Statewide Average Climatic History, North Carolina, 1887–1982', *Historical Climatology Series 6–1*, National Climatic Data Center, Asheville, North Carolina.

Karl, T. R., Metcalf, L. K., Nicodemus, M. L., and Quayle, R. G.: 1983c, 'Statewide Average Climatic History, South Carolina, 1887–1982', *Historical Climatology Series 6–1*, National Climatic Data Center, Asheville, North Carolina.

Karlen, W.: 1988, 'Scandinavian Glacial and Climatic Fluctuations during the Holocene', *Quatern. Sci. Rev.* **7**, 199–209.

LaMarche, V. C., Jr.: 1974, 'Paleoclimatic Inferences from Long Tree-Ring Records', *Science* **183**, 1043–1048.

Lamb, H. H.: 1977, *Climate: Present, Past, and Future*, Volume 2, Methuen, London.

Le Roy Ladurie, E.: 1971, *Times of Feast, Times of Famine*, Doubleday, New York.

SAS Institute, Inc.: 1989, *SAS/STAT User's Guide*, Version 6, 4th edition, Vol. 2, SAS Institute, Inc., Cary, North Carolina.

Stahle, D. W., Cleaveland, M. K., and Cerveny, R. S.: 1991, 'Tree-Ring Reconstructed Sunshine Duration over Central USA', *Int. J. Climatol.* **11**, 285–295.

Stahle, D. W. and Cleaveland, M. K.: 1992, 'Reconstruction and Analysis of Spring Rainfall over the Southeastern U.S.A. for the Past 1000 Years', *Bull. Amer. Meteorol. Soc.* **73**, 1947–1961.

Stahle, D. W., Van Arsdale, R. B., and Cleaveland, M. K.: 1992, 'Tectonic Signal in Baldcypress Trees at Reelfoot Lake, Tennessee', *Seismol. Res. Letters* **63**, 439–447.

Steele, R. G. D. and Torrie, J. H.; 1980, *Principles and Procedures of Statistics, Second Edition*, McGraw-Hill, New York.

Thompson, L. G., Mosley-Thompson, E., Dansgaard, W., and Grootes, P. M.: 1986, 'The Little Ice Age as Recorded in the Stratigraphy of the Tropical Quelccaya Ice Cap', *Science* **234**, 361–364.

Trenberth, K. E. and Paolino, D. A.: 1980, 'The Northern Hemisphere Sea Level Pressure Data Set: Trends, Error and Discontinuities', *Mon. Wea. Rev.* **108**, 855–872.

Villalba, R.: 1990, 'Climatic Fluctuations in Northern Patagonia during the Last 1000 years as Inferred from Tree-Ring Records', *Quatern. Res.* **34**, 346–360.

Whitehead, D. R.: 1972, 'Developmental and Environmental History of the Dismal Swamp', *Ecol. Monogr.* **42**, 301–315.

Williams, L. D. and Wigley, T. M. L.: 1983, 'A Comparison of Evidence for Late Holocene Summer Temperature Variations in the Northern Hemisphere', *Quatern. Res.* **20**, 283–307.

(Received 22 September, 1992; in revised form 18 October, 1993)