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Tree-ring Data Document 16th Century Megadrought Over North America

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The two most severe, sustained droughts in the continental United States during the 20th century occurred in the 1930s and 1950s. The 1950s drought was most extreme over the southwest and southern Great Plains, where ecological consequences are still evident on the landscape [*Swetnam and Betancourt*, 1998]. The Dust Bowl, vividly recounted in John Steinbeck's *The Grapes of Wrath*, was the nation's most severe, sustained, and widespread drought of the past 300 years, according to tree-ring reconstructions of the Palmer drought severity index (PDSI) across the continental United States [*Cook et al.*, 1999] (http://www.ngdc.noaa.gov/paleo/pdsiyear.html.

Droughts during the 1750s, 1820s, and 1850s-1860s estimated from tree rings were similar to the 1950s drought in terms of magnitude, persistence, and spatial coverage, but these earlier episodes do not appear to have surpassed the severity or extent of the Dust Bowl drought. However, longer tree-ring reconstructions of PDSI for the United States and precipitation for northwestern Mexico and western Canada indicate that the "megadrought" of the 16th century far exceeded any drought of the 20th century (Figure 1) [also see *Woodhouse and Overpeck*, 1998], and is considered to be the most severe prolonged drought over much of North America for at least the last 500 years [*Meko et al.*, 1995].

Cook et al. [1999] reconstructed summer (June-August) PDSI over the continental United States using a 2° x 3° latitude/longitude grid, and successfully calibrated and verified the reconstructions against instrumental PDSI data for 154 out of 155 possible grid points (failing only in peninsula Florida due to the absence of local tree-ring data). The PDSI reconstructions for all 154 grid points extend from at least A.D. 1700-1978, and place the 20th century into the context of the last 300 years. However, some drought-sensitive tree-ring chronologies extend well before 1700 and have been used to reconstruct summer PDSI back to A.D. 1500 or earlier for a reduced geographical suite of 96 grid points. These longer reconstructions cover the western United States, the Southeast, and the Great Lakes, and each grid site reconstruction passed the same set of calibration and verification tests performed on the fully replicated 1700-1978 network.

Figure 1 illustrates a representative selection of PDSI reconstructions for grid points covering most of the United States, along with a regional reconstruction of winter (November-March) precipitation for Durango, Mexico, and an annual (July-June) precipitation reconstruction for the Banff area in Alberta, Canada. These differences in seasonality are not as great as might appear because the "summer" PDSI integrates climate over the winter, spring, and summer seasons, and most of the western conifer chronologies are sensitive to winter precipitation in spite of their calibration with summer PDSI. All reconstructions of PDSI and precipitation were normalized and then smoothed with cubic splines to highlight decadal trends in drought (Figure 1).

The 16th and 20th centuries are compared with the available tree-ring reconstructions of PDSI or precipitation in Figure 1. The smoothed estimates indicate that drought conditions were prevalent throughout the 16th century over the Sierra Madre Occidental, Rocky Mountains, and Mississippi Valley, but they also show that the era of persistent drought developed in the 1540s, especially over northwestern Mexico (a severe megadrought is also reconstructed at this time for summer precipitation over Durango). The most intense episode of drought occurred over Mexico in the 1560s, and appears to have then spread to the north and east during the later half of the 16th century (Figure 1). The drought persisted in these decadally smoothed reconstructions from the 1540s to 1580s in Mexico, from the 1550s to 1590s over the Southwest, and from the 1570s to 1600s over Wyoming and Montana. Severe drought extended across most of the continental United States during the 1560s. Drought developed in the Mississippi Valley and Southeast during the 1560s and recurred with greater intensity over the Southeast during the 1580s to 1590s (Figure 1).

The precipitation reconstruction for Alberta also indicates extended drought during the late 16th century (Figure 1), but the severity, persistence, and spatial extent of this western Canadian drought is still in doubt, due in part to limited drought-sensitive tree-ring data for the 16th century. We also caution that the variance of the 16th century PDSI reconstruction for the Great Lakes sector (Figure 1) may be inflated by low tree-ring sample size.

These reconstructions suggest that the droughts of the 16th century exceeded the severity, persistence, and coverage of any drought witnessed in the United States during the period of instrumental meteorological or hydrological observation [see *Woodhouse and Overpeck*, 1998]. Tree-ring reconstructed drought during the 1930s exceeded the 16th century droughts only in the Pacific Northwest and western Canada. However, tree-ring data of sufficient length are not available for most of the Great Plains, and hydroclimatic impacts of the 1930s drought were most severe over the central and northern Great Plains. Nevertheless, for the large portions of North America covered by these tree-ring reconstructions, the 19th and 20th century period of meteorological and hydrological observation does not appear to represent the extreme drought conditions that have occurred under natural climatic conditions during the past 500 years.

The entire reconstructed time series of PDSI and precipitation are displayed for selected locations in Figure 2 (10-year spline smoothing). These time series make it clear that the 16th century drought was the most severe and sustained dry event recorded by tree-ring data in northwestern Mexico, the Southwest, Colorado, and Missouri from A.D. 1500 to present.

Droughts of equal or even greater severity and persistence are evident in these reconstructions at other times (Figure 2), but most of these examples predate 1500 and may be biased by low tree-ring sample size (for example, note the inflated variance and greater persistence in the decadal reconstructions for Colorado and New Mexico prior to 1500 in Figure 2). No other prolonged drought evident from A.D. 1200 to present in these selected reconstructions appears to match the intensity, persistence, and spatial coverage of the 16th century megadrought (Figure 2). The El Malpais precipitation reconstruction for western New Mexico (Figure 3) suggests that the 16th century drought was the most extreme prolonged drought in the past 2000 years [*Grissino-Mayer*, 1996], and this is supported for the past 1000 years by the precipi-

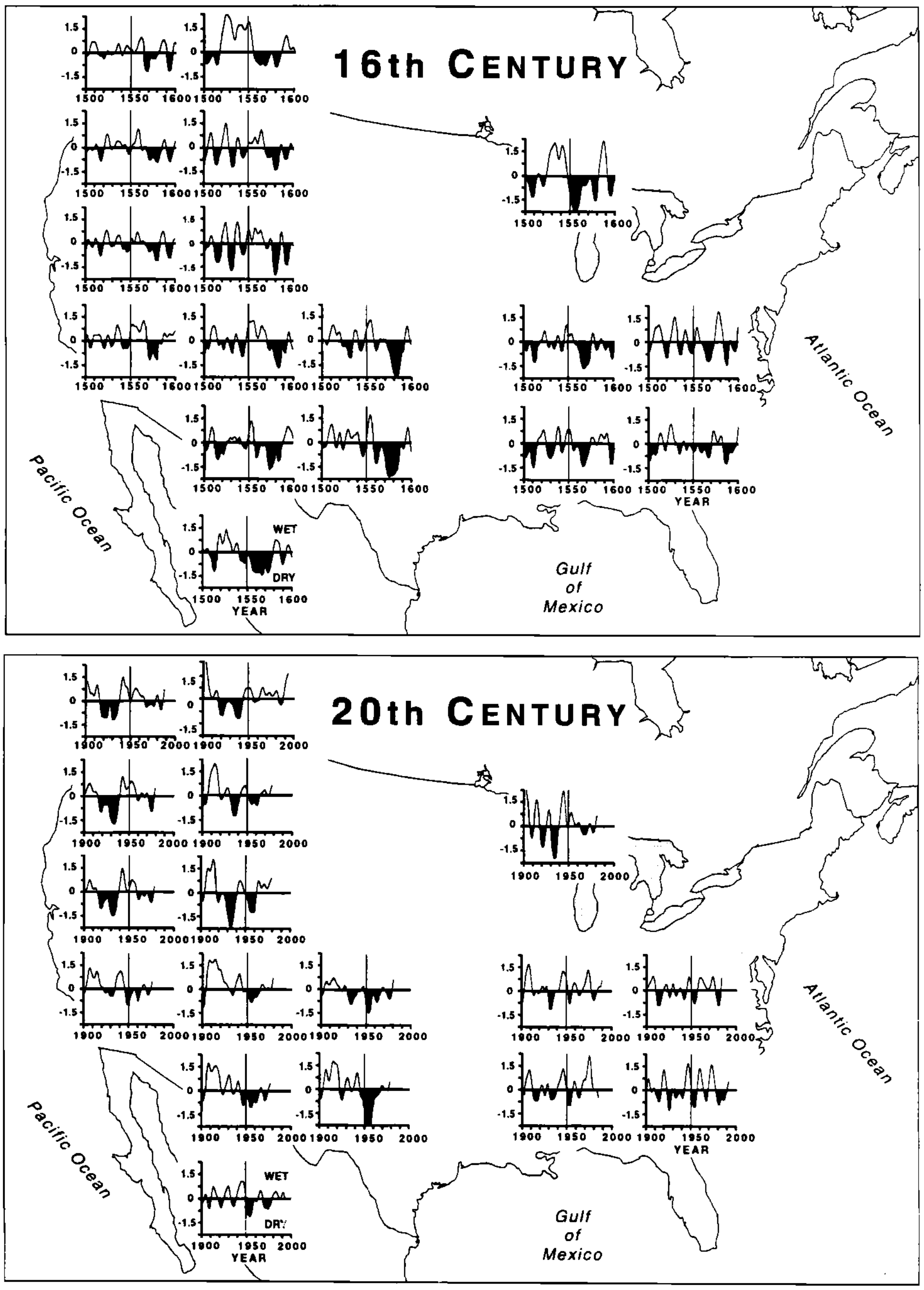

Fig. 1. The tree-ring reconstructed megadrought of the mid- to late-16th century over much of North America (top) is compared with tree-ring reconstructed drought and wetness during the 20th century (bottom). All reconstructions have been smoothed to highlight decadal variability and represent the PDSI, except in Mexico and western Canada (second column from left, upper time series), which are estimates of precipitation. All reconstructions have been normalized (plotted in standard deviation units) and smoothed to highlight decadal variability. Black shading emphasizes dryness. The time series are placed on the map close to their true geographical position.

tation reconstruction at Arroyo Hondo in northern New Mexico [*Meko et al.*, 1995].

The human impact of the epic 16th century drought must have been substantial across much of North America. This extreme event was certainly recorded in the Carolinas and Virginia at the early Spanish and English settlements in the New World. Tree-ring data indicate that drought lasted from 1559 to 1569, and then returned again in the 1580s. The Spanish colony of Santa Elena on Parris Island, South Carolina, was established in 1565. Archival records indicate that they experienced extreme drought and hardship from 1566 to 1569, highlighted by Juan Pardo's expedition into the interior to forage for food and seek tribute from the native chiefdoms [*Anderson et al.*, 1995]. Pardo dispersed his forces into a series of small forts along his route to relieve food pressure on the main force and on Santa Elena itself. However, these forts were soon destroyed and the occupants were all massacred. The Santa Elena Colony was finally abandoned in 1587, year of the most severe drought in 800 years over the Tidewater region of the Carolinas and Virginia, according to tree-ring records. It was also the same year that Sir Walter Raleigh's English colony on Roanoke Island disappeared from history [*Stahle et al.*, 1998]. The striking agreement between the tree-ring estimates of drought and the first-hand accounts of the Spanish leave little doubt that these precarious settlements, and the native chiefdoms from which they attempted to extract tribute, were seriously affected by the extraordinary droughts of the 16th century.

The 16th century drought was most extreme and prolonged over the Southwest and northern Mexico (Figures 1, 2, and 3), and in New Mexico, where "almost a dozen pueblos were permanently abandoned between 1540 and 1598, but not from causes attributable to the Spaniards" [*Schroeder*, 1968]. Citing tree-ring evidence, Schroeder concluded that severe drought was the most probable cause of these migrations, in part because the abandoned pueblos depended on dry farming technology.

In Zacatecas and Durango, Mexico, the Chichimeca War began in 1550 and "for forty years it raged on as the longest and most costly continuous conflict between European settlers and Native Americans" [*Naylor and Polzer*, 1986]. The fierce Chichimecs attacked the Spanish pack trains and settlements on the silver mining frontier, which had extended into the heart of their territory, and forced the Spanish to install a presidio and militia system along the silver trade routes. The mere coincidence of the war with the most extreme regional drought in 600 years (Figures 1 and 2) suggests that drought may have played an important and previously unrealized role in

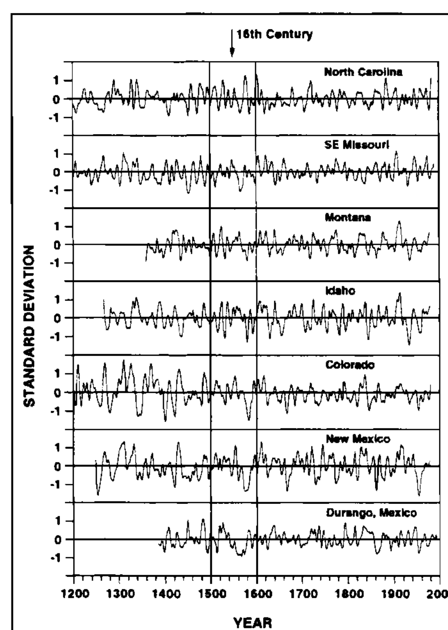

Fig. 2. Tree-ring reconstructions of PDSI (and precipitation in Durango only) for selected locations shown in Figure 1 (all decadally smoothed). The 16th century drought was the most severe and sustained drought from A.D. 1500 to present for Durango, New Mexico, Colorado, and Missouri, and was one of the worst droughts recorded in all of these selected time series (the amplitude and persistence of these estimates appear to be artificially inflated prior to 1500 for some reconstructions, probably by declining sample size).

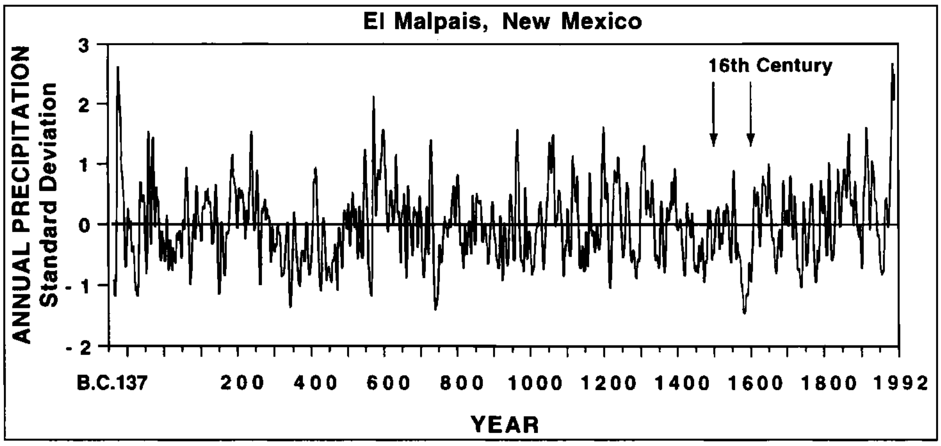

Fig. 3. The normalized and decadally smoothed tree-ring reconstruction of annual (July-June) precipitation over northwestern New Mexico based on ancient Douglas-fir from El Malpais [Grissino-Mayer, 1996]. *This reconstruction dates from 137 B.C. to 1992, but the variance of estimates prior to A.D. 600 may also be inflated by low sample size. Nevertheless, the epic drought of the 16th century stands out as the most severe sustained drought in this region for the past 1500 years, and perhaps for the past 2000 years. The unprecedented growth and reconstructed high precipitation after 1976 is part of a regionwide growth surge in conifer chronologies in Arizona and New Mexico. Winter-spring precipitation has been enhanced over the Southwest after 1976, and may partly reflect persistent warm conditions in the equatorial Pacific. However, the post-1976 increase in regional precipitation does not appear sufficient to explain the unprecedented surge in tree growth, and complex ecological and anthropogenic factors may also be involved* [Swetnam and Betancourt, 1998].

the initiation and perpetuation of hostilities. The annually resolved tree-ring reconstruction for Durango indicates that 9 of the 10 years prior to 1550 were dry (1540-1549), and 27 of the 40 years from 1550 to 1589 were also dry.

Careful case studies of prolonged drought in the modern, colonial, and prehistoric record are needed to document the occurrence of these climatic extremes, and to evaluate possible mechanisms for their development and persistence. Considering the epic proportions of the 16th century drought, especially in the southwestern United States and Mexico, it is difficult to ignore possible forcing from the equatorial Pacific. The reconstructed mean PDSI or precipitation for the 16th century (1500-1600) is lowest in northern Mexico, the Southwest, lower Mississippi Valley, and Georgia, which roughly coincides with the region of subtropical North America having the strongest and most consistent ENSO teleconnection today. Drought conditions are prevalent over this sector during La Niña events. It is therefore reasonable to hypothesize that extreme or prolonged cold conditions in the eastern equatorial Pacific, perhaps coincident with a cool phase of the Pacific Decadal Oscillation, may have played a role in the development and persistence of the 16th century drought.

The apparent migration of megadrought in time and space is also extremely interesting (Figure 1), but not easily explained. Coincidence alone could account for the development of drought in Mexico and its subsequent occurrence further north and east later in the 16th century. But the possible migration of prolonged drought may also have had a dynamical component. The decade-scale propagation of the sea-surface height and temperature anomaly associated with the 1982-1983 warm event into the western and northern Pacific [*Jacobs et al.*, 1994] provides an interesting (inverse) example of the long-term ocean wave dynamics that might prolong climate anomalies and shift their geographic focus. The validity of this persistent cold phase hypothesis, and its implication as a mechanism behind the prolonged 16th century drought, might be testable in the proxy records of sediments, ice sheets, corals, and tree rings from the equatorial Pacific region, and also amenable to experiment with coupled climate models. If a prolonged cold phase did occur during the mid-16th century, such an intense anomaly should be evident in many proxies.

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