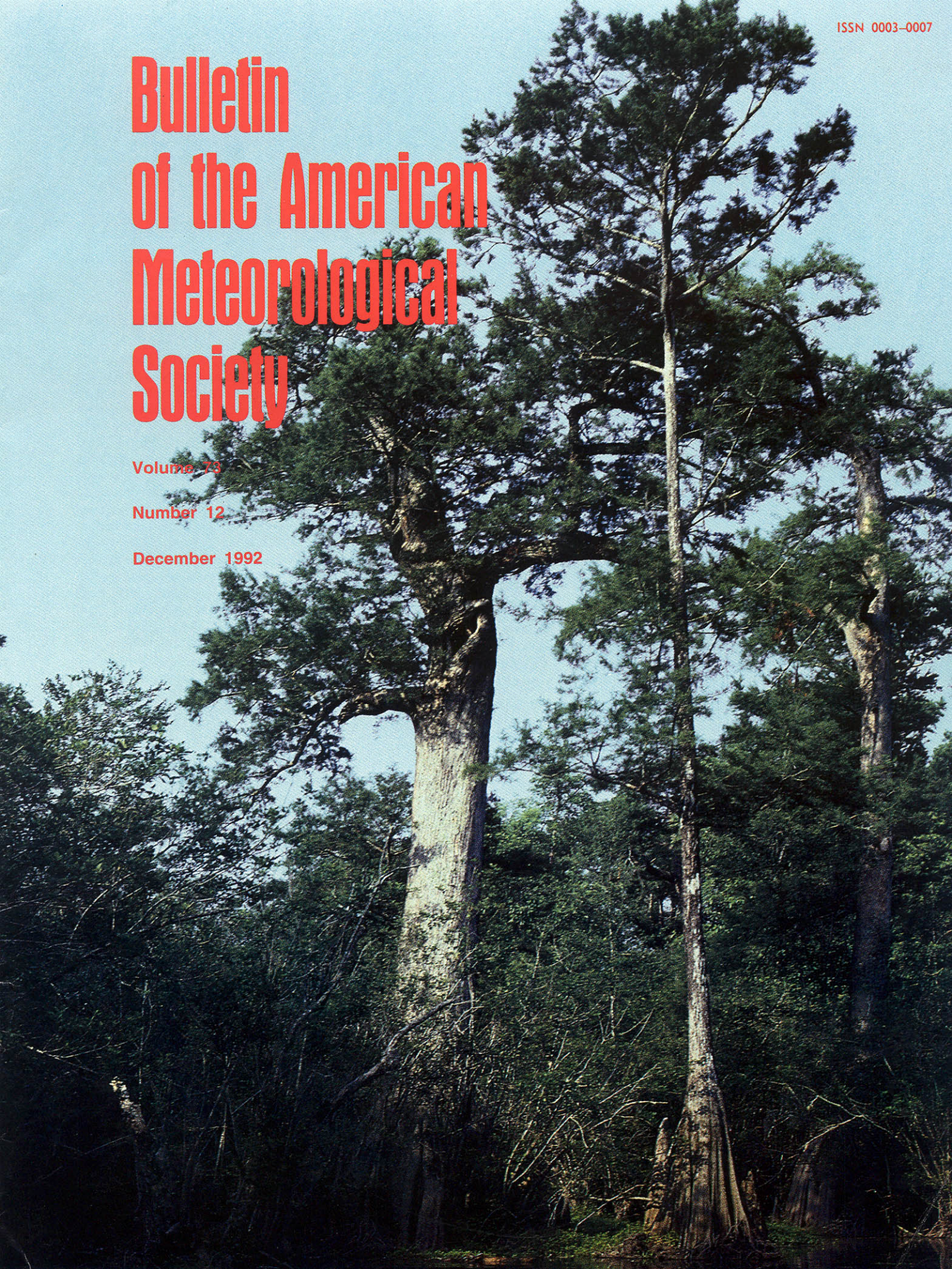


Bulletin of the American Meteorological Society

Volume 73

Number 12

December 1992



Reconstruction and Analysis of Spring Rainfall over the Southeastern U.S. for the Past 1000 Years

David W. Stahle and
Malcolm K. Cleaveland
Tree-Ring Laboratory,
University of Arkansas,
Fayetteville, Arkansas

Abstract

Tree-ring chronologies can provide surprisingly accurate estimates of the natural variability of important climate parameters such as precipitation and temperature during the centuries prior to the Industrial Revolution. Bald cypress tree-ring chronologies have been used to reconstruct spring rainfall for the past 1000 years in North Carolina, South Carolina, and Georgia. These rainfall reconstructions explain from 54% to 68% of the spring rainfall variance in each state, and are well verified against independent rainfall measurements. In fact, these tree-ring data explain only 6% to 13% less statewide rainfall variance than is explained by the same number of instrumental raingage records. The reconstructions indicate that the spring rainfall extremes and decade-long regimes witnessed during the past century of instrumental observation have been a prominent feature of southeastern United States climate over the past millennium. These spring rainfall regimes are linked in part to anomalies in the seasonal expansion and migration of the subtropical anticyclone over the North Atlantic. The western sector of the Bermuda high often ridges strongly westward into the southeastern United States during dry springs, but during wet springs it is usually located east of its mean position and well offshore. Similar anomalies in the western sector of the Bermuda high occurred during multidecadal regimes of spring rainfall over the Southeast. During the relatively dry springs from 1901 to 1939, the high often ridged into the Southeast, but the western periphery of the high was more frequently located offshore during the relatively wet period from 1940 to 1980. Spring and summer rainfall extremes and decade-long regimes over the Southeast are frequently out of phase, and the tendency for wet (dry) springs to be followed by dry (wet) summers also appears to reflect anomalies in the zonal position of the Bermuda high during spring and summer.

1. Introduction

The recent policy statement on global climate change issued by the American Meteorological Society (1991) recommends accelerated study of natural climate variability, including climate extremes such as the Dust Bowl droughts of the 1930s. Summer droughts are expected to increase over central North America during the next century, given the continued accumulation of greenhouse gases (Houghton et al. 1990). Detection of these anticipated anthropogenic climate changes requires representative data on the climate

fluctuations possible under natural conditions during the late Holocene. However, the number of single- and multiyear moisture anomalies witnessed during the modern period of meteorological instrumentation have been small even in drought-prone regions such as the Great Plains. The limited sample of climatic extremes during the period of surface- and particularly upper-air observations places heavy constraints on the statistical analysis of drought as a family of climate extremes (e.g., Namias 1981). Multiyear regimes of drought and wetness are even more intractable because only two or three such regimes have typically occurred during the past century, and each may have been initiated or sustained by different mechanisms (e.g., Trenberth et al. 1989). If significant anthropogenic impacts on regional or global climate have already occurred, then we can consult only the past century or so for instrumental observations of "natural" climate variation. These circumstances provide compelling justification to explore the proxy record of past climate. Deep-sea sediment cores, ice cores, and pollen analysis have provided valuable insight into the sweeping climate and environmental changes that have occurred on glacial and postglacial time scales, but these proxies are suitable for high-resolution climate analysis only when found in annually layered deposits. Unfortunately, varved sediment and ice deposits are rare and have yet to be widely exploited.

Annual tree-ring data are uniquely suited for high-resolution climate reconstruction, but their potential contribution to the analysis of climate extremes and long-term climate trends has certainly not been matched by their utilization in the climatological community. The accessibility of quality tree-ring data has been a major problem, but this has recently been solved with the acquisition of worldwide tree-ring data by the National Geophysical Data Center (NGDC) in Boulder, Colorado. New contributions continue to be made to the NGDC, and the temperate landmasses of the world are becoming increasingly well sampled with tree-ring chronologies over 250 years long, particularly the continental United States (e.g., Meko et al. 1992).

©1992 American Meteorological Society

The utilization of proxy tree-ring data by the climatological community seems also to have been impeded by an undercurrent of skepticism regarding the interpretation of these climate indicators. For example, the discussion of proxy and instrumental evidence for climate variations and change in the Intergovernmental Panel for Climate Change (IPCC) scientific assessment (chapter 7, Folland et al. 1990) did not cite a single tree-ring estimate of regional or large-scale climate variation, and stated that "[tree-ring] data have an increasing potential; however, their indications are not yet sufficiently easy to assess nor sufficiently integrated with indications from other data to be used in this report." In this paper we hope to dispel some of these doubts with examples from the southeastern United States, where we have developed millennium-long reconstructions of spring rainfall totals from bald cypress (*Taxodium distichum*) tree-ring chronologies.

We first discuss the development of valid tree-ring chronologies useful for climate reconstruction, and then the unique climate response of swamp-grown bald cypress trees. The bald cypress rainfall reconstructions are then compared with independent rainfall data and subjected to a series of statistical validation tests in order to evaluate the accuracy of the reconstructions. These validation tests are widely used in meteorology, and provide objective methods for specifying the degree to which the tree-ring reconstructions replicate the actual instrumental record of climate. These extensive validation tests make tree-ring reconstructions the most rigorously verified proxies of past climate routinely produced. To address the skeptics of dendroclimatology from another perspective, however, we also conduct a validation experiment where the accuracy of the tree-ring reconstructions of state averaged rainfall are compared with statewide rainfall estimates based on the same number of instrumental raingage records instead of tree-ring chronologies. The surprising results of this experiment provide a tangible benchmark for the interpretation of tree-ring reconstructions that may be particularly persuasive to the meteorological community.

The recent growing-season droughts over the Southeast during the 1980s have had enormous socio-economic and environmental impacts (e.g., Murray 1986), and graphically illustrated that the humid Southeast is subject to intense and prolonged drought. Furthermore, the droughts of the 1980s followed persistently favorable moisture conditions during the 1960s and 1970s (Karl et al. 1983a,b,c), which together demonstrate that the Southeast is subject to substantial fluctuations in climate on interannual and decadal time scales. The persistence of spring rainfall anomalies over the Southeast suggests a degree of large-scale

circulatory control, and we explore this possibility using both observed and reconstructed spring rainfall data. This circulation evidence is fundamentally important to an explanation of southeastern United States rainfall anomalies and an informed interpretation of the paleoclimatic record of rainfall during the late Holocene, and could be helpful in the effort to improve long-range forecasts of growing-season rainfall over the southeastern United States.

2. Climate-sensitive tree-ring chronologies

The recovery of valid climate information from tree-ring data relies upon the regular formation of distinctive annual-growth layers, the selection of trees from climate-sensitive forest sites, and on the accurate cross-dating of annual rings to their exact year of formation (e.g., Douglass 1941; Stokes and Smiley 1968; Fritts 1976). Clearly defined annual-growth rings are commonly found in temperate-latitude trees worldwide, where tree growth is always interrupted during the winter dormant season. But because all forest sites are not equally influenced by interannual variations in the regional climate, dendroclimatologists search for the particular marginal forest sites where precipitation or temperature variations strongly limit tree growth. In fact, the precise dating of tree rings to their exact calendar year of formation, known as cross-dating, is only possible when climate has repeatedly influenced the growth of annual rings in many trees within a given climatic region (e.g., southeastern United States). Cross-dating is the essence of dendrochronology, and it uses the unique time history of wide and narrow rings to compare and synchronize the ring-width series of all trees from a single collection site. The synchronized ring-width patterns from each site are also cross-dated with the ring-width patterns derived from other collection sites in the region. At sites where moisture is a dominant growth-limiting factor, the sequence of wide and narrow rings reflects the history of wet and dry years with surprising accuracy.

Exact calendar dating is established by coring living trees, where the date of the outermost ring is known to be the current or most recent growing season. Calendar dates can then be assigned to each previous ring, once the ring widths have been synchronized among many trees and sites to ensure that all possible complications associated with missing rings, false rings, or injury have been solved and the chronology is absolute.

Tree-ring chronologies are developed by averaging the detrended and indexed ring-width measurements available for each core at each calendar year. If some

of the core specimens included in a chronological average from a given site are incorrectly synchronized, the climatic signal will be smeared by averaging the growth measurements for different years. Fritts and Swetnam (1989) have demonstrated that these errors in dating radically alter the variance characteristics of the derived chronology, and this highly undesirable signal smearing will also degrade, if not entirely eliminate, any significant correlation with climatic variables. Unfortunately, the cross-dating procedure is sometimes omitted and dates are assigned to the growth layers by simply counting backwards from the known date of the outermost ring. Extreme skepticism would certainly be warranted for any climatic inferences drawn from such counted "chronologies."

The principal virtues of these tree-ring chronologies are dating that is precise to the exact season of growth, climate sensitivity, and great age. In some cases, tree-ring chronologies exceed the length of meteorological records by more than an order of magnitude.

Raw ring-width series often contain a marked nonclimatic growth trend related to the increasing age and size of the tree or to changes in the competition structure of the surrounding forest (Fritts 1976). The classical form of this growth trend is a negative exponential that extends over the full length of the series and can be rationalized with biological and geometrical arguments [i.e., average ring width decreases as trees lose vigor with age, and as the surface area covered by each annual growth increment increases (Fritts 1976)]. However, a wide range of growth trends may be observed at a given collection site due to both age-related and site factors, and while some of these trends may be climatic in origin, objective evidence to allow the discrimination of climatic and nonclimatic growth trends is not usually available. Therefore, it is usually necessary to detrend the raw ring-width series using empirical curve-fitting techniques (Fritts 1976; Cook and Peters 1981). In practice, the flexibility of the fitted curves is limited with the goal of removing very long-term trend on the century time scale believed to be largely nonclimatic in origin, while retaining the annual-to-multidecadal growth excursions that contain most of the readily extractable climate signal in tree-ring data. Briffa et al. (1992) describe procedures to recover more century-scale climate trend from tree-ring data, although the standard error associated with

the average values of these chronologies tends to be larger than for chronologies based on individually detrended ring-width series.

In addition to long-term growth trend, tree-ring chronologies also tend to be significantly autocorrelated. The degree of autocorrelation varies considerably due to site, species, and climatic factors, but this growth "memory" can also smear the high-frequency interannual climatic signal. For example, stored food reserves can be replenished during years with favorable climate, and these reserves may then ameliorate unfavorable climatic conditions during the following year. The persistence structure of tree-ring chronologies may also differ considerably from climatic persistence, and can lead to less-reliable growth-climate calibration models and to erroneous inferences concerning important aspects of past climate variability such as the persistence of extreme events. For these reasons, time-series methods for modeling and removing significant persistence from tree-ring chronologies have been used increasingly, in many cases with a considerable improvement in the quality of climate reconstructions (e.g., Cleaveland et al. 1992).

A strong regional climate signal can be recovered from tree-ring data by selecting collection sites from forest stands sensitive to climate variations, by sampling many different trees at the site, and by developing the mean index chronology from a large number of exactly synchronized specimens. The principal virtues of these tree-ring chronologies are dating that is precise to the exact season of growth, climate sensitivity, and great age. In some cases, tree-ring chronologies exceed the length of meteorological records by more than an order of magnitude. However, there are important limitations concerning the climatic application of tree-ring data, including the difficulty of recovering century-scale climate trend from tree-ring series that also usually have biologically based growth trends of comparable length. The climatic response of tree-ring chronologies is also sometimes asymmetrical, with a stronger linkage during drought years than during wet years (when nonclimatic factors such as low soil fertility or competition may limit the tree-growth response to the favorable moisture conditions). It is also possible to confuse nonclimatic disturbance effects on tree growth with climate forcing. A selective logging event might produce a period of above-average tree growth in the surviving trees for a decade or more after the event. This logging release might naively be attributed to a favorable climate regime. To guard against such erroneous inferences, it is preferable to base climate reconstructions on many tree-ring chronologies from undisturbed old-growth forests scattered across the study region.

3. The climatic response of bald cypress

This study is based on five 800- to 1600-yr-long tree-ring chronologies developed from relatively undisturbed bald cypress forests in North Carolina, South Carolina, and Georgia (Fig. 1). These excessively wet cypress swamps are certainly not the type of forests expected to produce rainfall-sensitive tree-ring chronologies. The strongest precipitation signal is normally found in trees from well-drained xeric sites where drought-induced reductions in available soil moisture strongly inhibit tree growth (Douglass 1941; Fritts 1976). Nevertheless, the highly significant direct correlations between bald cypress growth and rainfall range as high as +0.84 in Georgia (for the period 1892–1936), and demonstrate that generalizations regarding the interaction of habitat and the climate response of trees can be entirely species dependent.

Rainfall amounts during the spring and early summer are by far the most important climate influence on cypress growth yet detected. Cypress trees grow well in wet years and poorly in dry years, in spite of the frequently flooded conditions. This extraordinary direct correlation with rainfall is stronger than the statistically significant negative correlations with temperature, sunshine duration, or even the positive correlation with Palmer drought indexes (e.g., Stahle et al. 1985, 1988, 1991). The interesting rainfall response of bald cypress can be best explained by a combination of the direct growth-limiting effects of rainfall-controlled fluctuations in moisture supply, as well as by variations in sunshine duration and air temperature [both of which tend to be inversely related to spring rainfall amounts (e.g., Stahle et al. 1991)], the growth influence of important water-quality factors linked to rainfall, and the unique growth habit of the bald cypress root system.

Analyses of surface waters in many southeastern swamps indicate that dissolved oxygen (DO_2), pH, and nutrient concentrations tend to decline during low rainfall and low water levels, and increase during high water levels (e.g., Stolzy et al. 1981; Mitsch 1984; Dierberg and Brezonik 1984; Schlesinger 1991). Dissolved oxygen is a very important growth-limiting factor for emergent vegetation in terrestrial wetlands (e.g., Schlesinger 1991), and tends to be directly correlated with rainfall, water movement, and water temperature (e.g., Turner and Patrick 1968). There is also normally a sharp vertical decrease in dissolved oxygen with increasing depth in wetland soils (e.g., Howeler and Bouldin 1971; Stolzy et al. 1981). Whitford (1956) demonstrated that bald cypress root systems grow better in well-aerated water. Total aboveground cypress growth can also be strongly correlated with nutrient availability (Brown 1981), and some nutrient-

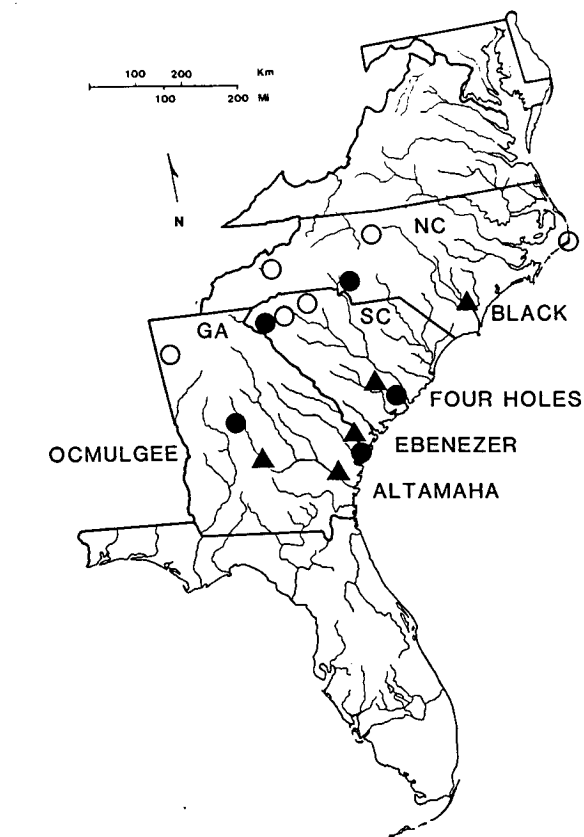


FIG. 1. Map of the collection sites for the five baldcypress tree-ring chronologies (labeled triangles) used to reconstruct growing-season rainfall in North Carolina, South Carolina, and Georgia. The five rainfall recording stations used for comparison with the tree-ring estimates of statewide rainfall are also located (solid circles). Instrumental rainfall data from these five stations, and the six additional stations located by open circles, were also used to examine the spatial coherence of rainfall during subperiods of the twentieth century (i.e., 1890–1936 vs 1937–1980).

poor cypress swamps depend almost entirely on nutrients supplied by rainfall (Ewel and Odum 1984).

These typical water-level and water-quality relationships can be logically related to the highly sensitive rainfall response of bald cypress tree-ring chronologies. First, high (low) rainfall amounts during the growing season would tend to be coupled with high (low) dissolved-oxygen levels and good (poor) cypress growth. Second, field observations indicate that part of the bald cypress root system, particularly the fine root hairs responsible for most moisture and nutrient uptake, tends to be stratified just below the mean water level in the upper 10–30 cm of organic soil where dissolved oxygen concentrations tend to be highest (e.g., Hall and Penfound 1943; Lugo et al. 1984). This root-stratification effect renders cypress trees vulnerable to partial drydown of the root system, internal moisture stress, and reduced growth with

even relatively small fluctuations below the mean water level. This root-system habit is vividly illustrated at Reelfoot Lake, Tennessee, which was formed by the New Madrid earthquakes of 1811/12 (Stahle et al. 1992). The water level was permanently raised approximately 2 m by this event, and the numerous cypress trees that survived have grown a new buttress and near-surface system of fine root hairs suspended in the lake just below the mean water level (so-called "hanging buttresses"; Kurz and Demaree 1934), presumably to exploit the higher dissolved-oxygen amounts in the near-surface waters.

During the historic southeastern drought of 1986, extensive root drydown occurred at all five bald cypress sites included in this study, often with full exposure of many fine root hairs, which normally feed directly from the swamp water. These observations suggest that water quality and water level are the rainfall-linked environmental variables that can limit cypress growth during dry years, but that water quality may be the principal rainfall-linked growth factor in wet years. Detailed field measurements of bald cypress growth, water levels, water quality, and the meteorological environment will be required to rigorously test these interpretations of the bald cypress climate response. Nevertheless, the highly significant statistical association between cypress chronologies and spring rainfall discussed below leaves no doubt about the proxy climate value of this interesting long-lived species.

4. The tree-ring and climate data

Five 800- to 1600-yr-long bald cypress chronologies were used to reconstruct spring rainfall amounts in North Carolina, South Carolina, and Georgia (Fig. 1). Each chronology includes over 40 exactly dated and carefully measured ring-width series from at least 25 different trees. The raw ring-width measurements for each specimen were first detrended by fitting negative exponential or inflexible cubic splines to the raw measurements and then dividing the measured value by the curve value at each year (using the computer program ARSTAN; Cook and Holmes 1985). The derived ring-width indices were then averaged among all specimens for each year using a robust mean value function designed to discount the effect of statistical outliers (Cook 1985). The resulting standardized tree-ring chronologies were prewhitened using autoregressive modeling procedures (Cook 1985). All five chronologies exhibit some positive skewness toward very large ring-width indices, but only the Black River chronology could not be approximated by a normal distribution. Because the spring

rainfall averages computed for each state are all normally distributed, a square-root transformation was used to make the Black River chronology approximate a normal distribution (Stahle et al. 1988).

Monthly precipitation amounts were obtained on a statewide basis from the *Historical Climatology Series* published by NOAA (Karl et al. 1983a,b,c). These valuable high-quality data extend from 1887 to 1982 in the Carolinas, and from 1892 to 1982 in Georgia. Blasing et al. (1981) have discussed the rationale for using regional average as opposed to single-station climate data in dendroclimatic analyses. The statewide rainfall data used here certainly obscure meaningful differences in the spatial distribution of rainfall in each state, but due in part to inevitable microclimatic differences between individual weather stations and tree-ring collection sites, tree-ring data tend to share much more common variance with the regional rainfall variation represented in the statewide data. Monthly precipitation data were also obtained for 11 individual weather-recording stations in the study area (Fig. 1; G.R. Lofgren, personal communication), and were used to help verify the accuracy of the three rainfall reconstructions and to investigate changes in the spatial homogeneity of spring rainfall through time.

5. Calibration of the tree-ring and precipitation data

Correlation analyses between the monthly precipitation data and the tree-ring chronologies available for each state were used to identify the months and season most important to bald cypress growth and therefore most suitable for reconstruction. The strongest correlations were observed from April through June in North Carolina, and from March through June in South Carolina and Georgia. Consequently, a "spring" rainfall average was computed for April–June in North Carolina and March–June in South Carolina and Georgia. Autoregressive modeling was also used to examine the persistence structure of these spring rainfall averages, and all three series were well approximated by a white-noise process (AR-0). These seasonal rainfall averages were then used to calibrate the prewhitened tree-ring data in each state.

The calibration or transfer function models used to reconstruct growing-season rainfall from the tree-ring data were based on either bivariate or multiple regression. All five tree-ring chronologies (Fig. 1) were considered as possible predictors of rainfall in each state, but the best models, which explained the largest fraction of rainfall variance (i.e., R^2 adjusted for loss of degrees of freedom, Table 1), were based on just the one or two available chronologies located within or

TABLE 1. Calibration and verification statistics computed for the tree-ring and weather station predictors of state-average spring rainfall in North Carolina, South Carolina, and Georgia.

State	Calibration period			Verification period (1937-1982)					
	Time period	R^2_{Adj}	Residual ^A autocorr.	Corr.	1st diff. Corr.	Sign test Pos. Neg.		t -test dif. mean	RE
<i>a. Tree-ring predictors</i>									
NC	1887-1936	0.54***	-0.09 (ns)	0.60***	0.52	39***	7	-2.01 (ns)	+0.23
SC	1887-1936	0.58***	-0.07 (ns)	0.51***	0.50	32**	14	4.02***	+0.17
GA	1892-1936	0.68***	0.10 (ns)	0.61***	0.59	32**	14	3.70***	+0.24
<i>b. Weather station predictors</i>									
NC	1887-1936	0.60***	-0.02 (ns)	0.54***	0.42***	32**	14	0.13 (ns)	+0.25
SC	1893-1936	0.70***	0.11 (ns)	0.76***	0.88***	38***	8	0.25 (ns)	+0.62
GA	1893-1936	0.81***	0.27*	0.78***	0.73***	40***	6	-3.07**	+0.56

* = $P \leq .05$ ^A = Durbin-Watson test for autocorrelation of residuals
 ** = $P \leq .01$ ns = not significant, $P > .05$
 *** = $P \leq .001$

immediately adjacent to each state. The rainfall data were split into two subperiods (i.e., 1887-1936 and 1937-1982), so that each subperiod and the full record could be compared with the tree-ring data to identify the best time period for calibration. The three regression models used for calibration are:

North Carolina:

$$\hat{Y}_t = 164.3 + 145 \cdot 8 X_t, \quad (1)$$

where \hat{Y}_t represents estimated total April-June rainfall in millimeters in year t , and X_t is the prewhitened and transformed Black River tree-ring chronology index also in year t , for the period 1887-1936.

South Carolina:

$$\hat{Y}_t = 172.9 + 128.6 X_{t1} - 87.2 X_{t2}, \quad (2)$$

where \hat{Y}_t represents estimated total March-June rainfall in millimeters in year t , X_{t1} is the Ebenezer Creek chronology index in year t , and X_{t2} is the Four Holes Swamp chronology index in year t for the period 1887-1936.

Georgia:

$$\hat{Y}_t = 147.1 + 268.7 X_t, \quad (3)$$

where \hat{Y}_t is the estimated Georgia March-June rainfall total in millimeters in year t , and X_t is the annual average of the Altamaha and Ocmulgee tree-ring chronologies in year t , for the period 1892-1936.

However, the Ocmulgee chronology does not extend earlier than A.D. 1206, and the Georgia chronology "average" is based only on the Altamaha chronology before 1206. For this reason, the variance of the Georgia chronology was much higher before 1206, and was therefore adjusted downward from 933 to 1205 using the ratio of chronology variances computed before and after 1206. Even though the Altamaha and Ocmulgee chronologies are very highly correlated with each other and with the spring rainfall data for Georgia, the reliability of the Georgia rainfall reconstruction is certainly lower before 1206.

The time series of observed and reconstructed spring rainfall are plotted from 1887 (or 1892) to 1982 in Fig. 2. The full reconstructions spanning the past 1000 years are plotted in Fig. 3a for each state, along with two smoothed versions emphasizing decadal and multidecadal rainfall variations (Fig. 3b,c). Selected statistics describing the regression models indicate that the tree-ring reconstructions explain from 54% to 68% of the variance in spring rainfall for each state, and that the regression residuals are randomly distributed (Table 1, a). The variance explained by the calibrations during this early subperiod is 10%-20% higher than explained by calibrations on the more recent subperiod (i.e., 1937-1982) or over the full period of meteorological observation (i.e., 1887 or 1892-1982). We selected the early subperiod for calibration because of the stronger tree-ring association with climate, and emphasize that these calibration models [Eqs. (1), (2), and (3)] verify against indepen-

dent rainfall data available for the alternate 1937–1982 subperiod (see section 6). These calibration models are therefore valid even though the strength of the regional average rainfall signal declines during the more recent subperiod.

The decline in rainfall variance explained by the tree-ring data from the early to late subperiods nonetheless indicates that the strength of the relationship between tree growth and statewide spring rainfall is subject to some variation over time. This variation could arise from real changes in the prevailing climatic regime, increasing levels of anthropogenic disturbances at the tree-ring sites in recent decades, or purely random fluctuations in the linkage between climate and growth. However, correlation analyses between 11 instrumental rainfall records located throughout the three-state area (Fig. 1) indicate that a real shift in the climate regime may account for much of the decline in rainfall variance calibrated by the tree-ring chronologies after 1936. The correlation between 78% of the various pairs of spring rainfall records was much lower during the more recent period (i.e., 1937–1980, compared with 1890–1936). This decline in the spatial homogeneity of observed spring rainfall over the Southeast may be related to the differences in the average zonal position of the Bermuda high during spring, which is discussed below.

6. How accurate are the tree-ring reconstructions?

The regression models used to calibrate the tree-ring and rainfall data indicate that the tree-ring estimates explain a large and highly significant fraction of the growing season rainfall variance in the Carolinas and Georgia (Table 1, a). However, these statistics are strictly relevant only to the common calibration period itself, and questions always arise concerning the reliability of the transfer function when applied to tree-ring data outside of the calibration period in order to reconstruct past climate.

There are several ways to check the accuracy of dendroclimatic reconstructions prior to the calibration period. Direct comparisons between real and reconstructed data are possible when instrumental meteorological measurements are available outside of the calibration period. For example, the spring rainfall reconstructions were calibrated with the state-average rainfall data available from 1887 (1892) to 1936, so the remaining, statistically independent measurements of statewide spring rainfall from 1937 to 1982 were used to verify the tree-ring estimates during this recent subperiod. These comparisons are illustrated in Fig. 2, and several statistical measures of association between the observed and reconstructed rainfall

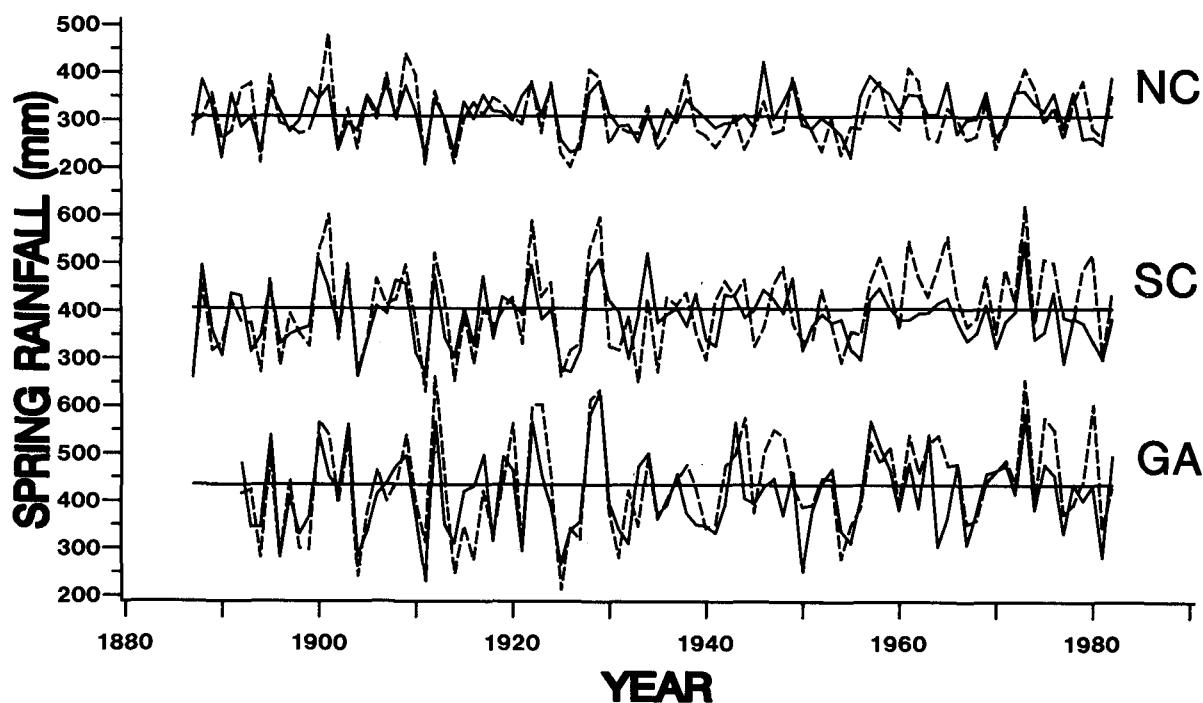


FIG. 2. Observed (dashed) and reconstructed (solid lines) rainfall for North Carolina (April–June), South Carolina, and Georgia (both March–June). The tree-ring data were calibrated against the state-average rainfall data from 1887 (1892 in Georgia) to 1936, and were verified against state-average rainfall available in the statistically independent period from 1937 to 1982.

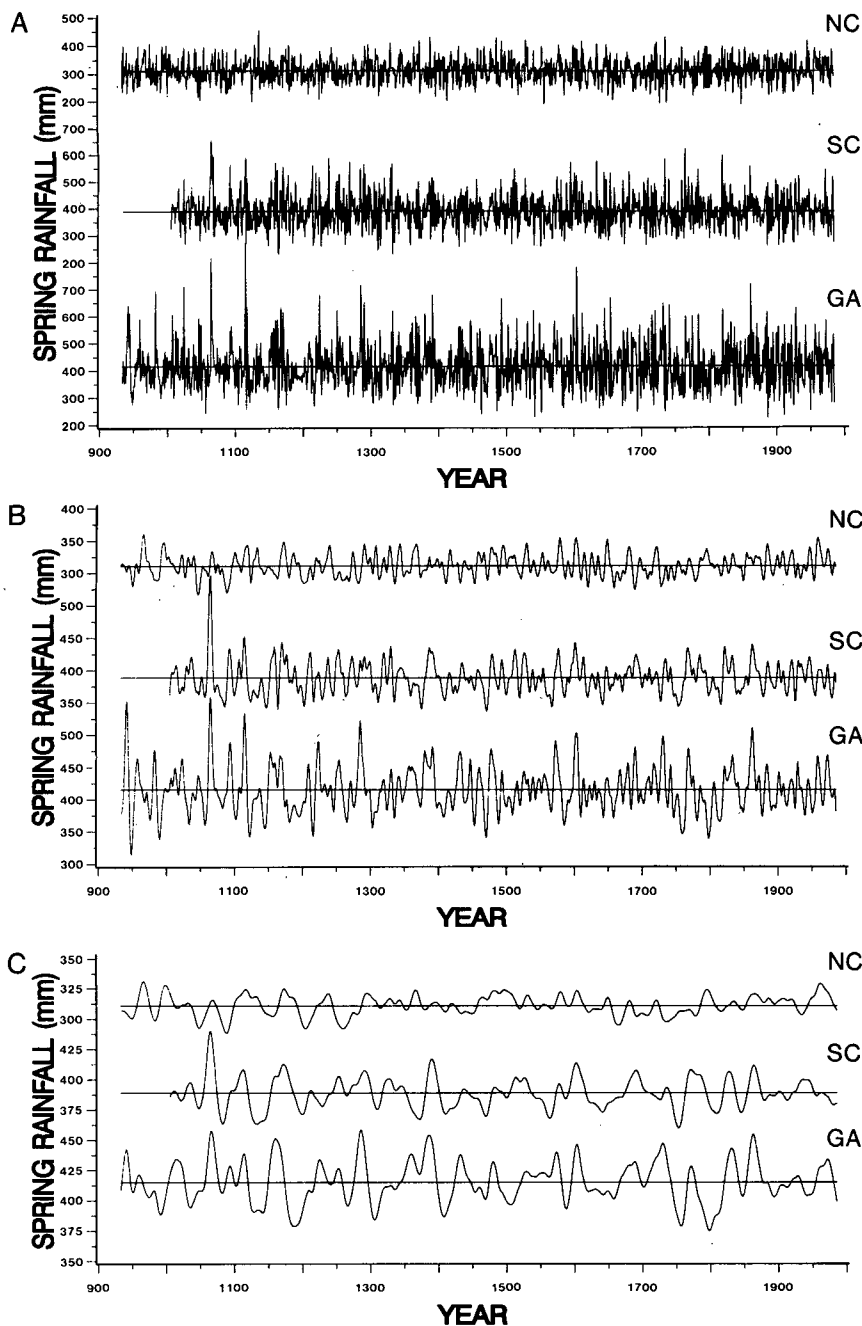


FIG. 3. Reconstructed statewide rainfall (a) for North Carolina (NC, April–June), South Carolina, and Georgia (SC and GA, March–June). The North Carolina and Georgia series extend from A.D. 933 to 1985, and the South Carolina series from A.D. 1001 to 1985. Each rainfall reconstruction was smoothed with cubic smoothing splines (Cook and Peters 1981) designed to reduce 50% of the variance in a sine wave with a period of 10 years (b) and 30 years (c). Note the interval and labeling differences on the y-axes in (a), (b), and (c).

data for each state during the verification period (1936–1982) are summarized in Table 1, a. These various comparisons demonstrate that the tree-ring reconstructions are generally quite accurate at reproducing the spring rainfall actually observed in each state,

servative estimates of the actual rainfall anomalies.

It is also apparent in Fig. 2 that the mean and variance of the actual growing-season rainfall increase southward from North Carolina to Georgia. The fact that the tree-ring estimates preserve this

even though the spatial homogeneity of spring rainfall was lower during the 1936–1982 period.

The correlation, sign test, and reduction of error (RE) statistics are all significant (Table 1, a), and indicate that the reconstructed data track the independent spring rainfall data quite well from 1937 to 1982. The observed and reconstructed rainfall means were also compared during the verification period, and *t* tests indicate that the South Carolina and Georgia reconstructions significantly underestimate the actual spring rainfall means in each state (Table 1, a). The reconstructed mean rainfall for Georgia during the verification period is above the long-term mean (933–1985), but does not fully reflect the huge surge in spring rainfall actually recorded in Georgia from 1937 to 1982. This is illustrated in Fig. 4, where the observed and reconstructed spring rainfall data from 1887 (or 1892) to 1982 were filtered with smoothing splines (Cook and Peters 1981) to emphasize decadal fluctuations. The data illustrated in Figs. 2 and 4, along with the calibration and verification statistics, indicate that the tree-ring reconstructions are quite accurate in reproducing the timing and duration of high- and low-frequency rainfall anomalies, but they do not fully reproduce the magnitude of annual or multidecadal rainfall surpluses or deficits. These observations, coupled with the fact that the regression residuals are randomly distributed, imply that the tree-ring reconstructions of spring rainfall extremes and regimes generally represent con-

important spatial component further confirms the validity of the reconstructions. (The North Carolina rainfall average represents only three months, April–June, but the changes in mean and variance are nonetheless present when the seasonal averages in each state are based on the identical three- or four-month period.)

Early weather measurements and narrative descriptions found in archival sources are also sometimes used to assess the accuracy of tree-ring reconstructions. We have not yet attempted to extensively compare the rainfall reconstructions with documentary climate evidence for the Southeast, but the spring rainfall estimates for South Carolina from 1565 to 1587 are strongly supported by descriptions of dry and wet growing seasons in the original documents surviving from the sixteenth-century Spanish colony of Santa Elena on Parris Island, South Carolina (cited in Anderson et al. 1993).

Finally, an experiment was also conducted using single-station rainfall measurements to estimate the statewide average of spring rainfall, in order to provide a simple estimate of how much state-average rainfall variance only one or two proxy tree-ring chronologies might be expected to explain under the best possible circumstances. The regression models used to calibrate the tree-ring and statewide rainfall data [i.e., Eqs. (1), (2), (3)] were duplicated as closely as possible using the same number of real instrumental rainfall measurements from nearby weather stations as predictors of state-average spring rainfall. Spring rainfall data for Charlotte were entered as the only predictor of North Carolina spring rainfall, the Clemson and Charleston gauge records were entered separately as predictors in South Carolina, and an average of the Macon and Savannah gauge records was entered as a single predictor in Georgia. The calibration and verification results are listed in Table 1, b for comparison with the same statistics computed for the tree-ring reconstructions. (Note that the calibration periods differed slightly between the tree-ring and raingage data for South Carolina and Georgia.) The calibration results indicate that the real raingages explain only from 6% to 13% more statewide rainfall variance than do the tree-ring chronologies, even though the raingage data were actually included in the computation of the statewide rainfall averages.

The raingage estimates based on two stations in South Carolina and Georgia definitely verify better than the tree-ring reconstructions, but there are no major differences between the verification results for the tree-ring and raingage estimates in North Carolina (Table 1).

These results indicate that the tree-ring reconstructions of spring rainfall are highly accurate, verifiable against independent rainfall data, and explain frac-

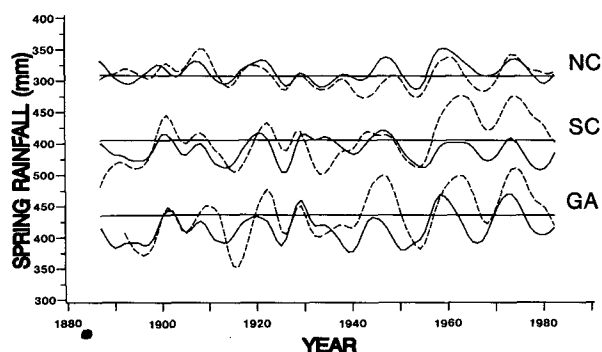


FIG. 4. The instrumental (dashed lines) and reconstructed (solid lines) rainfall data from 1887 (or 1892) to 1982 in the Carolinas and Georgia smoothed to emphasize 10-year variability (as described for the reconstructions in Fig. 3). Because the reconstructions extend earlier and later than the instrumental data in each state, minor differences between the two types of series are due to the end effects of curve fitting.

tions of rainfall variance that are not dramatically lower than can be achieved with the same number of raingages. Given the complex biological, chemical, and physical factors involved in tree growth, one might justifiably wonder why the tree-ring chronologies seem to be so representative of spring rainfall. Rainfall amounts certainly mediate many biogeochemical processes, and the apparent stratification of the fine root system just below the mean water level by the gradient in dissolved oxygen seems to greatly accentuate the rainfall sensitivity of swamp-grown bald cypress. But the riverine habitat of bald cypress may also enhance the spring rainfall response, because the water levels in these riverine cypress swamps integrate spring rainfall amounts over very large drainage basins. The description of tree-ring chronologies sensitive to season-long precipitation amounts as “integrating pluviometers” by T. J. Blasing is not entirely facetious, and may be particularly appropriate for bald cypress, which appear to integrate rainfall amounts over both time and space.

7. Analysis of observed and reconstructed spring rainfall

a. Low-frequency rainfall fluctuations

The foregoing validation tests demonstrate that the tree-ring data can provide remarkably accurate estimates of spring rainfall over the Southeast. The rainfall reconstructions are dominated by high interannual variability over the past millennium (Fig. 3a), comparable to the observed statewide averages over the past century (Fig. 2). However, smoothed versions of the reconstructions (Fig. 3b,c) also reveal many synchronous, region-wide regimes of spring drought and

wetness. The reconstructions in fact accurately replicate most of the decade to multidecadal variability apparent in the available instrumental rainfall data for North Carolina, South Carolina, and Georgia (Fig. 4). While the tree-ring reconstructions tend to underestimate the magnitude and duration of the observed rainfall regimes during the twentieth century (e.g., Georgia in Fig. 4), they are highly accurate at reproducing the occurrence of spring rainfall regimes. The low-frequency fidelity of the reconstructions can be substantiated with cross-spectral analyses (Jenkins and Watts 1968), which indicate that the three rainfall reconstructions are significantly coherent ($P \leq 0.05$) with their corresponding instrumental statewide rainfall average at all frequencies, but especially at frequencies between 8 and 40 years ($P \leq 0.01$).

Based on the ratio of variances, the 10-yr smoothed series represent from 12% to 18% of the overall

These analyses demonstrate that decade-long regimes of spring rainfall have been an important aspect of the natural background climate of the Southeast during the late Holocene, and these persistent moisture anomalies can certainly be expected to recur in the future.

variance in the rainfall reconstructions for each state, and from 15% to 22% of the variance in the instrumental series (the fraction is lowest in North Carolina and highest in Georgia for both types of data). The amplitude of the 10-yr smoothed departures can also be considerable, extending 10%–15% above or below the mean for both the observed and reconstructed data in all three states (Figs. 3 and 4). The amplitude of the 30-yr filtered reconstructions is higher and more spatially coherent among the three states during the medieval warm epoch (i.e., A.D. 1000–1300, Fig. 3c). This amplitude increase is particularly evident in North Carolina, but may be biased by the sample size problems before 1206 in Georgia.

These analyses demonstrate that decade-long regimes of spring rainfall have been an important aspect of the natural background climate of the Southeast during the late Holocene, and these persistent moisture anomalies can certainly be expected to recur in the future. The statistical significance of these rainfall regimes can be difficult to prove, but sustained growing-season rainfall deficits of 10% or 15% below the mean certainly have practical significance in terms of agricultural production, energy demand, and water

supply. This may be especially true for the many reconstructed dry regimes characterized primarily by an increase in the frequency of extreme drought years (Fig. 3), which may exact a heavier socioeconomic toll than other dry regimes characterized by more modest rainfall shortages sustained over a longer time period.

b. Large-scale circulation influences

The often synchronous, regionwide nature of growing-season rainfall extremes and regimes implies a degree of control by large-scale circulation features. We used Northern Hemisphere sea level pressure (SLP) data available on a 10 x 10 latitude/longitude grid from 20° to 70°N to search for circulation influences. Point correlations between gridded SLP and the observed and reconstructed growing-season rainfall data reveal significant negative correlations over the eastern United States (roughly 30°–40°N, 80°–100°W), and much weaker and less spatially coherent correlations over the North Pacific and central Canada. These point correlation patterns are vaguely reminiscent of the Pacific/North America (PNA) circulation pattern, which is significantly associated with southeastern climate variables during winter (e.g., Wallace and Gutzler 1981). However, we have not detected any consistent, statistically significant correlations between indices of the PNA, El Niño/Southern Oscillation (ENSO), or North Atlantic Oscillation (NAO) and growing-season rainfall over the Southeast. This is not altogether surprising because these prominent circulation features are most strongly teleconnected with climate over the eastern and southeastern United States during winter.

Composite analyses of Northern Hemisphere SLP during the wettest and driest springs over the Southeast indicate that anomalies in the location of the western periphery of the Bermuda high are linked with SLP and rainfall anomalies over the southeastern United States. Selected isobars of average SLP for the 10 wettest and 10 driest springs over the Southeast are plotted in Fig. 5 (using a three-state average of the instrumental rainfall data for March–June). These data indicate that the western flank of the Bermuda high ridges strongly westward of its mean position well into the Southeast during dry extremes, and is shifted east of its mean position and well offshore in the North Atlantic during wet extremes. The average SLP differences between the wet and dry years are statistically significant for a large region centered over the southeastern United States (Fig. 5).

We also computed an index of the difference between normalized SLP over Bermuda and New Orleans, Louisiana (i.e., 40°N, 60°W–30°N, 90°W), to measure the slope of the pressure gradient and anomalies in the western edge of the Bermuda high during

SEA LEVEL PRESSURE DURING SE USA RAINFALL EXTREMES

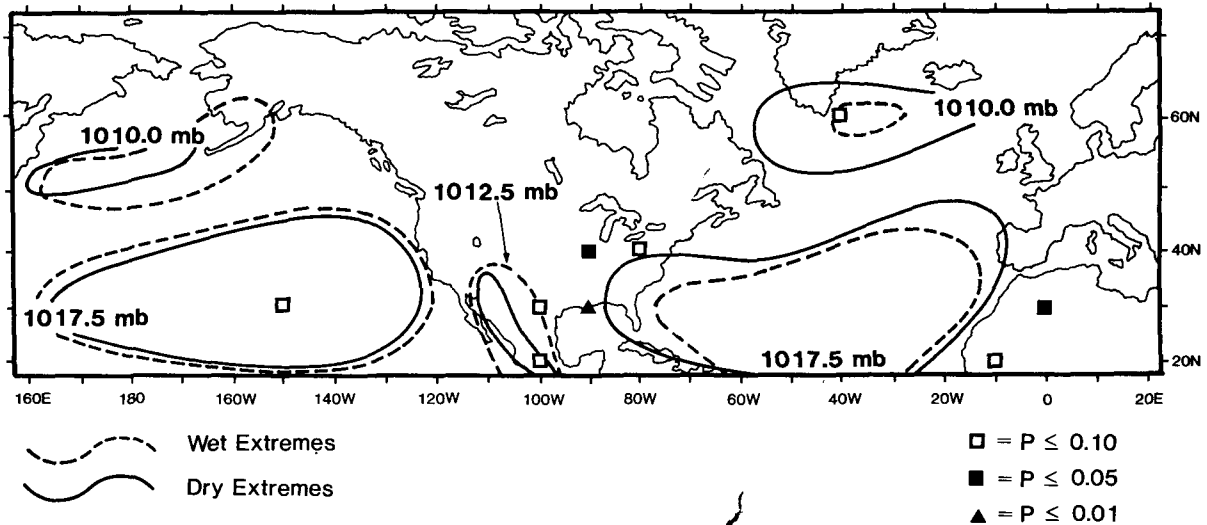


FIG. 5. Composite analysis of sea level pressure (using selected isobars only) during the 10 wettest (dashed isobars, 1900, 1901, 1909, 1912, 1922, 1928, 1929, 1958, 1961, and 1973) and 10 driest years (solid isobars, 1904, 1911, 1914, 1925, 1926, 1927, 1931, 1933, 1935, and 1954) of spring rainfall over the Southeast (the Carolinas and Georgia). The grid points where SLP was significantly different between the wet and dry years are indicated by squares and triangles. SLP increased during the dry extremes for all significant grid points illustrated, except for decreases at 60°N, 40°W, 30°N, 0°W, and 30°N, 150°W.

spring (March–June), and this index is significantly correlated with the regional average of March–June rainfall over the Carolinas and Georgia ($r = .38$, $p \leq .01$).

These results suggest that the western sector of the Bermuda high is associated with spring (March–June) rainfall extremes over the Southeast. Composite analyses of SLP also indicate that much of the low-frequency decade to multidecadal variations in southeastern rainfall may reflect similar persistent anomalies in the location of western flank of the Bermuda high during spring. The observed rainfall data in Fig. 4 indicate a general trend toward increased spring rainfall over the past century, so the SLP data were composited before and after 1940. During the relatively drier period before 1940, the mean SLP data indicate that the western sector of the Bermuda high ridged strongly westward into the Southeast, but during the wetter period after 1939 the western rim of the high was located eastward and well offshore. These differences are not shown, but are quite similar to the synoptic conditions illustrated for southeastern wet and dry extremes (Fig. 5), and all of the same grid points across the Southeast and others in the extreme western North Atlantic exhibit significant differences between the two subperiods of the past century.

Similarly, when the SLP data were compared between the decade-scale wet and dry regimes illustrated in Fig. 3b (i.e., the relatively dry periods were 1910–1920, 1925–1936, and 1950–1960, and the

relatively wet periods were 1895–1905, 1937–1949, 1961–1970, and 1972–1982), highly significant changes in the western sector of the Bermuda high were observed, with strong ridging westward into the Southeast during the dry decades.

A similar link between rainfall patterns in eastern China and the position of the western Pacific subtropical high has been reported (e.g., Wang and Li 1990), and the location of the high has been related in part to sea surface temperature anomalies. Coupled oceanic influences may also attend anomalies in the position of the Bermuda high and interannual to decadal fluctuations in southeastern rainfall, and this possibility may be addressed by the Atlantic Climate Change Program (e.g., Gordon et al. 1992).

c. Spring versus summer rainfall amounts

Further examination of SLP and warm-season rainfall data for the Southeast suggests that anomalies in the annual cycle of SLP over the subtropical North Atlantic may be responsible for many spring rainfall extremes and regimes. This apparent modulation of the annual cycle of SLP is suggested by an interesting out-of-phase relationship between spring (March–June) and summer (July–August) rainfall over the Southeast (Figs. 6 and 7). The Bermuda high typically migrates westward over the North Atlantic as it strengthens from winter through spring. By midsummer (June) the high usually migrates off to the northeast, and from fall to winter it tends to weaken and return to its mean

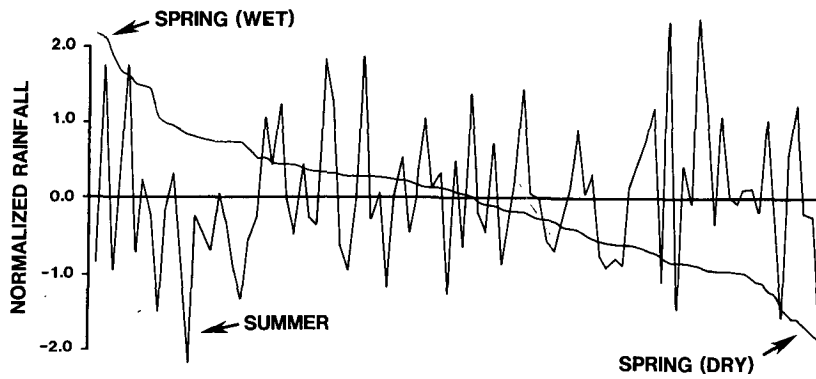


FIG. 6. The instrumental record of Southeastern spring (March–June) rainfall normalized and averaged for North Carolina, South Carolina, and Georgia from 1892 to 1982 has been ranked from the wettest to driest years (smooth curve). The Southeastern average rainfall for the summer (July–August) following each spring is also plotted (variable time series), and illustrates the out-of-phase tendency between spring and summer rainfall extremes.

position over the southeastern North Atlantic (e.g., Wolter and Hastenrath 1989; Sahsamanoglou 1990).

Annual and decade-scale anomalies in this mean annual cycle can have dramatic consequences for spring and summer rainfall over the southeastern United States. The southeastern (North Carolina, South Carolina, Georgia) spring and summer rainfall averages are totally uncorrelated over all years from 1892 to 1982, but the 20 wettest (driest) springs are usually followed by much drier (wetter) summers. This inverse relationship between spring rainfall extremes and rainfall during the following summer is graphically illustrated in Fig. 6, where all southeastern average spring rainfall departures from 1892 to 1982 are ranked and plotted along with their corresponding summer rainfall departures. Figure 6 clearly illustrates that the lack of correlation between spring and summer rainfall over all years is masking a highly nonrandom inverse relationship between spring and summer rainfall extremes. A Spearman's rank-order correlation between the normalized and ranked rainfall departures for the 20 wettest and 20 driest springs and their following summers is negative and highly significant ($r_s = -0.64$, $P \leq .001$, $n = 40$). The differences between the means of the 20 wettest and 20 driest springs and their following summers are also highly significant ($P \leq .0001$ for both t tests).

The inverse relationship between spring and summer rainfall extremes (Fig. 6) appears to be involved in much of the low frequency variance in both spring

(March–June) and summer (July–August) rainfall over the Southeast, which is also largely out of phase at decadal and century time scales (Fig. 7). The observed three-state southeastern rainfall averages for spring and summer were filtered to emphasize 10-yr variability, and the fluctuations of these smoothed series are generally out of phase from 1892 to 1982, except for the 1950s, when both spring and summer rainfall were well below average. Figure 7 also reveals a noticeable century-scale increase in spring rainfall, and a decrease in summer rainfall over the Southeast. The slopes of regression lines fit to the spring and summer rainfall are significantly different ($p < .0001$).

Maul and Hanson (1991) have also noted a similar difference in the century-scale trends of spring and summer rainfall over the Southeast, based on conventional seasonal subdivisions (i.e., MAM and JJA) for a six-state region. They found positive precipitation trends in the annually averaged data for the Southeast, and in all seasons except summer. Spring rainfall exhibited the largest trend, followed by autumn (Maul and Hanson 1991).

d. Circulation influences on spring versus summer rainfall

These results document an inverse relationship between spring and summer rainfall at annual, decadal, and century time scales, which may largely reflect anomalies in the annual expansion and migration of the Bermuda high. During those years when the Bermuda high expands strongly westward into the

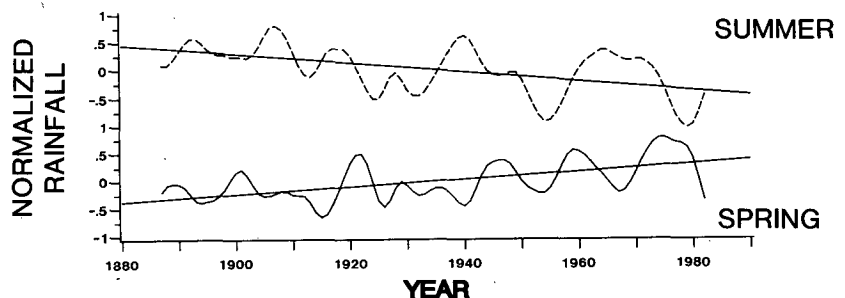


FIG. 7. Instrumental spring (March–June; solid line), and summer (July–August; dashed line), rainfall data normalized and averaged for North Carolina, South Carolina, and Georgia. The data were smoothed to emphasize decadal variations, and the slopes of the regression lines fit to each series are significantly different from each other ($P \leq 0.0001$). These time series indicate that the decadal and century-scale trends in spring and summer rainfall are largely out of phase over the Southeast, which may reflect anomalies in the annual cycle of SLP over the subtropical North Atlantic.

Southeast in spring, low-level moisture advection would often be diverted farther west around the expanded periphery of the high, which, coupled with subsidence under the prevailing anticyclonic conditions, would favor below-normal spring rainfall over the Carolinas and Georgia. This pattern frequently changes in mid-summer as the high drifts off to the northeastern North Atlantic, permitting moisture advection into the Southeast around the western and southern periphery of the Bermuda high and more-frequent summer rainfall (e.g., 1925, 1980). The opposite conditions also occur, however, when the Bermuda high fails to expand westward during the spring, only to then build strongly westward in summer (e.g., 1958, 1974). This anomalous seasonal migration favors a wet spring and dry summer over the Southeast.

Composite analyses of SLP comparing the 20 wettest springs over the Southeast with the following summers confirm that the western flank of the Bermuda high was usually retracted east of its mean position during the wet springs, and expanded west of its mean position and into the Southeast during the typically dry summers that followed. The opposite SLP patterns prevailed during and after the 20 driest springs. Composite analysis of summer (July–August) SLP indicates that the western sector of the Bermuda high was significantly farther west from 1940 to 1980 when southeastern summer rainfall was relatively low compared with the earlier period of wetter summers (1892–1940). These trends in summer SLP and southeastern rainfall, along with the opposite trends in spring SLP and rainfall over the Southeast, suggest that much of the century-scale trends in spring and summer rainfall over the Carolinas and Georgia may reflect long-period anomalies in the seasonal expansion and migration of the Bermuda high.

8. Summary and conclusions

Exceptionally old bald cypress trees still survive in relatively undisturbed swamp forests scattered thinly throughout the southeastern United States. These remnant old-growth bald cypress stands are most frequently found in noncommercial forest tracts where the trees often grow slowly and produce low-quality timber. Nevertheless, the long tree-ring chronologies developed from these unique forests represent valuable proxies of growing-season climate during the late Holocene. The five cypress chronologies used in this study have provided accurate and well-verified reconstructions of spring rainfall over the past 1000 years in the Carolinas and Georgia. In fact, the fraction of state-average rainfall variance that these reconstructions represent is only 6%–13% lower than the fraction of

state-average rainfall variance accounted for by the same number of instrumental raingages in each state. These raingage results realistically estimate the largest fraction of state-averaged rainfall variance likely to be explained by the same number of rainfall proxies. These objective comparisons, along with the statistical cross-validation tests between tree-ring reconstructions and independent instrumental climatic data, make tree-ring reconstructions the most rigorously verified paleoclimate estimates routinely produced.

The three rainfall reconstructions demonstrate that the regionwide, decade-scale regimes of spring drought and wetness apparent in the meteorological records of the past century have been a prominent feature of southeastern climate over the past millenium. These decade-long fluctuations in growing-season rainfall have not been widely investigated, but they represent accumulated rainfall departures as much as 10%–15% above or below the mean, and have major socioeconomic and environmental implications. Coupled with the identification of multiyear regimes of annual temperature (Maul and Hanson 1990), in the frequency of severe arctic outbreaks (Michaels 1990), and in the landfall of intense hurricanes (Gray 1990), the spring and summer rainfall results indicate that multiyear regimes may be an important feature of natural climate variability over the Southeast in every season.

Analyses of twentieth-century rainfall and SLP suggest that warm-season rainfall extremes and multiyear regimes of either sign often arise from anomalies in the annual cycle of SLP over the subtropical North Atlantic. Other atmospheric and oceanic factors must also influence southeastern spring rainfall, and further diagnostic studies will be required to determine the consistency of the Bermuda high effect. Nevertheless, the evidence for a plausible large-scale circulation influence on southeastern rainfall during the agriculturally important growing season has implications for seasonal rainfall forecasting. For example, the inverse association between spring and summer rainfall extremes seems to be linked in part to anomalies in the timing and magnitude of seasonal movements in the Bermuda high, and might be incorporated into statistical forecasts of late-summer rainfall conditional upon spring rainfall extremes and observations of the Bermuda high.

The valuable tree-ring evidence concerning interannual climate variation over the Southeast during the past millennium cannot be directly obtained from any other source, because other high-resolution climate proxies such as archival records (prior to the seventeenth century) and sediment varves are not available for the region. However, there is considerable potential to investigate the behavior of the Bermuda high

during the past millennium by coupling the southeastern bald cypress chronologies with other high-resolution climate proxies located elsewhere under the influence of the North Atlantic subtropical high. One tantalizing example would be the centuries-long tree-ring chronologies of Atlas cedar (*Cedrus atlantica*) available and under development in Morocco. The winter-spring rainfall of Morocco is significantly influenced by SLP anomalies in the subtropical North Atlantic (Lamb and Pepler 1991), and some of the available chronologies of Atlas cedar are sensitive to winter-spring rainfall (Chbouki 1992).

In spite of the rich climate information recorded in tree-ring chronologies (e.g., Blasing and Fritts 1976; Jacoby and D'Arrigo 1989; Briffa et al. 1992), these data have not been easily accessible to, nor widely exploited by, the climatological community. But given the great age and extensive spatial coverage of tree-ring chronologies in the temperate latitudes of the Northern Hemisphere (e.g., Stockton et al. 1985), these exactly dated and climate-sensitive proxies can provide one of the best sources of information on natural climate fluctuations during the Holocene needed to measure the anticipated climate changes of the future.

Acknowledgments. This research was supported by the National Science Foundation, Climate Dynamics Program (Grant ATM-8914561) and the National Oceanic and Atmospheric Administration, Climate and Global Change Program (Grant NA 98AA-D-AC199). We thank Robert Lofgren for providing the Northern Hemisphere sea level pressure data, and the rainfall data for selected weather-recording stations in the Southeast. We thank Charles Wharton, Julie Moore, and Norman Brunswig for assistance in locating old-growth bald cypress in the Southeast, and the National Audubon Society, the Nature Conservancy, and the Benjamin Cone estate for permission to core selected old trees at Four Holes Swamp, South Carolina, and Black River, North Carolina.

References

American Meteorological Society, 1991: Policy statement of the American Meteorological Society on global climate change. *Bull. Amer. Meteor. Soc.*, **72**, 57–59.

Anderson, D.G., D.W. Stahle, and M.K. Cleaveland, 1993: Dendroclimatology, paleoclimate, and the potential food reserves of Mississippian societies in the southeastern U.S.A. *Amer. Antiq.*, in press.

Blasing, T.J., and H.C. Fritts, 1976: Reconstructing past climate anomalies in the North Pacific and western North America from tree-ring data. *Quat. Res.*, **6**, 563–579.

—, D.N. Duvick, and D.C. West, 1981: Dendroclimatic calibration and verification using regionally averaged and single station precipitation data. *Tree-Ring Bull.*, **41**, 37–43.

Briffa, K.R., P.D. Jones, T.S. Bartholin, D. Eckstein, F.H. Schweingruber, W. Karlen, P. Zetterberg, and M. Eronen, 1992: Fennoscandian summers from A.D. 500: Temperature changes on short and long time scales. *Clim. Dyn.*, **7**, 111–119.

Brown, S., 1981: A comparison of the structure, primary productivity,

and transpiration of cypress ecosystems in Florida. *Ecological Monogr.*, No. 51, 403–427.

Chbouki, N., 1992: Spatio-temporal characteristics of drought as inferred from tree-ring data in Morocco. Ph.D. dissertation, Dept. of Geosciences, University of Arizona, Tucson, Arizona, 243 pp.

Cleaveland, M.K., E.R. Cook, and D.W. Stahle, 1992: Secular variability of the Southern Oscillation detected in tree-ring data from Mexico and the southern United States. *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*, H.F. Diaz and V. Markgraf, Eds., Cambridge University Press, in press.

Cook, E.R., 1985: A time series approach to tree-ring standardization. Ph.D. dissertation, University of Arizona, Tucson, Arizona, 171 pp.

—, and K. Peters, 1981: The smoothing spline: A new approach to standardizing forest interior ring-width series for dendroclimatic studies. *Tree-Ring Bull.*, **41**, 45–53.

—, and R.L. Holmes, 1984. *Program ARSTAN and Users Manual*. Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona, 28 pp.

Dierberg, F.E., and P.L. Brezonik, 1984: Water chemistry of a Florida cypress dome. *Cypress Swamps*, K.C. Ewel and H.T. Odum, Eds., University of Florida Press, 472 pp.

Douglass, A.E., 1941: Crossdating in dendrochronology. *J. For.*, **39**, 825–828.

Ewel, K.C., and H.T. Odum, Eds., 1984: *Cypress Swamps*. University of Florida Press, 472 pp.

Folland, C.K., T. Karl, and K. Ya. Vannikov, 1990: Observed climate variations and change. *Climate Change, the IPCC Scientific Assessment*. J.T. Houghton, G.J. Jenkins, and J.J. Ephraums, Eds., Cambridge University Press, 195–238.

Fritts, H.C., 1976: *Tree-Rings and Climate*. Academic Press, 567 pp.

—, and T.W. Swetnam, 1989: Dendroecology: A tool for evaluating variations in past and present forest environments. *Adv. Eco. Res.*, **19**, 111–188.

Gordon, A.L., S.E. Zebiak, and K. Bryan, 1992: Climate variability and the Atlantic Ocean. *Eos*, **73**, 161–165.

Gray, W.M., 1990: Strong association between West Africa rainfall and U.S. landfall of intense hurricanes. *Science*, **249**, 1251–1256.

Hall, T.F., and W.T. Penfound, 1943: Cypress-gum communities in the Blue Girth swamp near Selma, Alabama. *Ecology*, **24**, 208–217.

Houghton, J.T., G.J. Jenkins, and J.J. Ephraums, Eds., 1990: *Climate Change, the IPCC Scientific Assessment*. Cambridge University Press, 365 pp.

Howeler, R.H., and D.R. Bouldin, 1971: The diffusion and consumption of oxygen in submerged soils. *Soil Sci. Soc. Am. Proc.*, **35**, 202–208.

Jacoby, G.C., and R. D'Arrigo, 1989: Reconstructed Northern Hemisphere annual temperature since 1671 based on high latitude tree-ring data. *Climatic Change*, **14**, 39–59.

Jenkins, G.M., and D.G. Watts, 1968: *Spectral Analysis and Its Applications*. Holden-Day, 525 pp.

Karl, T.R., L.K. Metcalf, M.L. Nicodemus, and R.G. Quayle, 1983a: *Statewide Average Climatic History, North Carolina 1887–1982*. National Climatic Data Center, 35 pp.

—, —, —, and —, 1983b: *Statewide Average Climatic History, South Carolina 1887–1982*. National Climatic Data Center, 33 pp.

—, —, —, and —, 1983c: *Statewide Average Climatic History, Georgia 1892–1987*. National Climatic Data Center, 37 pp.

Kurz, H., and D. Demaree, 1934: Cypress buttresses and knees in relation to water and air. *Ecology*, **15**, 36–41.

Lamb, P.J., and R.A. Pepler, 1991: West Africa. *Teleconnections*

- Linking Worldwide Climate Anomalies*. M.H. Glantz, R.W. Katz, and N. Nicholls, Eds., Cambridge University Press, 121–189.
- Lugo, A.E., J.K. Nessel, and T.M. Hanlon, 1984: Root distribution in a north-central Florida cypress strand. *Cypress Swamps*, K.C. Ewel and H.T. Odum, Eds., University of Florida Press, 472 pp.
- Maul, G.A., and K. Hanson, 1990: A century of southeastern United States climate change observations: Temperature, precipitation, and sea level. *Global Change: A Southern Perspective, Proc. 1990 Southeast Climate Symposium*, Southeast Regional Climate Center, Columbia, South Carolina, 139–155.
- Meko, D.M., E.R. Cook, D.W. Stahle, C.W. Stockton, and M.K. Hughes, 1992: Spatial patterns of tree-growth anomalies in the USA. *J. Climate*, **5**, in press.
- Michaels, P.J., 1990: Global climate change and the U.S. Southeast: Much more research is needed. *Global Change: A Southern Perspective, Proc. 1990 Southeast Climate Symposium*, Southeast Regional Climate Center, Columbia, South Carolina, 41–59.
- Mitsch, W.J., 1984: Seasonal patterns of a cypress dome in Florida. *Cypress Swamps*, K.C. Ewel and H.T. Odum, Eds., University of Florida Press, 25–33.
- Murray, M., 1986: Why the Southeast is sweltering. *Sci. News*, **130**, 68.
- Namias, J., 1981: Severe drought and recent history. *Climate and History*. R.T. Rotberg and T.K. Rabb, Eds., Princeton University Press, 117–132.
- Sahsamanoglou, H.S., 1990: A contribution to the study of action centers in the North Atlantic. *Int. J. Climatol.*, **10**, 247–261.
- Schlesinger, W.H., 1991: *Biogeochemistry, An Analysis of Global Change*. Academic Press, 443 pp.
- Stahle, D. W., M.K. Cleaveland, and J.G. Hehr, 1985. A 450-year drought reconstruction for Arkansas, United States. *Nature*, **316**, 530–532.
- , —, and R.S. Cerverny, 1991: Tree-ring reconstructed sunshine duration over central USA. *Int. J. Climatol.*, **11**, 285–295.
- , —, and J. G. Hehr, 1988: North Carolina climate changes reconstructed from tree rings: A.D. 372 to 1985. *Science*, **240**, 1517–1519.
- , R. VanArsdale, and M.K. Cleaveland, 1992: Tectonic signal in baldcypress trees at Reelfoot Lake, Tennessee. *Seismological Res. Lett.*, **63**, 439–448.
- Stockton, C.W., W.R. Boggess, and D.M. Meko, 1985: Climate and tree-rings. *Paleoclimate Analysis and Modeling*. A.D. Hecht, Ed., J. Wiley & Sons, Inc., 71–161.
- Stokes, M.A., and T.L. Smiley, 1968: *An Introduction to Tree-Ring Dating*. University of Chicago Press, 73 pp.
- Stolzy, L.H., D.D. Focht, and H. Fiuhrer, 1981: Indicators of soil aeration status. *Flora*, **171**, 236–265.
- Trenberth, K.E., G.W. Branstator, and P.A. Arkin, 1989: Origins of the 1988 North American drought. *Science*, **242**, 1640–1645.
- Turner, F.T., and W.H. Patrick, 1968: Chemical changes in waterlogged soils as a result of oxygen depletion. *Trans. Ninth Int. Congress Soil Science*, **4**, 53–65.
- Wallace, J.M., and D.S. Gutzler, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev.* **109**, 784–812.
- Wang, W.-C., and K. Li, 1990: Precipitation fluctuation over semiarid region in northern China and the relationship with El Niño/Southern Oscillation. *J. Climate*, **3**, 769–783.
- Whitford, L.A., 1956: A theory on the formation of cypress knees. *J. Mitchell Soc.*, **56**, 80–83.
- Wolter, K., and S. Hastenrath, 1989: Annual cycle and long-term trends of circulation and climate variability over the tropical oceans. *J. Climate*, **2**, 1329–1351.

RADAR

AMERICAN
METEOROLOGICAL
SOCIETY

in METEOROLOGY

This landmark volume, the work of more than 200 contributors, brings alive the remarkable achievements of the past four and one-half decades of radar meteorology. Organized into three segments, the book covers the history, current status, and expected developments in the technological, scientific, and operational subject areas. This is much more than a narrow treatise on radar meteorology. Although the technological chapters deal explicitly with various aspects of the instruments, remaining chapters discuss a broad spectrum of scientific and operational problems such as cloud microphysics and dynamics to synoptic meteorology, nowcasting, severe-storm detection and warning, and hazards to aviation such as low level wind shear. Radar in Meteorology, a product of the entire meteorological community,

Edited by David Atlas. 1990, 806 pp., 420 illustrations, \$81 AMS Members/\$101 List (clothbound). Prices include shipping. Send prepaid orders to: Publications Dept., AMS, 45 Beacon St., Boston, MA 02108-3693.