Interannual to decadal climate and streamflow variability estimated from tree rings

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Introduction

Tree-ring dating (dendrochronology) is the most accurate and precise dating method in geochronology. Tree-ring chronologies are dated to the exact calendar year, and can be directly calibrated with instrumental climatic data with seasonal to annual resolution. Hundreds of moisture-sensitive tree-ring chronologies have now been developed for North America, and most are available from the International Tree-Ring Data Bank at the National Geophysical Data Center. These annually resolved time series present many unique opportunities for socially relevant research into the dynamics and impacts of regional to global climate systems. Tree-ring data can be used to document natural hydroclimatic variability prior to the period of anthropogenic climate modification, including severe drought extremes not witnessed in the instrumental record. Climate reconstructions from tree rings can be linked with social, economic, and ecological data to explore the human and environmental impact of past climate extremes. This chapter highlights selected tree-ring research in the continental United States, with a particular emphasis on hydroclimatic variability, environmental and human impacts, and recent developments with new multi-century tree-ring chronologies in the eastern and western United States.

Hydroclimatic Applications of the Continental Network of Tree-Ring Chronologies

The network of centuries-long tree-ring chronologies now available for North America extends from the tropics of southern Mexico to the boreal forest, and from the Pacific to Atlantic coasts (Fig. 1). This may be the finest large-scale network of high-resolution paleoclimatic proxies yet produced worldwide, and its development has been funded primarily by the National Science Foundation, Climate Dynamics and Paleoclimatology Programs. This abundance and wide distribution of centuries-long tree-ring chronologies (Fig. 1) testifies to the fact that ancient forests still survive across North America, particularly on remote rugged terrain and on xeric sites where tree growth is slow and the woodlands unsuited for lumber production or agriculture (Stahle, 2002).

All of the tree-ring chronologies located in Fig. 1 span at least the last 200 years, and the vast majority date back to A.D. 1700 or earlier. The chronologies are coded by species, and several moisture-sensitive species in the white oak group dominate the network in the eastern United States (especially *Quercus alba*, *Q. stellata*, and *Q. prinus*). Eastern hemlock (*Tsuga canadensis*) and baldcypress (*Taxodium distichum*) are heavily represented in the eastern network. Ponderosa pine (*Pinus ponderosae*) and Douglas-fir (*Pseudotsuga menziesii*) are the most important species in the western network. Recent sampling of Douglas-fir in small isolated higher elevation microenvironments of central and southern Mexico (Therrell *et al.*, 2002), and near the northern limit of the species in British Columbia (Watson & Luckman, 2002) provide a single-species array that extends over nearly 40 degrees of latitude. Few tree species have such an impressive latitudinal range, and even fewer are as valuable for climatic reconstruction as Douglas-fir.

Many of the chronologies illustrated in Fig. 1 were used by E.R. Cook *et al.* (1999) to reconstruct the summer Palmer Drought Severity Index (PDSI) on a $2 \times 3^{\circ}$ latitude/longitude grid covering the entire coterminous United States from A.D. 1700–1979. These reconstructions have been validated in most regions against independent PDSI data not used in the calibration process, and some of the reconstructions extend much earlier over sub-regions of the country (e.g. back to A.D. 1500 over most of the West and Southeast). These gridded tree-ring reconstructions of summer PDSI faithfully capture the main regional modes of drought and wetness variability across the United States, as identified with instrumental PDSI data from A.D. 1895–1981 by Karl & Koscielny (1982).

Fye *et al.* (2003) have used composite analysis of the Cook *et al.* (1999) summer PDSI reconstructions to map the largest decadal moisture excursions of the 20th century and place them into the historical perspective of the past 500 years. The tree-ring reconstructions generally reproduce the geography, timing, and relative intensity of the major moisture regimes actually observed over the United States during the 20th century, but not the absolute intensity. Thus, the largest dry and wet regimes seen in the instrumental record during the 20th century were also the largest in the reconstructions during the same interval. These decadal regimes included the early 20th-century pluvial, the Dust Bowl drought, and the 1950s Southwestern-Southern Plains drought (also note Karl, 1988; Trenberth, 1991).

The drought of 1934 was the worst that was recorded by both the instruments and tree rings from A.D. 1895 to present, and over the past 500 years may have been surpassed only once by the extreme and widespread drought of A.D. 1580 (Fye *et al.*, 2003). The prolonged Dust Bowl drought of the 1930s is one of the few decadal droughts to impact most of the United States. The tree-ring reconstructions suggest that the Dust Bowl drought may have been the most severe, sustained, and widespread drought to impact the continental

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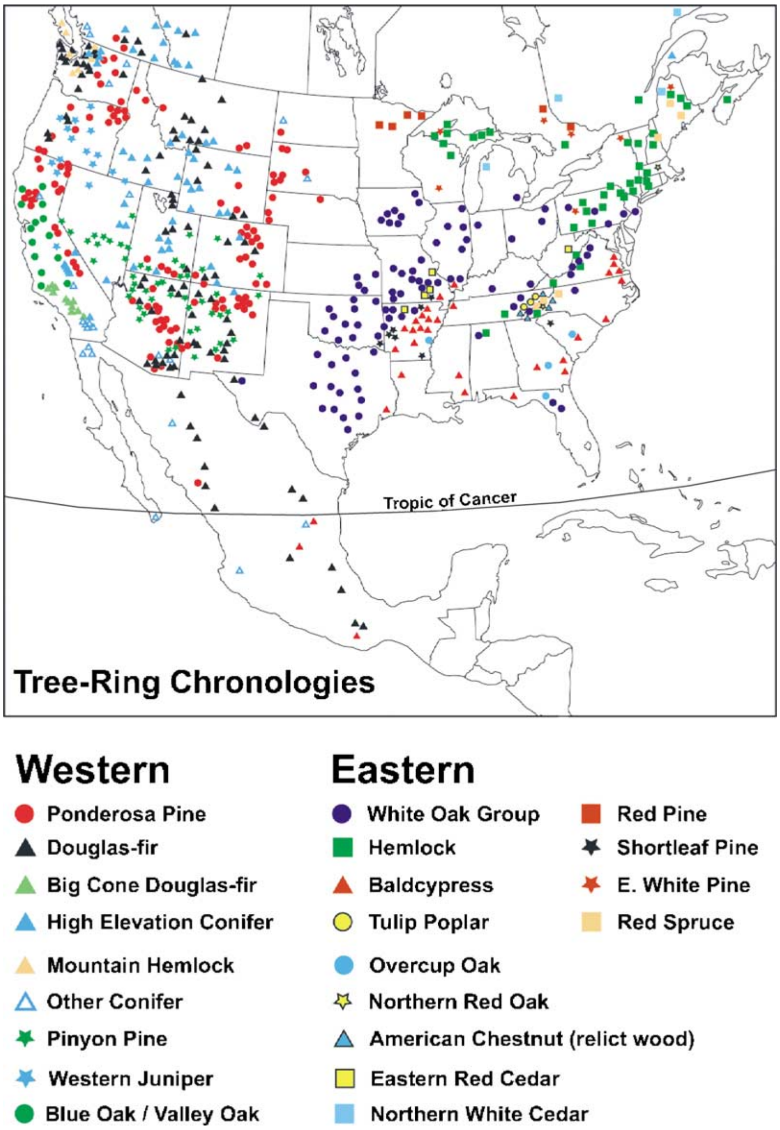


Fig. 1. Locations of tree-ring chronologies at least 200 years long that are now available for the United States, southern Canada, and Mexico. These chronologies have been developed by the combined efforts of the tree-ring community, following the initial work of A.E. Douglass and E. Schulman. The chronologies are coded by species and most are available from the International Tree-Ring Data Bank at the National Geophysical Data Center in Boulder, Colorado.

United States since the mega-drought of the 16th century (Fye *et al.*, 2003). The 1950s drought was the second most severe and sustained drought of the 20th century, and was concentrated over the Southwest-Southern Plains (Fig. 2). The geography of the 1950s drought is reasonably well reproduced by the tree-ring reconstructions, and appears to have been replicated by ten similar decadal droughts over the past 500 years (Fig. 2). These 1950s-like droughts varied from 5- to 21-years in duration, and include the 16th-century mega-drought from A.D. 1567–1587.

Because drought is limiting to tree growth, tree-ring chronologies are generally more accurate proxies of drought than wet conditions. Nevertheless, the Cook *et al.* (1999) PDSI estimates provide a good representation of the early 20th-century pluvial actually recorded in the instrumental PDSI data from approximately 1905–1923 (Fig. 3). The long tree-ring reconstructions suggest that the early 20th-century pluvial may have been the most intense and prolonged wet anomaly across the western two thirds of the country in 500 years, although two near analogs occurred in the early 19th and early 17th centuries (Fye *et al.*, 2003; Fig. 3). Thus the 20th century period of instrumental climate observation appears broadly representative of the annual and decadal PDSI variability of the past 400 years, but not before (e.g. Cook & Evans, 2000).

The extended wet episode during the early 20th century certainly biased estimates of mean runoff during the negotiations leading up to the Colorado River Compact. Compact negotiators assumed a mean flow at Lee Ferry of 17.5 million acre feet/year (MAF/yr) and allocated 7.5 MAF/yr to the upper basin, 7.5 MAF/yr to the lower basin, 1.5 MAF/yr to Mexico, and the remaining 1.0 MAF/yr as a bonus to the lower basin (Reisner, 1986). California alone was entitled to 4.4 MAF/yr under the compact. However, a tree-ring reconstruction of annual stream flow at Lee Ferry by Stockton (1975) indicated that the period from 1906–1930 included the highest runoff totals estimated for the Colorado in 400 years, and from 1930–1952 “the discharge of the Colorado River

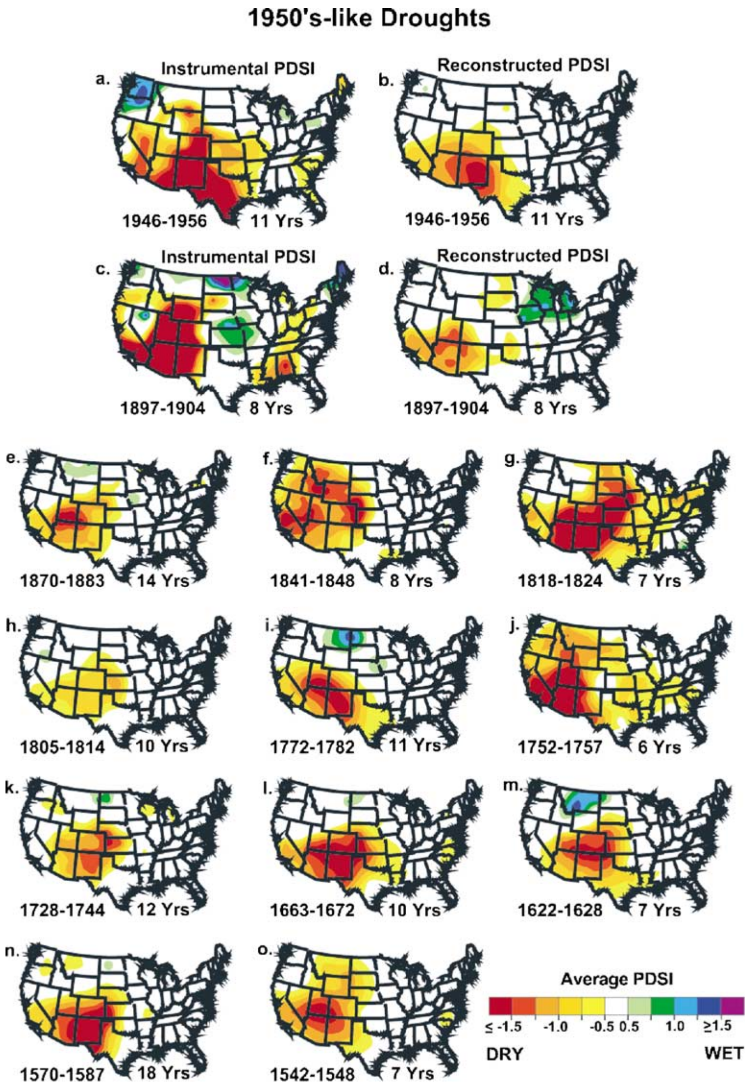


Fig. 2. The summer PDSI reconstructions of Cook et al. (1999) have been used to average and map consecutive episodes of drought that resembled the 1950s drought over the past 500 years (Fye et al., 2003). The instrumental measurements of the 1950s drought are illustrated (top left), along with the tree-ring reconstructions for 1946–1956 (top right). These 1950s-like droughts varied from 6- to 18-years in duration, and were concentrated over the Southwest.

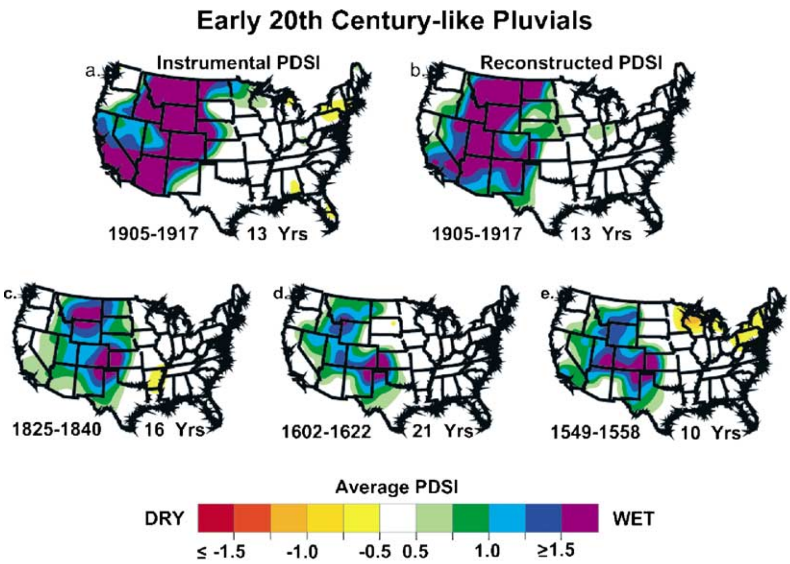


Fig. 3. The summer PDSI reconstructions of Cook et al. (1999) have been used to average and map prolonged wet episodes over the past 500 years, including the early 20th century pluvial (Fye et al., 2003). The instrumental measurements for the early 20th century pluvial are illustrated (top left), along with the tree-ring reconstructions for 1905–1917 (top right). Prolonged and widespread wet episodes occurred over the western United States in the 16th, 17th and 19th centuries, but the early 20th century pluvial as estimated from tree rings appears to have been unmatched in magnitude over the past 500 years (Fye et al., 2003).

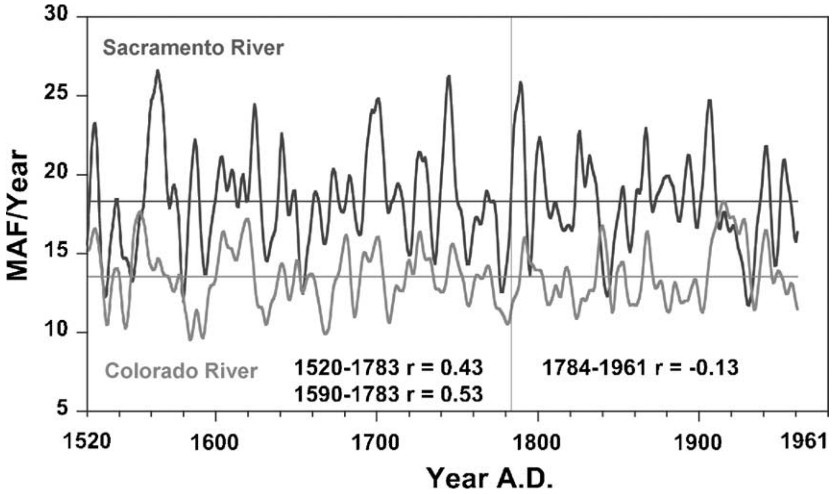


Fig. 4. Tree-ring reconstructed annual streamflow for the Sacramento and Colorado Rivers in millions of acre feet per year (from Meko et al., 2001; Stockton, 1975). To highlight the decadal variability in the data, both time series have been smoothed with a cubic smoothing spline reducing 50% of the variance in a sine wave with a period of 10 years (Cook & Peters, 1981). The full Sacramento River record extends from 869–1977, with an estimated mean annual flow of 17.9 MAF/yr (Meko et al., 2001). Only the period from 1520 to 1961 is illustrated here for the Sacramento, when the estimated mean flow was 18.3 MAF/yr. The long term mean streamflow for the Colorado is estimated at 13.5 MAF/yr for 1520–1961 (see Meko et al., 1991, 2001, for discussion of the estimated error associated with both reconstructions). Note the apparent break in decadal covariance between these two series in the 1780s (the correlation between segments of the smoothed time series is also reported).

at Lee Ferry (near the Arizona-Utah border) . . . averaged only 11.7 MAF" (Raymond Hill quoted in Reisner, 1986). Stockton's (1975) tree-ring-based estimate of long-term mean runoff for the Colorado River at Lee Ferry of only 13.5 MAF/yr remains today as perhaps the most famous single number ever calculated with tree-ring data (Fig. 4, bottom).

Meko *et al.* (2001) report a new high-quality reconstruction of Sacramento River flow using an expanded network of precipitation-sensitive chronologies that includes blue oak (*Q. douglasii*) and western juniper (*Juniperus occidentalis*). This reconstruction explicitly accounts for the uncertainty associated with the changing suite of tree-ring predictors back in time, and indicates that certain single-year droughts and extended drought episodes before A.D. 1600 may have exceeded any witnessed on Sacramento during the period of instrumental observation.

As noted by Meko *et al.* (1991) the co-occurrence of drought over the major watersheds of the Sierra Nevada and Rocky Mountains could seriously impact water resource allocations in Southern California and the Southwest. The overall correlation between decadally smoothed versions of the long Colorado and Sacramento River reconstructions is only $r = 0.31$, but the two estimated flow series were more coherent at decadal scales during the 17th and 18th centuries than afterward (the correlation is $r = 0.53$ for A.D. 1585–1783, Fig. 4). The 16th century mega-drought, for example, does appear to have impacted runoff in both the Rockies and Sierra Nevada (Figs 2 and 4). These results suggest that there may be natural large-scale climate conditions under which decadal drought and wetness regimes can impact both watersheds simultaneously. The water storage facilities constructed for both the Sacramento and Colorado have enormous capacity to deal with extended drought and wetness regimes (Dracup & Kendall, 1991), however, a repeat of the severe sustained droughts of the late 16th, mid-17th, and late 18th centuries could seriously constrain water supply and allocation across the Southwest, especially if they were to occur over both the Sacramento and Colorado watersheds.

Tree-Ring Estimates of Climate Forcing Factors

H.C. Fritts first demonstrated the usefulness of the North American tree-ring chronology network for estimation of large-scale ocean-atmospheric forcing of inter-annual and decadal climate variability (e.g. Fritts, 1976). In fact, tree-ring data from subtropical North America record one of the strongest ENSO signals in climate proxies worldwide, and are highly correlated with oxygen isotope chronologies developed from annually banded corals in the equatorial Pacific (Cleaveland *et al.*, 2003). Lough & Fritts (1985) developed the first tree-ring reconstruction of the El Nino/Southern Oscillation (ENSO), estimating the Southern Oscillation Index (SOI) from North American tree-ring chronologies from A.D. 1600–1965. Stahle *et al.* (1998a) used tree-ring data from North America and Indonesia to reconstruct the winter SOI from A.D. 1706–1979, and estimated a significant shift in the envelope of reconstructed winter SOI variance during the 19th century. However, both SOI reconstructions rely heavily on the ENSO teleconnection to subtropical North America, which Cole & Cook (1998) show may not have been stationary during the last 150 years.

Lough & Fritts (1985) point out that the potential extra-tropical proxies of ENSO have large uncertainties associated with the teleconnection filter through which the tropical ENSO signal must propagate into the extra-tropics. This is a problem that underlies many attempts to use remote proxies to estimate climate-forcing mechanisms that reside in the coupled ocean-atmospheric system. One solution for the paleoclimatic reconstruction of ENSO variability might be the development of annually or seasonally resolved marine and terrestrial proxies from the centers of action of ENSO in the equatorial Pacific. Certain annually banded coral and tree species found in the Indonesian archipelago offer some hope of defining equatorial ENSO variability for several centuries (e.g. Allan & D'Arrigo, 1999). These extended ENSO estimates would then be valuable in conjunction with climate-sensitive tree-ring chronologies in the extra-tropics for mapping past teleconnection patterns. For example, Cole *et al.* (2002) use coral data from Miana atoll to identify extended cold conditions in the central equatorial Pacific during the mid-19th century, that they link to the tree-ring reconstructed drought that occurred simultaneously over North America (see Fig. 9, bottom right, in Cole & Cook, 2002).

The dramatic shift in North Pacific/North American climate at 1976–1977 has been linked to the Pacific Decadal Oscillation (Mantua *et al.*, 1997). Gedalof & Smith (2001) used tree-ring chronologies of mountain hemlock (*Tsuga mertensiana*) near the North Pacific and Gulf of Alaska to reconstruct a PDO index. They used an intervention detection algorithm to identify the three suspected regime shifts in instrumental PDO during the 20th century, and nine earlier shifts in the reconstructed record that extends from A.D. 1600 to the present. Their results suggest that the North Pacific has experienced regimes of alternately warm and cold sea-surface temperatures (SST) over the last 400 years, and that transitions between regimes tend to be abrupt, similar to the regime shifts witnessed during the 20th century in instrumental data. Other tree-ring reconstructions of the PDO have been reported (e.g. Biondi *et al.*, 2001; D'Arrigo *et al.*, 2001). These reconstructions to some degree share large-scale paleoclimate variance that is influenced by the PDO and other large-scale climate-forcing mechanisms, and Biondi *et al.* (2001) specifically attempt to remove ENSO variability from their estimate of inter-decadal variability. It is interesting that the PDO reconstructions of Biondi *et al.* (2001) and Gedalof & Smith (2001), using completely different tree-ring data sets from southern California-Baja California and the Pacific Northwest-Canada-Alaska, respectively, both located immediately downstream of the North Pacific Ocean, identify the same large decade-scale reversals of North Pacific climate near 1750, 1946 and 1977, and perhaps lesser events as well.

The Southwest or Mexican Monsoon (Douglas *et al.*, 1993; Higgins *et al.*, 1999) is an important component of summer precipitation over the United States and northern Mexico, and seems to exhibit a weak out-of-phase relationship with summer precipitation amounts over the Midwest and Florida (Douglas & Englehart, 1996; Higgins *et al.*, 1999). Unfortunately, many tree-ring chronologies from western North American conifers do not have a strong response to mid- to late-summer precipitation totals, and may be more highly correlated with winter-spring precipitation totals. This response is believed to relate to soil-moisture recharge at the onset of the spring growing season and to physiological factors controlling stored photosynthate during the summer, fall, and winter preceding growth (e.g. Fritts, 1966). However, separate chronologies of earlywood (EW) and latewood (LW) width have been developed in attempts to isolate a useful record of summer precipitation in the monsoon region. EW chronologies in the Tex-Mex sector (the southwestern USA and northern Mexico) have been shown to have stronger winter precipitation and ENSO signal than the total-ring-width chronologies derived from the same trees (Cleaveland *et al.*, 2003). LW chronologies from the Tex-Mex sector are more highly correlated with summer precipitation, and some appear to be correlated with the onset of the Mexican Monsoon (Therrell *et al.*, 2002). Meko & Baisan (2001) have shown considerable promise for the use of latewood width and other latewood properties for the estimation of summer monsoon precipitation over Arizona.

The potential role of solar-lunar forcing on climate variability over the United States occupied much of A.E. Douglass' research during the early development of dendrochronology. Cook *et al.* (1997) recently revisited the analyses of drought area across the United States conducted by Mitchell *et al.* (1979). Using a greatly expanded set of tree-ring chronologies, Cook *et al.* (1997) identified the statistically significant bi-decadal drought rhythm reported in the earlier work. This bi-decadal drought rhythm over western North America is perhaps the most stable and statistically robust solar-lunar band signal yet detected in annually resolved paleo data. But it does not appear to explain more than 10% of the variance in drought area over western North America and the physical mechanisms involved in this hypothesized solar-lunar forcing of surface climate remain unclear (Cook *et al.*, 1997).

Multiproxy Paleoenvironmental Research and Tree Rings

Tree-ring chronologies have many virtues for climate reconstruction, including exact calendar dating, a well-specified climatic signal, massive replication of tree-ring time series per collection site, and repetition of chronologies across the landscape. But these time series are derived from living organisms with certain characteristics that limit their usefulness for reconstructing all dimensions of climate variability, particularly lower-frequency secular changes in climate and long-duration dry or wet regimes. These biological characteristics are discussed below and include a degree of tree-growth adaptability to changing environmental conditions, a survivor effect, and the nonstationarity of radial growth attending the increasing size and age of the plant.

For an example of growth adaptability, field observations suggest that baldcypress root systems may act as a natural high-pass filter on the derived time series of radial growth. The fine feeder root systems of baldcypress tend to stratify in the well oxygenated zone of near surface waters, and appear capable of tracking persistent multi-decadal changes in mean water level with the adventitious growth of new root mass (e.g. Stahle & Cleaveland, 1992). This growth tracking tends to smooth out the tree-ring registration of low-frequency shifts between dry and wet regimes, and the resulting baldcypress chronologies are dominated by high frequency inter-annual to decadal changes in precipitation.

A survivor effect may contribute to an underestimation of drought severity from tree-ring data. Old living trees in a forest do record past droughts. But the tree-ring chronologies derived from still-living trees may underestimate the true severity of a past drought because some trees experience such severe growth reductions that they do not survive the drought to contribute to the derived chronology.

The systematic change in mean growth removed with statistical detrending of individual ring-width time series prior to computation of the mean index chronology can also reduce the tree-ring registration of low-frequency climatic trends. The magnitude of this potential detrending bias varies inversely with the length of the individual ring-width time series used to compile the mean chronology (the so-called "segment length curse" Cook *et al.*, 1995). Recent analyses have attempted to deal more explicitly with the detrending issue, basically exploiting the coherence or "cross-dating" of low-frequency growth excursions sometimes seen among multiple trees (the so-called RCS or regional curve standardization method, Briffa *et al.*, 1992a). These studies have reconstructed greater low-frequency temperature variability that appears to agree better with independent indications of large temperature excursions of the past millennium (e.g. Briffa *et al.*, 1992a; Esper *et al.*, 2002).

Regardless of the statistical methodologies employed, the biological realities of tree growth may always to some degree limit the tree-ring registration of long climate regimes and trends. When feasible, the multiproxy approach can improve the registration of the full range of paleoenvironmental variability. For example, Woodhouse & Overpeck (1998) employed several paleoenvironmental indicators including early instrumental records, historical documents, tree-ring reconstructions, lake and alluvial sedimentary records, eolian deposits, and archaeological remains to construct a drought chronology for the central United States. They concluded that several droughts more severe than those recorded during the 20th century occurred over the past 2000 years, and that droughts before A.D. 1600 may have been more persistent and widespread. Large decadal drought variability before A.D. 1600 is also indicated by regional tree-ring data (Meko *et al.*, 1995), and by an analysis of the gridded PDSI reconstructions for the southwestern United States extended back to A.D. 1200 (Cook & Evans, 2000).

The colonial and historic periods offer many opportunities for multiproxy reconstruction of past climate and environmental variability. Guyette (2002) has integrated tree-ring-dated fire scars with rural population levels and cultural practices to construct a long historical sequence of natural and human-caused fire and landscape change for the Ozark Plateau and forest transition zone of Missouri. Brunstein (1996) developed a detailed event chronology of latewood frost rings in bristlecone pine of Colorado, and linked them to historic late-summer snowstorms and subfreezing temperatures. These frost-ring records were integrated with independent tree-ring reconstructions and historical accounts of winter temperature, snowstorms, and glacier advance to identify the terminal Little Ice Age period of early 19th century as one of the most anomalous in the past 2000 years (also see Briffa *et al.*, 1992b; Mann *et al.*, 1998). The large-magnitude volcanic eruptions during the early 19th century, including Tambora, Indonesia, and Cosequina, Nicaragua, have been implicated in this large-scale cold interval, and the bristlecone pine frost-ring record has itself been linked to the chronology of cataclysmic eruptions (LaMarche & Hirschboeck, 1984).

The potential for detailed meteorological and climatological reconstructions using ring-width data, frost rings, documentary accounts, and early instrumental measurements has been illustrated for A.D. 1828. Frost rings in oaks of the eastern United States (Stahle, 1990) indicate that 1828 was one of the major "false spring" episodes of the past 350 years. False spring includes both a climatologically warm winter, followed by a meteorologically significant spring freeze event. The available instrumental and documentary records for 1828 confirm and greatly elaborate on the anomalous climate and weather events of 1828 (Fig. 5). Mean winter temperatures (Dec–Mar) were anomalously warm across eastern North America in 1828, peach trees blossomed at Christmas 1827 in Little Rock, Arkansas, and temperatures exceeded 22 °C (70 °F) on several occasions in January and February at Nashville, Tennessee. David Ludlum (1968) described the winter of 1827–1828 as "the warmest winter in the American experience." At the same time, fur trapper reports and a few thermometer records from trading posts in Canada indicate that the winter of 1828 was colder than average in the Northern Rockies. These winter surface temperature anomalies suggest an upper-air flow pattern marked by a persistent ridge over the East and trough over the West. Conditions changed abruptly in early April of 1828, when a severe outbreak of cold air swept across the United States, and caused frost damage to oak trees, extensive fruit tree and crop damage, widespread reports of frost and freeze, and sub-freezing temperatures readings across the South (C.J. Moek, pers. comm.).

Human Impacts of Tree-Ring Reconstructed Climate Extremes

Henri Grissino-Mayer's (1996) Douglas-fir reconstruction of annual precipitation from El Malpais, New Mexico, is particularly long and outstanding (Fig. 6). The El Malpais reconstruction has been used to document past drought extremes that exceed anything witnessed during the 20th century, and provides a long-term climatological framework for the major social and environmental changes that have occurred in this region over the past two millennia. For example, the 8th-century mega-drought at El Malpais extended from approximately A.D. 735 to 765, and was one of the two or three most severe and prolonged

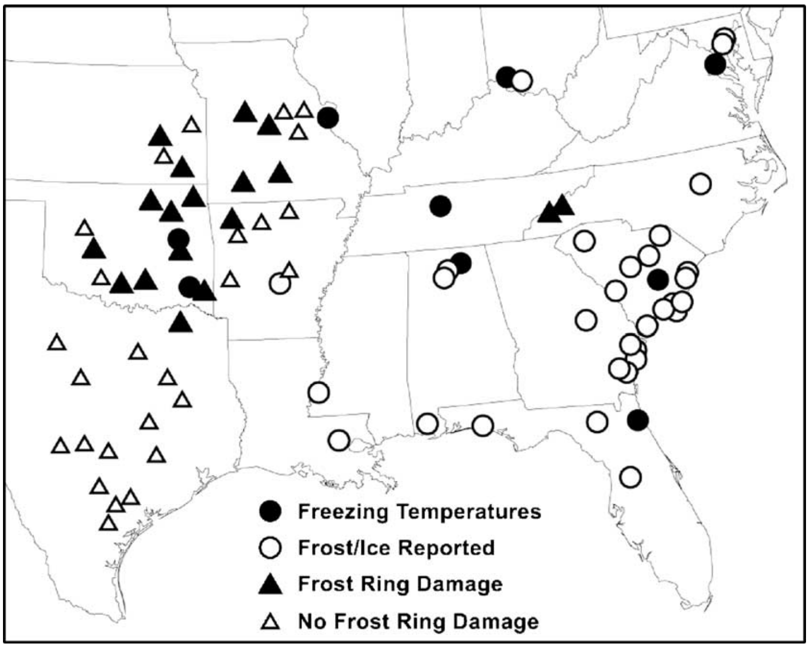


Fig. 5. The false-spring episode of 1828 was recorded by tree ring, documentary, and thermometer data across the southeastern United States. Temperatures below −5 °C are required to cause frost ring damage in oak trees of the eastern United States, and the absence of frost damage to oaks south of the Red River indicates that the −5 °C isotherm did not penetrate into Texas during the early April event (C.J. Mock et al., 2003, pers. comm.).

droughts to impact the Southwest region in the past 2000 yr (Fig. 6).

The "Great Pueblo Drought," during the late 13th century, was registered at El Malpais (Fig. 6), and has been implicated in Anasazi migrations. Burns (1983) used tree-ring data and dryland crop yields from southwest Colorado to estimate reduced crop yields over the Four Corners region during the Great Drought. Salzer (2000) developed a long record of bristlecone pine growth for the San Francisco Peaks in northern Arizona and identified a period of extended warm-dry conditions during the late 13th century, contemporaneous with the Anasazi depopulation of the Colorado Plateau.

The 16th-century mega-drought at El Malpais may have been the most severe sustained drought to impact New Mexico in the last 2000 yr (Figs 2 and 6; Cook & Evans, 2000; Grissino-Mayer, 1996; Meko *et al.*, 1995; Stahle *et al.*, 2000). The summer PDSI reconstructions of Cook *et al.* (1999) cover most of the conterminous USA back to A.D. 1500 (114 out of 154 reconstructed grid points), with good chronology coverage over the Southeast and West. The onset and end of a prolonged drought can be difficult to specify, but a composite of 21 consecutive years during the heart of the mega-drought (A.D. 1567–1587) illustrates the magnitude of this drought that was centered over the southwestern USA (Fig. 2). However, the 16th-century mega-drought certainly did not end at the Mexican border (Fig. 2n). In fact, existing tree-ring data from Durango, Mexico (Stahle *et al.*, 2000), and a new chronology from Puebla, indicate that the mega-drought may have begun over the highlands of Mexico in the 1540's, and then may have expanded north and eastward to impact most of the continent before it played out in the 1590s.

The 16th-century mega-drought occurred at the dawn of European colonization in North America, but the available evidence indicates that there were significant socioeconomic and environmental impacts of this record drought. Some Tewa and Keres Pueblo villages were abandoned during this time, and may have been particularly vulnerable to prolonged drought because they depended on dryland farming (Schroeder, 1968). Taos Pueblo is believed to have been continuously occupied since the 15th century, and may have survived the drought with irrigation agriculture.

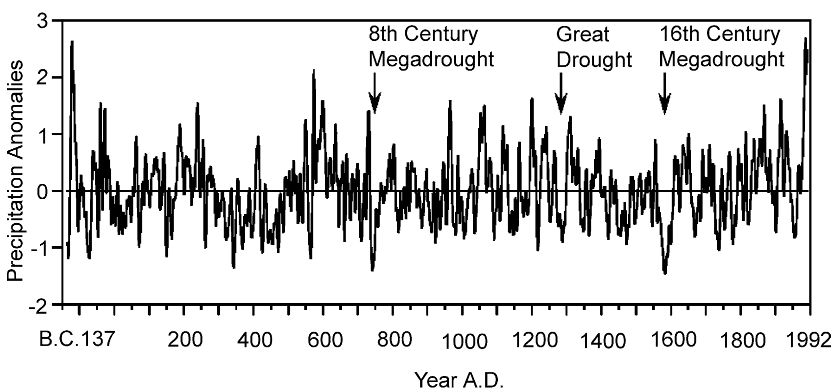


Fig. 6. The tree-ring reconstruction of annual precipitation at El Malpais, New Mexico (normalized units), based on ancient Douglas-fir trees and relic wood (Grissino-Mayer, 1996, 1997). The reconstruction has been smoothed to highlight decadal variability (as in Fig. 4).

The Spanish sphere of influence extended from Florida north into the Carolinas during the 16th century, and included the colony of Santa Elena on Parris Island, South Carolina. Santa Elena was occupied from A.D. 1565 to 1587, and documents survive which describe severe drought during the 1560s (Parr, 1999).

The year 1587 was momentous over the southeastern USA. Santa Elena was abandoned by the Spanish, and Sir Walter Raleigh's Lost Colony on Roanoke Island (North Carolina) disappeared from history. The tree-ring data indicate that A.D. 1587 was the driest year in 800 years in the Tidewater region, and the period A.D. 1587–1589 was the driest three-year episode in 700 years (Stahle *et al.*, 1998b). The Spanish and English colonist alike depended heavily on trade and tribute from the Native Americans, but the documentary record indicates that these tribesmen suffered heavily during drought. The fate of the Lost Colonists may be partly attributed to hardship arising from extreme drought, which may have been part of the continental-scale mega-drought of the 16th century extending into the eastern United States.

The most extreme consequences of the mega-drought during the tumultuous 16th century may have occurred in Mexico, where extreme drought interacted with conquest, colonization, enslavement of the native population under the encomienda system of New Spain, and with terrible outbreaks of epidemic disease to result in one of the great demographic catastrophes in world history (Acuna-Soto *et al.*, 2002). Precipitation estimates from tree-ring data for Durango, Mexico, indicates that the 16th-century mega-drought was the worst drought over Mexico in the past 600 years (Cleaveland *et al.*, 2003).

A wealth of historical, early instrumental, and proxy data enrich the study of the environmental and human impacts of climate extremes during the 19th century. West (1995) has described the 19th-century Cheyenne and Arapaho of the central High Plains as a people in crisis. West (1992) advanced the hypothesis that environmental cycles of wetness and drought interacted with emigration by Native Americans and Europeans, over-exploitation of bison, and the destruction of critical riparian habitat and to result in the disappearance of bison from the central High Plains by A.D. 1860. West (1995) cited tree-ring evidence for an extended wet period during the early 19th century, followed by intense and prolonged drought over the Central Plains as a key element in the bison population decline.

Fye *et al.* (2003) use the gridded PDSI reconstructions of Cook *et al.* (1999) to map the spatial structure of the early 19th century wet period over the central United States (Fig. 7, top). This pluvial period lasted from approximately 1825 to 1840, and was one of the longest and most widespread wet episodes over the United States in the last 500 years (perhaps second only to the early 20th-century pluvial period).

The environmental impact of the early 19th-century pluvial is only beginning to emerge. The longest fire-free interval in the composite fire-scar chronology for two Kipuka fire records from El Malpais National Monument occurred during the early 19th-century pluvial (Grissino-Mayer & Swetnam, 1997). The Kipuka fire record represents a very

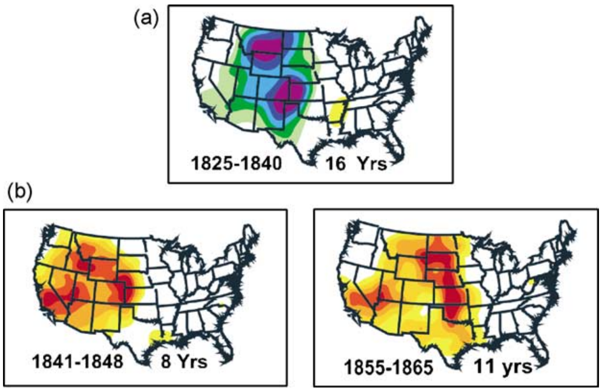


Fig. 7. The Cook et al. (1999) reconstructions of summer PDSI have been used to map the extended wet and dry regimes over the United States during the 19th century. The early 19th-century pluvial period appears to have had a large effect on ecosystem dynamics over much of the West (a), and the subsequent droughts (b) may have interacted with human activities to result in habitat degradation over the central High Plains (West, 1995).

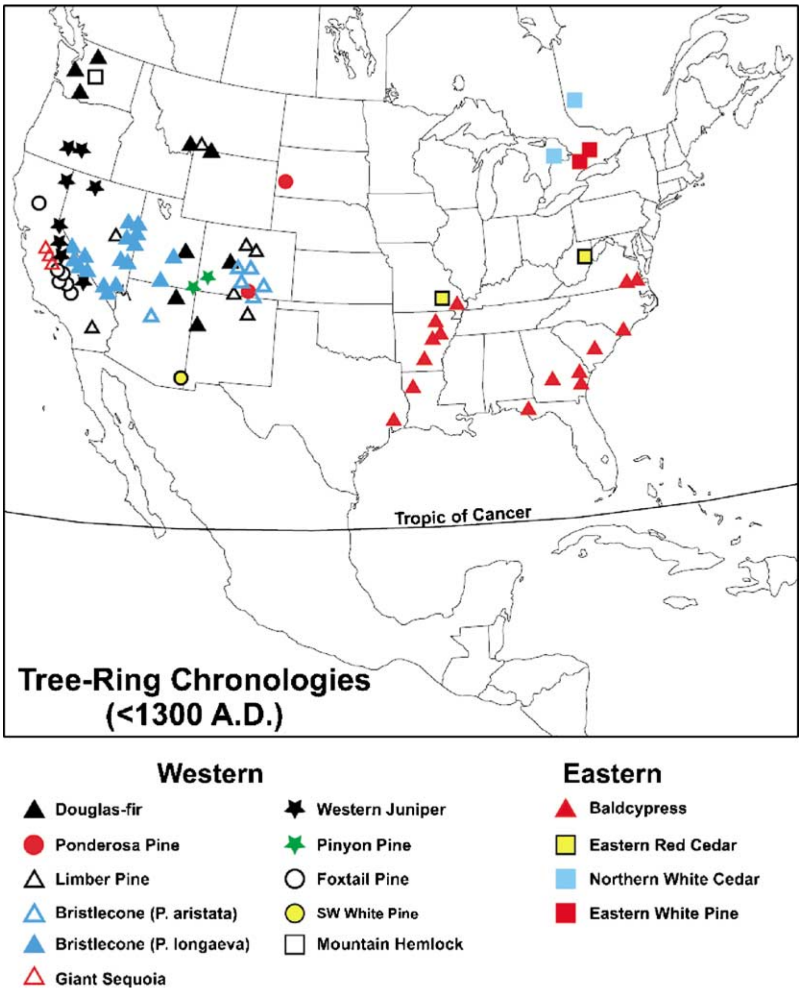
isolated habitat type and may be one of the only fire-scar chronologies in western North America without major anthropogenic effects on fire frequency. The wet conditions during the early 19th century were also reflected by abundant forage and large animal populations across the Central Plains (West, 1995). However, severe drought developed in the mid-1840s over Colorado and continued into the 1860s over portions of the Central Plains (Fig. 7; Woodhouse *et al.*, 2002). These dry conditions occurred while human and livestock utilization of the critical riparian corridors was increasing, and West (1992) argues that this convergence of events led to extensive deterioration of habitat and may have contributed to bison decline in the region.

Multi-Century Long Tree-Ring Chronologies

The remarkable sub-fossil tree-ring records from Western Europe now span the past 10,000 years, and include some of the longest tree-ring chronologies in the world (e.g. Briffa & Matthews, 2002; Leuschner *et al.*, 2002). But a well-replicated network of millennia-long tree-ring chronologies has also been developed for the western United States, including several exceptional lower-elevation bristlecone pine chronologies developed by Don Graybill (e.g. Graybill & Funkhouser, 2000). Other millennium-long tree-ring chronologies have been developed in the western United States for western juniper (Meko *et al.*, 2001), Foxtail pine (*P. balforiana*; Graumlich, 1993), Limber pine (*P. flexilis*; Schulman, 1956), and Douglas-fir (Grissino-Mayer, 1996).

Chronologies at least 700 yr long are located in Fig. 8, but Hughes & Graumlich (1996) report at least 80 tree-ring chronologies over 1000 yr long, and 22 chronologies over 2000 yr long from the greater Southwest. They also used the Methuselah Walk bristlecone chronology to develop an

Fig. 8. Same as Fig. 1, except only those chronologies dating before A.D. 1300 are included.



8000-yr-long annual precipitation reconstruction for southern Nevada, the longest calibrated tree-ring reconstruction yet produced. Hughes & Funkhouser (1998) selected a subset of six well replicated, climate-sensitive bristlecone pine chronologies at least 1700 yr long to repeat the precipitation reconstruction for southern Nevada, and identify extended dry periods from the 10th to 14th centuries that roughly correspond with geomorphologic evidence for low stands at Mono Lake reported by Stine (1994).

Brown *et al.* (1992) confirmed and expanded upon A.E. Douglass' classic tree-ring work with giant sequoia (*Sequoiadendron giganteum*). Three sequoia chronologies at least 2300 yr long, and a regional composite chronology 3200 yr long are now available for sequoia in central California. Due in part to strong fire-related impacts on growth, these remarkable sequoia chronologies are not linearly related to precipitation amounts. But Hughes & Brown (1992) used a threshold of low growth to construct an event chronology

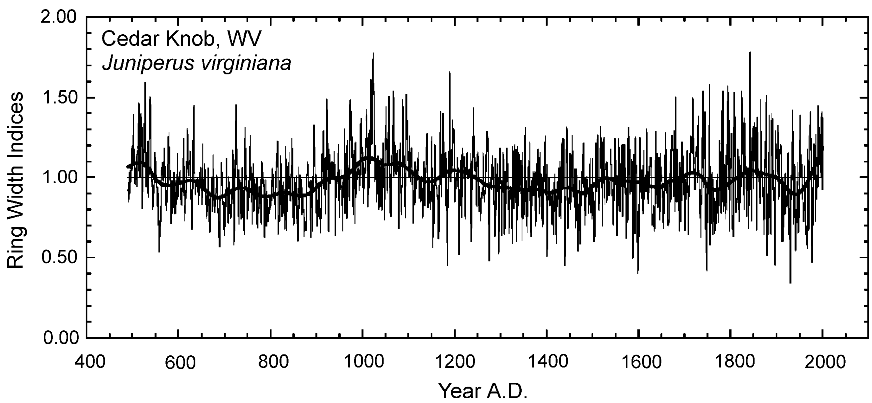


Fig. 9. The long tree-ring chronology of eastern red cedar from Cedar Knob, West Virginia, is plotted, along with a smooth curve highlighting century-scale variability in the time series (E.R. Cook & B. Buckley, pers. comm.).

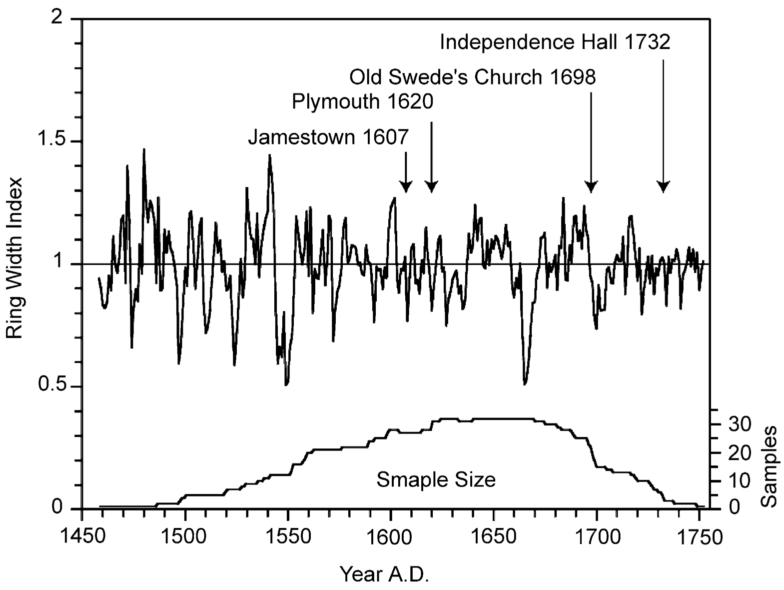


Fig. 10. The exactly dated composite tree-ring chronology developed from white oak timbers preserved in historic buildings at Philadelphia, Pennsylvania (E.R. Cook, personal communication). The changing sample size in the chronology, tree-ring dated construction episodes for selected structures, and other significant historical events are also noted.

of extreme drought over the Sierra Nevada for the past 2100 yr.

The longevity records of the western conifers are unmatched by species native to the eastern woodlands, but eastern species over 1000 yr old have been discovered, and chronologies 1500 to over 2000 yr long have been developed (Stahle *et al.*, 1988; Larson & Kelly, 1991). Currently there are 22 tree-ring chronologies that are at least 700 yr long, and ten that are over 1000 yr long in the eastern woodlands (Fig. 8).

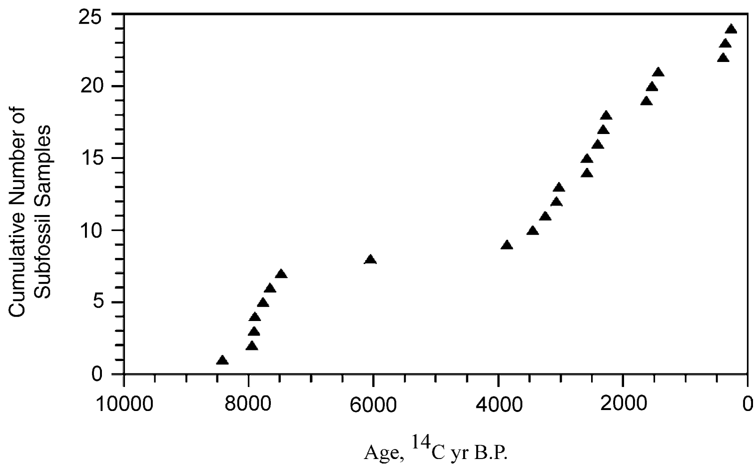
The longest tree-ring chronologies now available for the eastern woodlands have been developed from northern white cedar (*Thuja occidentalis*) found on limestone-dolomite cliffs and talus slopes of the Niagara Escarpment (Larson & Kelly, 1991). A 2787-yr-long white-cedar chronology has been developed from living trees and relic white-cedar wood on islands off the Bruce Peninsula in Lake Huron, and the outer well-replicated portion of this chronology has been calibrated with the Palmer drought index (B. Buckley pers. comm.). Ancient white-cedar sites extend from New England across the Great Lake region and promises to provide a new high-resolution climate record for the late Holocene.

Guyette *et al.* (1989) have developed an 850-yr-long red-cedar (*Juniperus virginiana*) chronology for the Missouri Ozarks, and another red-cedar chronology has recently been developed for Cedar Knob, West Virginia, that dates back to the 5th century A.D., using living trees and relic wood (Fig. 9). The Cedar Knob chronology has been processed to retain low-frequency variability (the RCS method), and appears to reflect the Medieval Warm Epoch, Little Ice Age, and the 20th century warming trend. The climate response of this chronology is still under investigation, but growing season length may partly explain the long-term trends (E.R. Cook, 2002, pers. comm.).

Blackgum (*Nyssa sylvatica*) may also contribute to the development of a network of multi-century tree-ring chronologies in the Northeast. Individual blackgum trees over 600 yr old have been found, making it one of the longest-lived hardwoods known (N. Pederson, pers. comm.).

Historic buildings across the eastern United States represent an important potential resource for long chronology development. The early historic buildings of the eastern United States were often constructed with native timbers cut

Fig. 11. The radiocarbon dates derived for 24 sub-fossil hardwood logs recovered from buried alluvial deposits in northern Missouri (after Guyette & Dey, 1999). Note the clusters of sub-fossil wood recovered from ca. 8000 ^{14}C yr B.P. and between 3500 and 2000 ^{14}C yr B.P.



from virgin forests, and some structures preserve valuable tree-ring records of climate variability for colonial and pre-colonial America (e.g. Therrell, 2000). The Tree-Ring Lab at Lamont-Doherty Earth Observatory is developing the early historic dendrochronology for the vicinity of Boston and Philadelphia. The master dating chronology for Philadelphia white oak timbers now dates back to A.D. 1460 (Fig. 10), and includes tree-ring samples extracted from the trusses in Independence Hall and other significant 17th and 18th century structures (E.R. Cook, pers. comm.).

Old logging debris and sub-fossil wood represent another important resource for developing long chronologies in the East. In fact, most long baldcypress, red-cedar, and white-cedar chronologies have been augmented and extended with relic or sub-fossil wood sometimes still found on the ground surface. Baldcypress sinker logs (cut logs lost during historic logging operations) and sub-fossil logs (natural deadfall) are often found submerged in river channels or swamps (Stahle & Cleaveland, 1992). Sinker logs and sub-fossil timbers are also occasionally found in the Great Lakes and other natural streams and lakes throughout the East. Guyette & Cole (1999) recovered well-preserved eastern white pine (*P. strobus*) logs from natural lakes in Ontario. These logs represent old-growth lake-margin pine that fell into the lake and were preserved. Using these timbers, Guyette & Cole (1999) have developed two long white-pine chronologies dating back to A.D. 982 and 1187.

Buried wood of great age has also been reported for several eastern species (e.g. Lyell, 1849), including sub-fossil hardwoods from late glacial and post-glacial deposits in Mississippi (Grissinger *et al.*, 1982; Jackson & Givens, 1994). Recently, Guyette & Dey (2000) have recovered quantities of course woody debris from small streams in the glaciated terrain of northern Missouri. The wood debris includes large logs to nearly whole trees, and is dominated by the genus *Quercus*. Radiocarbon dating indicates that the available samples span the past 8000 ^{14}C yr, with a cluster of samples dating near 8000 ^{14}C yr B.P. (Fig. 11). The prospects for developing an exactly dated, continuous chronology for 8000 ^{14}C yr from these buried timbers are daunting indeed, because most specimens contain only 100–200 annual rings, and because significant temporal gaps may have occurred in the deposition and/or preservation of this buried wood resource (R.P. Guyette, 2002, pers. comm.). However, the outstanding long sub-fossil oak and pine chronologies in Germany and Ireland were constructed from similar relatively short ring sequences, so a major chronology development effort with the buried wood resources in Missouri and Mississippi may well be justified.

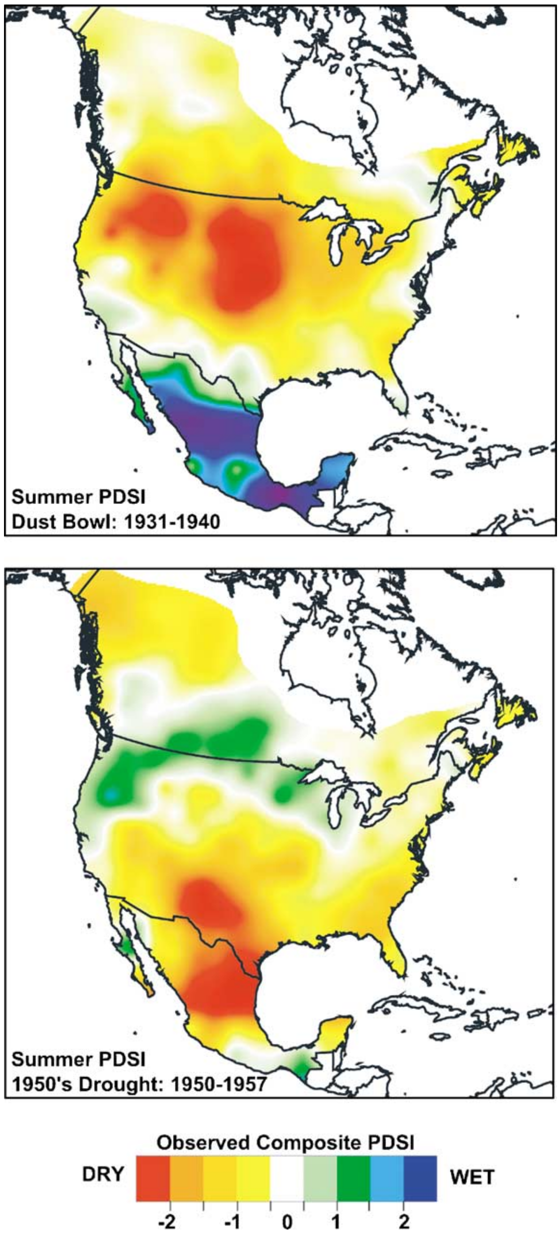


Fig. 12. The 2.5 × 2.5° latitude/longitude grid of instrumental summer PDSI data compiled for the United States, southern Canada, and Mexico by E.R. Cook (personal communication) have been used to map the 10-year average moisture anomalies across the continent during the Dust Bowl (1931–1940) and during eight years of the 1950's drought (1950–1957). Note the prolonged wetness in Mexico during the Dust Bowl drought, and over the northern United States and southern Canada during the 1950s drought.

Conclusions

The tree-ring community has been actively pursuing the development of long, climate-sensitive tree-ring chronologies in the United States, including novel species and habitat types. However, a comparison of the chronology network illustrated in Fig. 1 with the continent-scale moisture anomalies illustrated in Fig. 12 makes it clear that additional tree-ring chronology development across North America will be needed to capture the full spatial detail of the two most intense drought regimes of the 20th century, and presumably for many decadal extremes during the pre-instrumental era (e.g. Figs 2 and 3). For example, the composite maps of the instrumental summer PDSI network recently compiled by E.R. Cook (2002, personal communication) illustrate that the Dust Bowl drought of the 1930s was attended by wetness well above average in Mexico, while the decadal drought over the Tex-Mex sector in the 1950s included a pronounced band of persistent wetness across portions of the northern United States and southern Canada (Fig. 12).

The emerging continent-wide network of moisture-sensitive tree-ring chronologies (Fig. 1) will be exceptionally valuable for documenting the geographical impact and recurrence of great drought extremes. The hemispheric footprint of these decadal moisture regimes might also be used to constrain the concurrent large-scale ocean-atmospheric circulation (e.g. Fritts, 1976). But new chronologies are still needed in the United States (including Alaska), Canada, and Mexico to complete a representative hemispheric array. Much greater effort will also be needed to extend selected tree-ring records across the continent before A.D. 1600 when the variability of past climate appears to have been fundamentally greater at inter-annual and decadal timescales than that estimated for the past 400 years.

One of the most important applications of the North American tree-ring network has been to place the industrial era of anthropogenic climate modification into long-term perspective. Unfortunately, many of the chronologies located in Fig. 1 where collected in the 1980's and therefore do not represent the climate and environmental changes that have occurred in the last 20 years. The dendroclimatic community has focused primarily on expanding the geographic scope and time depth of this outstanding network. But to maximize the social and scientific value of this unparalleled array of natural environmental proxies we need to institute procedures and secure funding for the timely updating of selected high quality chronologies across North America to monitor climatic variability and change as they occur.

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