possible that the autotrophic nitrifiers could also be inhibited by the low concentrations of inorganic carbon of acidified lakes [L. S. Jahnke, C. Lyman, A. B. Hooper, *Arch. Microbiol.* **140**, 291 (1984)].
11. We have identified three categories of lakes with respect to nitrification: case 1, the natural situation (pH >5.4 to 5.7, ammonium <7 μmol/liter), where nitrification converts most of the ammonium to nitrate under ice (Lakes 223 and 302S before acidification); case 2, acidified lakes, where early winter pH values are below 5.4 to 5.7 and inhibition of nitrification results in ammonium accumulation (Lakes 223 and 302S after acidification and Lake 302N, where 1 year after acidification by hydrochloric acid addition nitrification has been inhibited); case 3, lakes where ammonia concentrations are high (70 to 140 μmol/liter) and early winter pH is above 5.4 to 5.7. Under these circumstances, the population of nitrifiers that develops at the early winter pH is capable of remaining active until nitrification has reduced the pH to 4.0 to 4.5 {Lake 304 [D. W. Schindler, M. A. Turner, R. H. Hesslein, *Biogeochemistry* **1**, 117 (1985); L. d'Orta and R. A. Vollenweider, *Mem. Ist. Ital. Idrobiol. Dott. Marco Marchi* **16**, 21 (1963)]}. This third pattern is also shown in the growth of nitrifying bacteria in the laboratory [M. Gerletti and A. Provini, *Prog. Water Technol.* **10**, 839 (1987)].
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North Carolina Climate Changes Reconstructed from Tree Rings: A.D. 372 to 1985

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Millennium-old bald cypress trees (*Taxodium distichum* [(L.) Rich.] have been used to develop a 1614-year reconstruction of the June Palmer drought severity index for North Carolina. This proxy paleoclimatic record indicates that the growing season climate of North Carolina has undergone many changes between significantly different regimes of drought and wetness that persist for approximately 30 years. Alternating wet and dry regimes were particularly well developed during the Medieval Warm Epoch (A.D. 1000 to 1300). The record June droughts in 1985 and 1986 and the preceding three decades of much wetter than average conditions both appear to have been rare climatic events, equaled only five times each since A.D. 372.

LIVING BALD CYPRESS TREES UP TO 1700 years old have been discovered along Black River, a nutrient-poor blackwater tributary of the Cape Fear River in southeastern North Carolina (Fig. 1). Millennium-old trees are rare, and the swamp-grown bald cypress at Black River are the oldest trees in eastern North America. Annual ring width in these trees reflects precipitation and temperature variations during the growing season (*1*). We have used the Black River cypress to reconstruct the statewide June Palmer drought severity index (PDSI) (*2, 3*) from A.D. 372 to 1985.

Increment cores were extracted above the bald cypress root buttress, and the cross-dated annual rings were measured to within 0.01 mm (*4*). A cross-correlation procedure was used to confirm the dating and measurement accuracy of each ring width series (*5*).

The Black River tree ring chronology was calculated as a mean-value function of the prewhitened ring width index series available at each year since A.D. 372, after nonclimatic age trend and significant low-order autocorrelation in the ring measurement series were removed (*6–8*). A long-term variance trend remained in the 1614-year chronology. We removed this undesirable trend by fitting a stiff cubic spline to the absolute departures from the mean, dividing by the spline values, restoring the sign of the departures, and rescaling so that the series had no negative values and mean of 1.0 [the spline reduced 50% of the variance in a sine function with a 200-year wavelength (*9*)]. The distribution of the original chronology index values was also non-normal (positively skewed), and a square root transformation before variance detrending made the series approximate a normal distribution.

The Palmer index is a soil-water balance model that measures departures from average moisture conditions and is calculated from monthly temperature averages and precipitation totals (*2*). The PDSI has been successfully used in many dendroclimatic analyses of trees from a variety of habitats (*1, 10*), in part because it approximates the response of tree growth and the soil moisture reservoir to current and antecedent climatic conditions. Correlations between the Black River cypress chronology and monthly PDSI values were all positive and significant during the bald cypress growing season (primarily April to July), but the highest correlation was obtained for June, as has been observed for other cypress chronologies from Arkansas (*1*) and South Carolina.

A split-period regression procedure involving autoregressive (AR) modeling (*7, 8*) of both the predictor (Black River tree rings) and predictand [North Carolina average June PDSI (*3*)] was used to calibrate tree growth and climate during the period of meteorological observation. The weak persistence in the observed June PDSI series (first-order serial correlation = 0.176) was modeled as a lag 1 autoregressive process [$AR(1)$ coefficient = 0.188]. Persistence in the 89 tree-ring series composing the Black River chronology was modeled on average as a lag 4 autoregressive process [$AR(1)$ to $AR(4)$ coefficients equal 0.0573, 0.1270, 0.0199, 0.0922, respectively (*7, 8*)]. The large $AR(2)$ and $AR(4)$ terms are not evi-

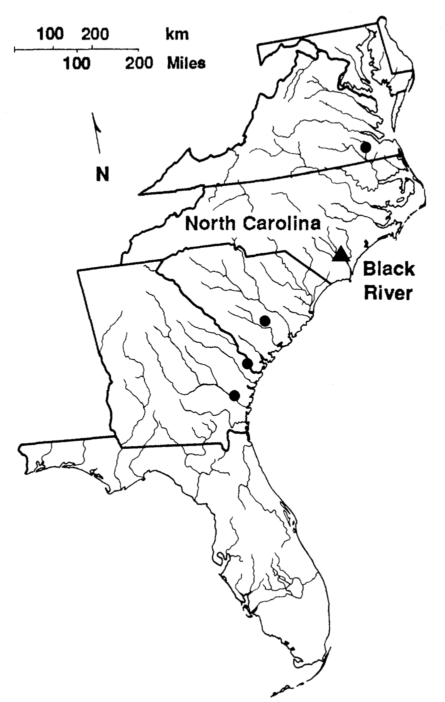

Fig. 1. Tree-ring samples were obtained from old-growth bald cypress trees in an undisturbed swamp forest along Black River, North Carolina (triangle). This swamp covers 100 hectares and contains the largest concentration of millennium-old bald cypress currently known. Four additional 1000-year-long cypress chronologies are under development elsewhere in the Atlantic Coastal Plain (circles).

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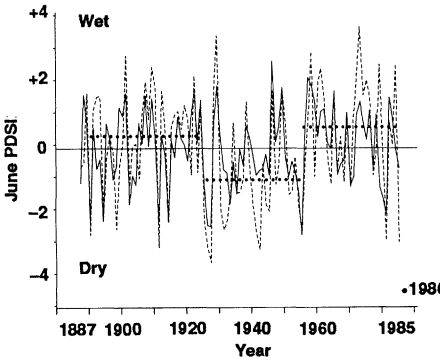

Fig. 2. Actual (dashed line) and reconstructed (solid line) June PDSI for North Carolina from 1887 to 1985. The full 99-year regression model was used for this reconstruction ($r^2_{adj} = 0.47$, Table 1). The Palmer index scales drought (−) and wetness (+) anomalies as: 0 to ±1 = near normal; ±1 to ±2 = mild; ±2 to ±3 = moderate; ±3 to ±4 = severe; ≤−4 = extreme drought, ≥+4 = extreme wetness. The means for three significantly different June PDSI regimes on the basis of the actual statewide data are indicated by the horizontal dotted lines (1891 to 1924, 1925 to 1955, 1956 to 1984), along with the overall mean (solid line). The North Carolina June PDSI observed in 1986 (circle) was the lowest recorded value in 100 years (*3*).

Table 1. Regression coefficients (B_0 is the intercept and B_1 is the slope; Eq. 1) and selected calibration and verification statistics calculated for two subperiods and for the full time interval (1887 to 1985) actually used to calibrate the 1614-year June PDSI reconstruction.

Calibration				Verification			
Period	B_0	B_1	r^2_{adj}*	Period	r†	Sign test‡	RE§
1887–1930	−4.20	4.06	0.56	1931–1985	0.65‖	43/12‖	+0.39
1931–1985	−4.01	3.64	0.38	1887–1930	0.74‖	30/12¶	+0.53
1887–1985	−4.12	3.85	0.47				

*The square of the multiple correlation coefficient adjusted for loss of degrees of freedom. †The Pearson correlation coefficient (*12*). ‡The sign statistic tests the sign of paired observed and reconstructed departures from the mean on the basis of the number of agreements/disagreements (*12*). §The reduction of error statistic (*13*). ‖$P \leq 0.001$. ¶$P \leq 0.01$.

dent in the climate data but do occur in all eight bald cypress tree-ring chronologies that we have investigated. This suggests that physiological factors, rather than climate, have caused most of the low-order autocorrelation in the growth of bald cypress. However, some of the weak, lag 1 persistence of climatic origin may also have been removed from the tree-ring series. For this reason, an $AR(1)$ component equal to the observed climatic persistence was added to the reconstruction derived from the serially random tree-ring indices (*11*).

The prewhitened June PDSI and tree-ring data were entered into linear regression for three calibration periods (1887 to 1930, 1931 to 1985, 1887 to 1985) (Table 1). The variance explained is highest for the early calibration period, but there is no statistical difference between the regression coefficients for each model (Table 1) and no significant autocorrelation in the regression residuals for the three calibration periods (*12*). We also compared the estimate of June PDSI [with $AR(1)$ persistence added] from the two subperiod models with the actual statewide June PDSI data for the alternate, statistically independent subperiod [Table 1 (*13*)]. These various statistical comparisons confirm that the regression coefficients for the subperiod models are stable with time. The final 1614-year June PDSI reconstruction was derived from the longest calibration interval (1887 to 1985) because (i) the coefficients for this model are not statistically different from the verified coefficients derived from the short subperiods, and (ii) the longer calibration interval should provide the most accurate estimate of the regression coefficients possible.

We calculated the final reconstruction by solving the regression equation for June PDSI:

$$\hat{Y}_i = -4.12 + 3.85\, X_i \qquad (1)$$

where $\hat{Y}_i$ is the prewhitened June PDSI estimate for year i and X_i is the prewhitened tree-ring chronology value for the same year (Fig. 2). The weak $AR(1)$ persistence model observed in the actual June PDSI data was then added to the serially random June PDSI estimates from A.D. 372 to 1985 to complete the reconstruction. Cross-spectral analysis (*14*) between the final reconstruction and the unwhitened June PDSI data for the period 1887 to 1985 indicates that the reconstruction is also coherent with the actual data in the frequency domain (*15*).

The 1614-year June PDSI reconstruction is plotted in Fig. 3 along with a filtered version designed to emphasize long-term variance [the filter is a cubic spline passing 50% of the variance in a sine function with a wavelength of 25 years (*9*)]. Significant interannual variance is the most obvious feature of the reconstructed June PDSI, but, because the reconstruction does not reflect the full variance in the actual PDSI data, it should be regarded as only a conservative estimate of past fluctuations. Spectral analysis (*14*) of the long reconstruction indicates possible quasi-periodicities near the 3.7-, 10.1-, and 17.9-year frequency ranges (*16*).

The reconstruction (Fig. 3) indicates that in North Carolina several prolonged droughts occurred during the Medieval Warm Epoch [A.D. 1000 to 1300 (*17*)], and that relatively wet conditions prevailed during the onset of the Little Ice Age [from approximately 1300 to 1600 (*17*)]. Significant interannual, decadal, and long-term variability in June PDSI occurred during both of these climate episodes, however. Early summer climate conditions appear to have become drier during the later stages of the Little Ice Age (1650 to 1750, Fig. 3), and there has since been a long-term in-

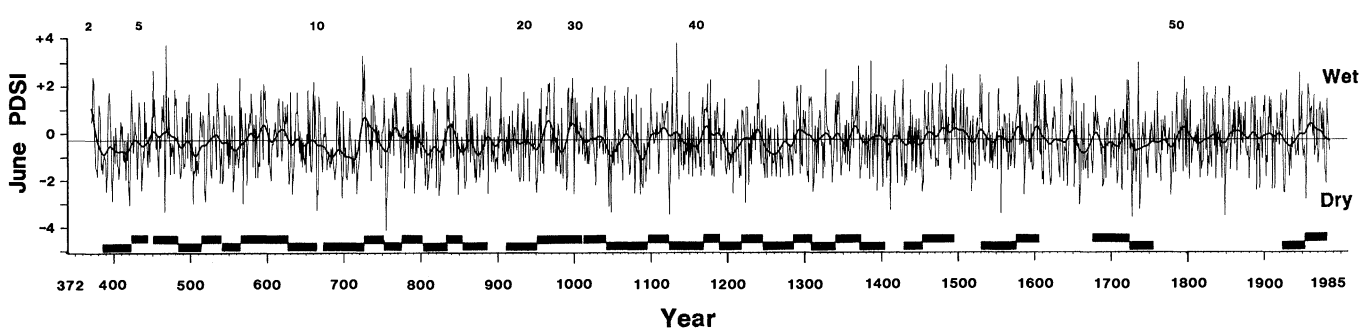

Fig. 3. The tree-ring reconstruction of June PDSI for North Carolina plotted annually from A.D. 372 to 1985, along with a smoothed version designed to emphasize low-frequency variance (*9*). The number of specimens in the predictor chronology increases through time as indicated above the series. The timing of the statistically different regimes of drought (lower bars) and wetness (upper bars) is indicated below the time series.

crease in average June PDSI. The slope of a regression line fitted to the reconstructed June PDSI data from 1659 to 1985 is $+0.0017$ per year ($P < 0.02$). Average June PDSI for the past century has been above the 1614-year mean (Figs. 2 and 3) and appears to be the culmination of the positive trend that began in the mid-17th century.

Both the observed and the reconstructed data (Figs. 2 and 3) suggest that North Carolina June PDSI has tended to oscillate between persistent regimes of drought and wetness. These wet and dry regimes, which last for some 30 years each, are statistically significant in both the observed and reconstructed series (Figs. 2 and 3). A sequence of wet-dry-wet regimes is evident in the meteorological data from 1887 to 1985 (Fig. 2) (*3*). The observed June PDSI mean for the dry period from 1925 to 1955 was -1.10, which is significantly drier than the means for the preceding or following wet periods [1891 to 1924 = $+0.27$ ($P < 0.001$) and 1956 to 1984 = $+0.62$ ($P < 0.0001$), on the basis of t tests for differences of mean (*12*)]. Climatic differences between these same approximate periods have been recognized in previous studies of meteorological data (*18*). The bald cypress reconstruction of June PDSI indicates that the period from 1956 to 1984 was one of the five wettest 29-year periods in North Carolina during the past 1614 years (Fig. 3). However, the droughts that followed in 1985 and 1986 were the two worst years of June drought experienced in North Carolina since 1887 [June PDSI = -3.04 and -4.54, respectively (*3*)]. A comparable 2-year sequence of such intense drought appears to have occurred only five times since A.D. 372 (*19, 20*).

Analysis of the 1614-year reconstruction indicates that 28 periods were significantly wetter or drier than the following three decades. These statistically different regimes average 34 years in length (ranging from 21 to 63 years) and are illustrated in Fig. 3. The differences in means between successive periods could have been caused in part by persistence in the time series (*8*); therefore, the same periods were tested in a version of the reconstruction without persistence added. Of the 28 significant differences reported above, 19 were still significant, more than would be expected by chance (*21*).

A virtually uninterrupted sequence of significantly different wet and dry regimes appears to have occurred from A.D. 372 to 1400, including six large magnitude changes ($P < 0.01$) during the Medieval Warm Epoch (1043 to 1310, Fig. 3). The number of statistically different regimes in the reconstruction declines after 1600, but we cannot determine from the available data whether this decline indicates that a climate change occurred during the Little Ice Age or reflects some sort of unexplained bias affecting that part of the predictor chronology. Additional long tree-ring chronologies will be needed to confirm the temporal and spatial aspects of the apparent changes in growing season moisture regimes.

There is no evidence that the interannual variance of the reconstructed June PDSI also changes for the ~30-year intervals that were tested; however, there are several shorter 10-year periods when the frequency of large magnitude, interannual changes in June PDSI increases dramatically. In the full reconstruction, interannual changes exceeding two standard deviations occur in 11.6% of the years (or about once per decade), but such changes occur from four to six times in 11 separate 10-year periods since A.D. 372.

These data suggest that the growing season climate of North Carolina has been subject to statistically significant changes in both average conditions on a 30-year time scale and interannual variability on a 10-year time scale. These changes may have been associated with differences in atmospheric circulation during the spring and early summer, but the physical or stochastic mechanisms that might have been responsible remain to be documented. Approximately one-third of the 28 significant transitions resemble a step function change in the mean (for example, 1924 to 1925, 1955 to 1957, Fig. 2), and such changes could have important practical and theoretical implications. The record June droughts of 1985 and 1986, for example, could signal the end of the relatively wet regime that began in 1956, but this possibility remains highly speculative in the absence of a physical explanation for the changes between regimes.

Whatever physical or stochastic mechanisms may ultimately be involved, a change to a new regime could have important environmental and economic consequences. We estimate that the chance for a severe drought in 10 years is 56% on the basis of the entire 1614-year reconstruction (June PDSI at or below -3.00; *20, 22*). However, the probability of a severe drought rises to 78% in 10 years during dry regimes, and it is only 26% in 10 years during wet regimes (Fig. 3). The potential impact of a regime drought on agriculture, energy demand, and water supply justify continued efforts to confirm and explain the long-term changes in growing season climate over North Carolina.

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21. There are 47 consecutive 34-year periods in 1614 years, and only 2.3 periods would be expected to have statistically different means by chance [$P \leq 0.05$ (*12*)]. In t tests between each successive pair of 34-year periods extending arbitrarily from 1985 back to 382, five comparisons had significantly different means ($P \leq 0.05$). This a priori analysis demonstrates that the tendency for North Carolina June PDSI to oscillate between 34-year regimes of drought and wetness is greater than would be expected by chance. The significantly different regimes in Fig. 3 were selected a posteriori; 28 of the 46 differences were significant, including 9 at $P \leq 0.01$, 10 at $0.01 < P \leq 0.05$, and 9 at $0.05 < P \leq 0.10$.
22. Compared to a 40% chance for severe drought in 10 years calculated from the observed data during the wetter than average period from 1887 to 1985 (*20*).

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