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Tree-ring reconstructed megadroughts over North America since A.D. 1300

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Abstract Tree-ring reconstructed summer Palmer Drought Severity Indices (PDSI) are used to identify decadal droughts more severe and prolonged than any witnessed during the instrumental period. These "megadroughts" are identified at two spatial scales, the North American continental scale (exclusive of Alaska and boreal Canada) and at the sub-continental scale over western North America. Intense decadal droughts have had significant environmental and socioeconomic impacts, as is illustrated with historical information. Only one prolonged continent-wide megadrought during the past 500 years exceeded the decadal droughts witnessed during the instrumental period, but three megadroughts occurred over the western sector of North America from A.D. 1300 to 1900. The early 20th century pluvial appears to have been unmatched at either the continental or sub-continental scale during the past 500 to 700 years. The decadal droughts of the 20th century, and the reconstructed megadroughts during the six previous centuries, all covered large sectors of western North America and in some cases extended into the eastern United States. All of these persistent decadal droughts included shorter duration cells of regional drought (sub-decadal $\approx$ 6 years), most of which resemble the regional patterns of drought identified with monthly and annual data during the 20th century. These well-known regional drought patterns are also characterized by unique monthly precipitation climatologies. Intense sub-decadal drought shifted among these drought regions during the modern and reconstructed multi-year droughts, which prolonged large-scale drought and resulted in the regimes of megadrought.

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1 Introduction

The Dust Bowl drought of the 1930s and the Southwestern drought of the 1950s were the two most intense and prolonged droughts to impact North America during the 20th century period of instrumental weather observation (Worster 1979; Diaz 1983; Fye et al. 2003). Long-term tree-ring data suggest that these 20th century events may have been exceeded in severity and duration by multidecadal droughts of the recent past, including the 16th century “megadrought” which may have been the most extreme drought to impact North America in the last 500 years (Meko et al. 1995; Stahle et al. 2000). This multidecadal drought was temporally and spatially complex, but during the mid- to late-16th century drought extended across most of the North American continent. The recurrence of multidecadal droughts at large sub-continental to continental scales would have serious socioeconomic and environmental impacts, and raise fundamental questions concerning the possible internal or external mechanisms of climate variability that might initiate and perpetuate megadrought simultaneously across multiple climatic provinces and over several large river basins.

In this paper we use an expanded grid of tree-ring reconstructions of the summer Palmer drought severity indices (PDSI; Cook et al. 2004) covering the United States, southern Canada, and most of Mexico to examine the timing, intensity, and spatial distribution of decadal to multidecadal moisture regimes over North America. We discuss the socioeconomic significance of the moisture regimes and include historical examples that provide some qualitative validation for the PDSI reconstructions in the pre-instrumental era. Due to the declining sample size and decreasing spatial coverage of long moisture-sensitive tree-ring chronologies, two spatial–temporal scales are analyzed: the last 500 years for most of North America (“continental” scale), and the last 700 years for western North America (“sub-continental” scale; Fig. 1a). We do not analyze the Medieval era (± 800–1300) because the sparse proxy network and large magnitude droughts of that era (Cook et al. 2004) make unbiased spatial comparisons difficult. Simple objective definitions of the terms “megadrought” and “pluvial” are adopted in this analysis, which may facilitate comparisons between the reconstructed PDSI regimes and other paleoclimatic estimates and simulations based on climate models.

2 Observed and tree-ring reconstructed PDSI for North America

Cook et al. (2004) have used 835 tree-ring chronologies to reconstruct the PDSI on a 2.5°× 2.5° latitude/longitude grid covering the United States, southern Canada, and Mexico north of Chiapas and the Yucatan (hereafter referred to as North America; Fig. 1a). The gridded instrumental PDSI data for Canada and the United States were calculated from single-station precipitation and temperature records in the historical climatology network and then interpolated to the grid using inverse distance weighting (Cook et al. 2004). The Mexican PDSI data were obtained from the PDSI grid for global land areas (Dai et al. 1998) and then heavily screened for statistical outliers and discontinuities in the monthly records. Optimal interpolation was used on a regional, sub-continental basis to estimate missing monthly values for some grid points in Mexico and Canada and to extend all 286 North American grid points back to 1900 (Cook et al. 2004).

The network of tree-ring chronologies used in the Cook et al. (2004) reconstructions is the combined work of the dendrochronological community over the past 30 years and earlier. It includes individual tree-ring chronologies that are 245- to over 2000-years in

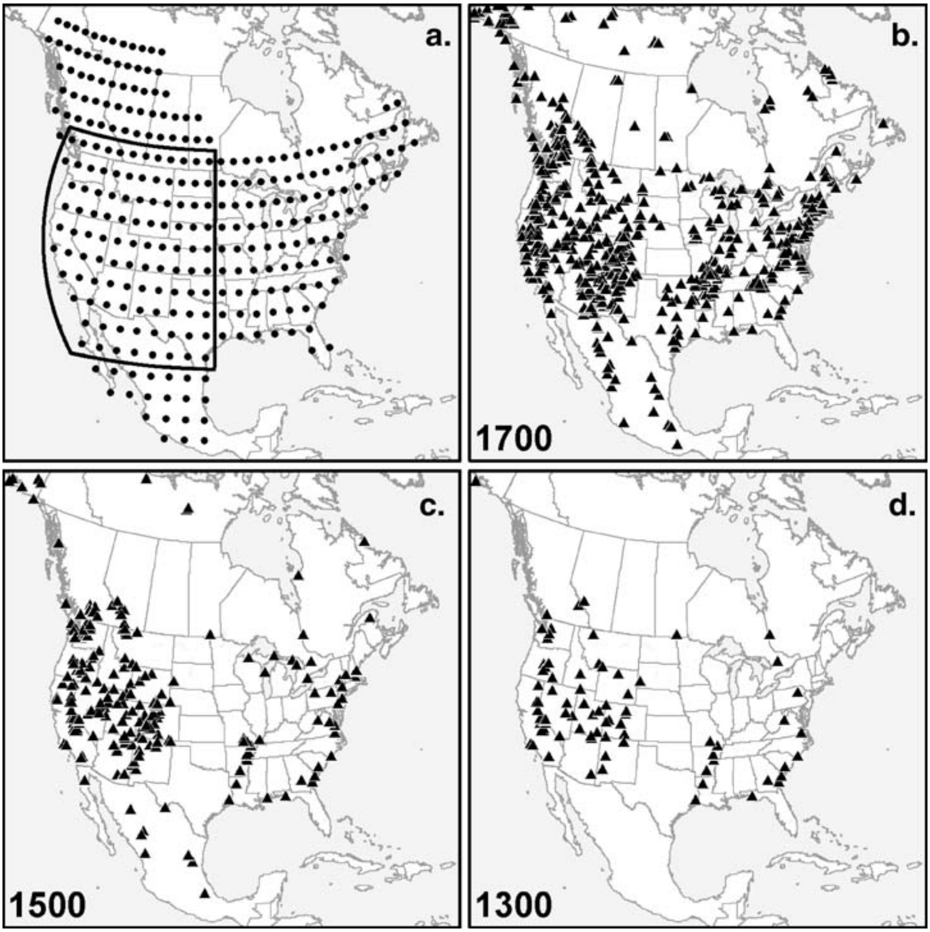

Fig. 1 (a) The 286 grid points used by Cook et al. (2004) to reconstruct summer PDSI over North America. The sub-continental region referred to as "the West" includes 103 grid point reconstructions (*box*). The tree-ring chronologies for North America (excluding Alaska and northwest Canada) used to reconstruct gridded summer PDSI are located for all series dating back to at least A.D. 1700 (b), 1500 (c), and 1300 (d)

length. The median length of these chronologies is 421 years and all end no earlier than A.D. 1979. There are now 929 chronologies from 711 separate locations that extend back to 1700, 286 back to 1500, and 97 back to 1300 (including multiple chronologies from some sites, Fig. 1b, c, and d). The tree-ring community continues to add to this network, but much more work is needed to fill spatial voids, particularly prior to A.D. 1700.

A point-by-point (PPR) principal components regression method was used to reconstruct summer (JJA) PDSI at each grid point from the nearest available tree-ring chronologies (Cook et al. 1999, 2004). All tree-ring chronologies extend outward to at least 1978. But because the inner date of the tree-ring chronologies near each grid point varies, several nested principal components regression models were developed for each segment of the reconstruction with a different sample size (of tree-ring chronologies), and the estimates of summer PDSI from this set of time-varying models were then linked into a single long time series of reconstructed summer PDSI for each grid point. All PPR models were calibrated with the instrumental PDSI data from 1928–1978, and were validated against the instrumental PDSI from 1900–1927 at each grid point. The tree-ring data successfully calibrate and verify against the instrumental PDSI at all grid points in the United States (except near Ft. Lauderdale, Florida) and at most grid points in Canada and Mexico, with an average calibration period variance explained of 0.45 and an average verification period Pearson correlation coefficient (squared) of 0.40, both of which are higher on average over the West. A total of 286 grid points in North America have been reconstructed back to A.D. 1500, and 103 grid points in "the West" back to 1300, in spite of the decline in the sample size of predictor tree-ring chronologies. The variance of each grid point reconstruction was restored to match the variance of instrumental summer PDSI at the same grid point during the calibration period.

3 Historical validation and socioeconomic significance of the PDSI reconstructions

The regional averages of instrumental and reconstructed summer PDSI are well correlated at the continental and sub-continental scale during the 20th century (Fig. 2). The decadal droughts of the 1930s and 1950s dominate the observed PDSI time series, and the tree-ring reconstructions faithfully reproduce the decadal variability in these large-scale time series (Fig. 2) even though they were estimated on the basis of annually-resolved data reconstructed at each of the 286 regional grid points (Cook et al. 2004).

The instrumental and tree-ring reconstructed PDSI at each grid point have been averaged and mapped for the decadal droughts of the 1930s and 1950s (Fig. 3). In both cases, the tree-ring data provide reasonable estimates of the spatial pattern and severity of these famous 20th century drought episodes, including the shifting epicenters of drought at sub-decadal (6-year) timescales within these prolonged decadal droughts. These results indicate that the tree-ring reconstructions of the 1950s and 1930s decadal droughts are reliable and can be used to compare these famous 20th century events with tree-ring evidence for prolonged droughts in the pre-instrumental era.

The accuracy of the PDSI reconstructions in the pre-instrumental period can also be validated on a qualitative basis with historical information. There are many interesting parallels between the tree-ring estimates of past moisture extremes and historical records on social and environmental impacts. There are also notable disagreements between tree-ring reconstructed summer PDSI and known historical events. These disagreements may highlight reconstruction errors or the simple fact that the tree-ring data integrate moisture conditions during and sometimes preceding the growing season, and may not well represent fall or winter conditions. The integration of the PDSI reconstructions with historical information on environmental conditions and the activities of Euroamerican and Native American societies is a largely unexploited opportunity that promises significant new insight into American history and environmental change (e.g., West 1995; Stahle et al. 1998).

Three extreme years during the 19th century vividly illustrate the promise and challenge of this proxy climate integration with the historical record. The tree-ring reconstructions of continent-average summer PDSI for North America indicate that 1833 was the wettest single year in the past 500 years, with extreme to severe wetness extending from the Great Plains into central Mexico (Figs. 4a and 5a). This extraordinary event was known as the year of "the Great Overflow" among the American settlers in central Texas, when heavy rains and extreme high water conditions were reported from March until late June (Geiser 1937:75). In eastern Oklahoma and western Arkansas, record flooding occurred on the Arkansas, Canadian, and Verdigris Rivers during the first week of June 1833. Large parties of Creek

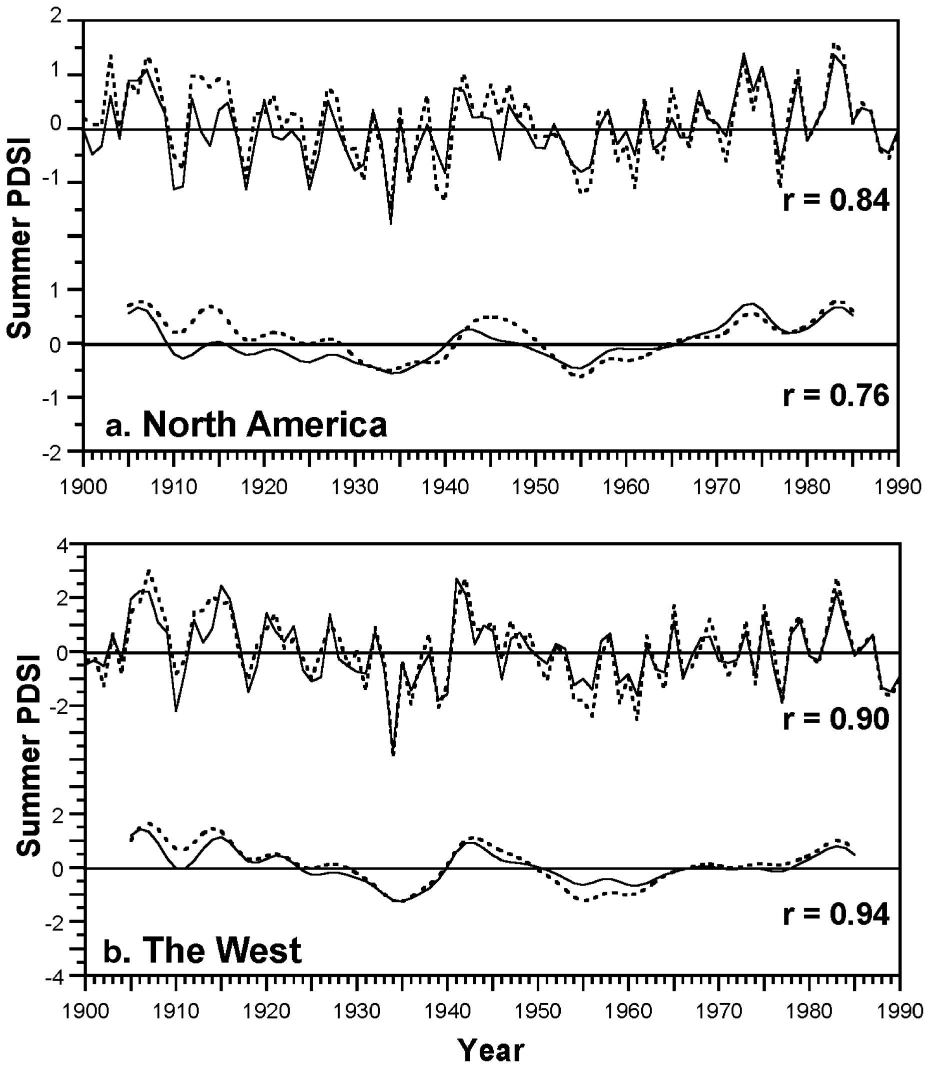

Fig. 2 (a) Time series of instrumental (*solid line*) and tree-ring reconstructed (*dashed line*) summer PDSI from 1900–1990 averaged for all 286 North American grid points [annual values (*top*) and Julian filtered 10-year smooth values (*bottom*)]. (b) The same type of time series were also computed for just the 103 grid points over western North America [annual values (*top*) Julian filtered 10-year smooth values (*bottom*)]

and Seminole were recently forced into Indian Territory on the "Trail of Tears," and 950 native people were drowned on their newly established floodplain farmsteads (Foreman 1934), a tragic confirmation of the record wetness reconstructed by tree rings for 1833.

The summer of 1855 was known among the Kiowa of the southern Great Plains as the "summer of sitting with legs crossed and extended" (Mooney 1979:300). A calendar history of the Kiowa was recorded by Set-tan, or Little Bear, for 60 years from 1833 to 1892. The Set-tan calendar included winter and summer counts, and each season was annotated by the most unusual or memorable event of the season, including battles, notable deaths,

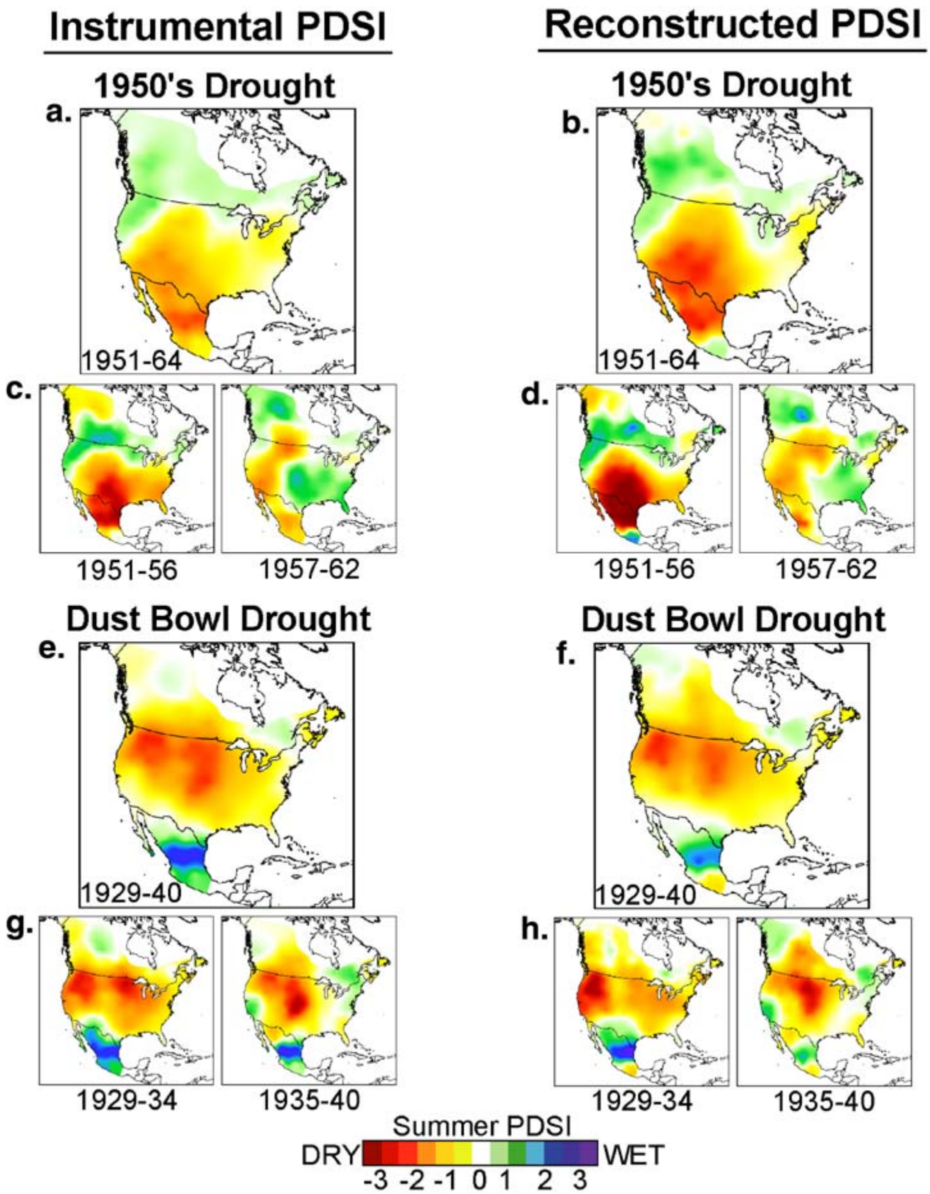

Fig. 3 Instrumental and tree-ring reconstructed summer PDSI were averaged at each grid point and mapped for the 1950s and 1930s droughts (1951–64 and 1929–40, respectively, a, b, e, f). The tree-ring reconstructions reproduce the spatial patterns of the 1950s and 1930s droughts, but over-emphasize the 1950s drought (Figs. 3a vs. 3b and 3e vs. 3f). Each decadal drought regime was split in half, and shorter sub-decadal averages were computed and mapped (1951–56 and 1957–62; 1929–34 and 1935–40). The 1950s and 1930s droughts both included distinctive sub-decadal regional drought cells that are well replicated with the tree-ring reconstructions (Figs. 3c vs. 3d and 3g vs. 3h)

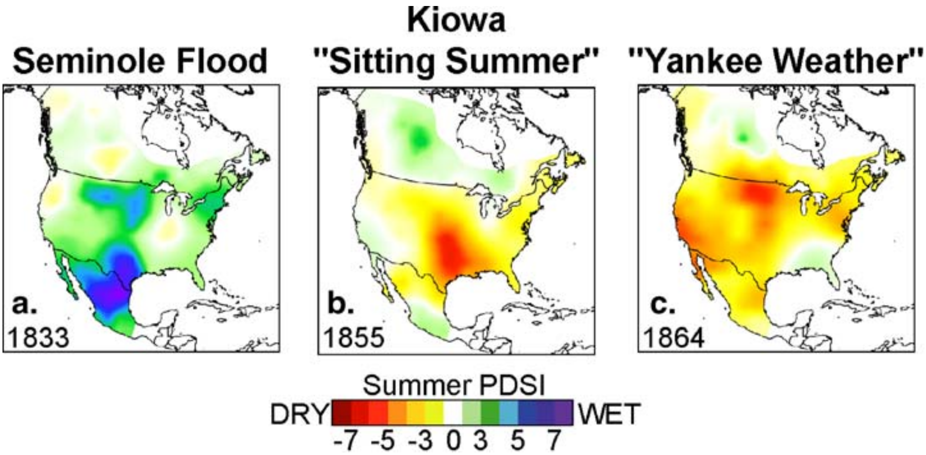

Fig. 4 Tree-ring reconstructed summer PDSI mapped for the extremely wet year of 1833 when severe flooding drowned many Creek and Seminole people in eastern Oklahoma (a); the severe Southern Plains drought of 1855 known among the indigenous Kiowa as the "sitting summer" (b); and for the extraordinary continent-wide drought of 1864 during the American Civil War (c)

epidemics, sun dances, and sometimes the weather. Drought conditions were recorded among the Kiowa during the summer of 1855 (Mooney 1979). The weather was reported to have been extremely hot, the prairie grasses were dried out, and their horses were emaciated. The nomadic Kiowa were frequently obliged to stop and rest their weakened horses (Mooney 1979). The "sitting summer" of the Kiowa independently supports the tree-ring reconstructions for 1855, which was estimated to have been one of the most extreme dry summers of the past 500 years across the southern Great Plains (Fig. 4b; Stahle and Cleaveland 1988).

The driest single year in the continent-wide reconstructions since A.D. 1500 occurred in 1864 (Fig. 5a), when Sherman's famous March to the Sea from Atlanta to Savannah, Georgia, was favored in part by "Yankee Weather" (Ludlum 1968). Dry, warmer than normal weather prevailed during the Union army's march in November and December of 1864. However, the tree-ring data estimate moderate to severe drought over most of the continent, but incipient wetness over Georgia and the Southeast (Fig. 4c). Most of the tree-ring data used to reconstruct summer PDSI in the Southeast are primarily sensitive to precipitation and temperature during the March–June growing season and do not represent conditions during the fall and winter (e.g., Stahle and Cleaveland 1992). The incipient wetness indicated by the tree-ring data for the summer of 1864 over Georgia must have deteriorated by late autumn when dry weather and low rivers levels were encountered by the Union army.

Prolonged droughts in the tree-ring reconstructions of summer PDSI have been compared with historical information on social and environmental conditions by Stahle and Dean (2007) and Cook et al. (2007), including the megadroughts identified in Table 1. The 19th century megadrought over the West has been associated with natural and anthropogenic environmental damage and bison decline by West (1995). The 16th century megadrought across North America impacted English and Spanish colonies, particularly in Mexico where drought interacted with social change and epidemic disease during one of the most catastrophic demographic declines in human history (Acuña Soto et al. 2002). The

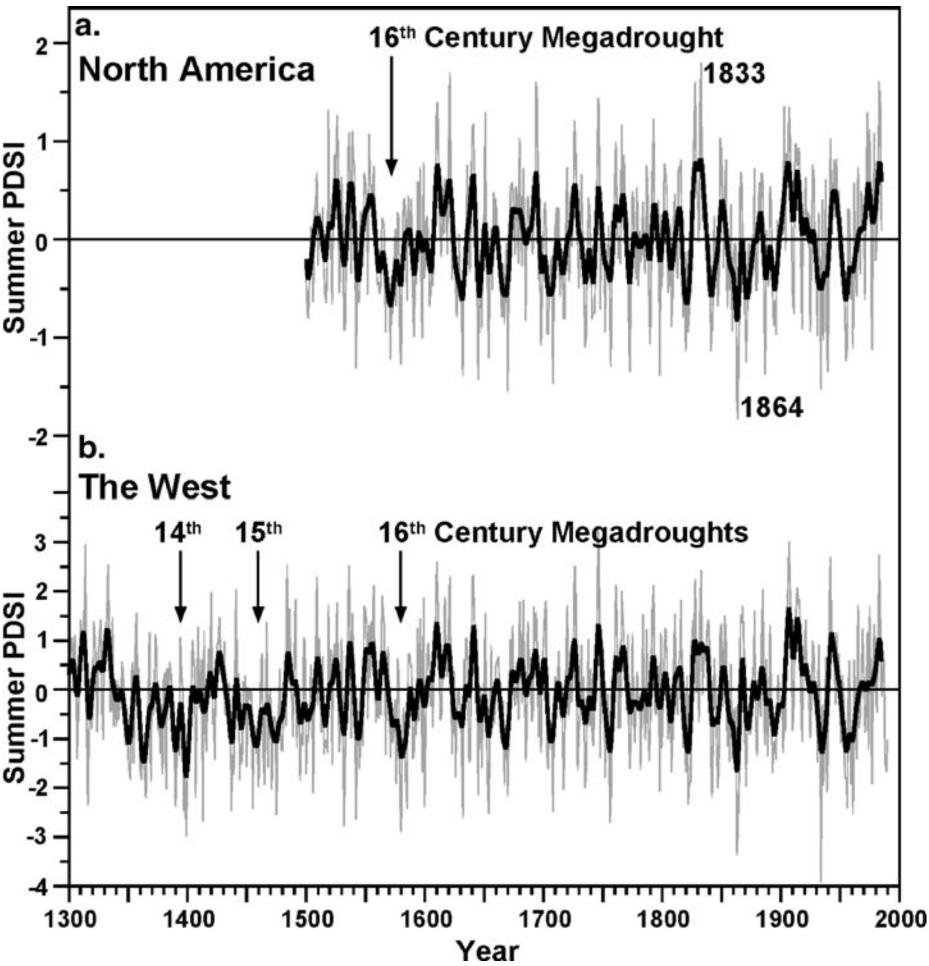

Fig. 5 (a) Time series of the tree-ring reconstructed summer PDSI averaged for all 286 grid points across North America from A.D. 1500–1990 (annual and decadally-smoothed using the Julian filter). Note the 16th century megadrought and that 1833 was the wettest year and 1864 was the driest year in these estimates. (b) Same as (a), averaged for the 103 grid points restricted to western North America, dating from A.D. 1300–1990. Note the western megadroughts during the 14th, 15th, and 16th centuries

severe decadal droughts over the central United States during the 15th and 14th centuries may have contributed to the decline of Mississippian agricultural societies (Cook et al. 2006), and appears to have shaped the age structure of the old-growth cypress forests along Bayou DeView, Arkansas, the rediscovery site of the endangered ivory-billed woodpecker (Stahle et al. 2006).

4 A simple operational definition for megadrought

To simply and objectively define the start and end dates of multi-year droughts in the modern and pre-instrumental periods, we use the time interval when the decadally-smoothed *reconstructed* summer PDSI remains at or below average during each event (based on the mean of the calibration period, 1928–1978). Decadal smoothing was calculated with the Julian symmetrical low-pass filter (Julian and Fritts 1968; Fritts 1976) slightly modified as follows:

$$\text{Smoothed PDSI} = 0.2256P_{t=0} + 0.1933P_{t=1,t=-1} + 0.1208P_{t=2,t=-2} + 0.0537P_{t=3,t=-3} + 0.0161P_{t=4,t=-4} + 0.00033P_{t=5,t=-5}$$

where t = year and P = summer PDSI for the same year. The resulting smoothed time series is very similar to decadal smoothing accomplished with a cubic smoothing spline, where the 50% variance reduction criteria is set at a period of 10 years (Cook and Peters 1981). We estimate the magnitude of modern and pre-instrumental drought regimes simply by adding the annual reconstructed summer PDSI for the same years when the decadally-smoothed PDSI were at or below average (or were above average for wet regimes).

By these simple criteria, the tree-ring reconstructed Dust Bowl drought at the continental scale lasted 12 years from 1929 to 1940, and the Southwest drought lasted 14 years from 1951 to 1964 (Table 1, Fig. 2). Earlier drought regimes defined at the continental, and sub-continental scale for the West, are also listed in Table 1. For both spatial scales, we use the *tree-ring reconstructions* to define the duration and magnitude of the Dust Bowl, 1950s, and early 20th century events so direct comparisons can be made with decadal moisture regimes reconstructed during the pre-instrumental era.

To compare the spatial impact of these epic 20th century moisture regimes with previous events, the instrumental and reconstructed summer PDSI data were averaged at each grid point from 1929–1940 and from 1951–1964, and the resulting gridded averages were mapped over North America (Fig. 3; grid point data interpolated to color maps using the thin plate spline, Mitasova and Hofierka 1992). The spatial patterns of instrumental drought and wetness during these 20th century regimes are reproduced with great fidelity by the tree-ring reconstructions. However, the tree-ring reconstructions indicate that the 1950s drought was nearly as intense and more prolonged than the 1930s Dust Bowl drought (Table 1, Figs. 2 and 3). This is not the case for the instrumental summer PDSI, which indicate that the Dust Bowl drought was more intense than the 1950s drought at both the

Table 1 Tree-ring reconstructed summer PDSI has been used to identify the time period, duration, and magnitude of decadal to multidecadal droughts over North America and "The West"

	Instrumental			Reconstructed		
	Time period	Duration	Magnitude	Time period	Duration	Magnitude
North America:	1949–1964	16	−3.778	1951–1964	14	−5.262
	1917–1939	23	−7.661	1929–1940	12	−6.023
				1559–1582	24	−8.948
The West:	1953–1964	12	−7.258	1951–1964	14	−13.227
	1929–1939	11	−10.072	1931–1939	9	−8.838
				1571–1586	16	−15.351
				1444–1481	38	−27.019
				1387–1402	16	−16.663

The droughts estimated to have exceeded the 20th century events in duration and magnitude are referred to as megadroughts at each spatial scale. [Note: the JJA PDSI means of the calibration period (1928–1978) for the instrumental and reconstructed data were −0.060 and −0.254 for North American and the West, respectively.]

continental and sub-continental scale (Table 1, Figs. 2 and 3). This inconsistency may arise from subtle biases related to the spatial distribution and seasonal climate response of the chronologies included in the proxy tree-ring network. The network of tree-ring chronologies is relatively sparse over the central and northern Great Plains (Fig. 1b), one of the spatial centers of the Dust Bowl drought (Fig. 3). However, the network of tree-ring chronologies, including chronologies of exceptional sensitivity to soil moisture (Schulman 1956; Fritts et al. 1965; Stahle and Cleaveland 1988), is much more representative over the Tex-Mex sector which was the region most severely impacted by the 1950s drought (Figs. 1 and 3).

Differences in the seasonal distribution of precipitation during these 20th century drought regimes may have also influenced the tree-ring proxies. Winter dryness was especially severe during the 1950s drought, while summer dryness was more pronounced during the Dust Bowl. Many western tree-ring chronologies respond more strongly to late winter–spring climate than to full summer conditions. These differences in climate response are mitigated to a degree by the strong persistence built into the monthly PDSI (Palmer 1965), by the averaging of June–July–August monthly PDSI, and by the principal components regression procedures used to estimate JJA PDSI from multiple tree-ring predictors in proximity to each grid point (Cook et al. 2004). Nevertheless, some of the difference between the instrumental and reconstructed 1950s and Dust Bowl droughts (Figs. 2 and 3) may arise from spatial gradients in the seasonal response of the tree-ring predictors.

The largest difference between the instrumental and tree-ring reconstructed droughts concerns the timing of the Dust Bowl at the continental scale (Fig. 2a bottom panel, and Table 1), which was specified arbitrarily by the negative runs in the Julian filtered time series. However, the close agreement between the spatial pattern and intensity of the Dust Bowl from 1929–1940 for the instrumental and reconstructed summer PDSI (Fig. 3) indicates that the tree-ring reconstructed Dust Bowl does indeed provide a useful comparative benchmark for reconstructed decadal droughts during the pre-instrumental period.

The term "megadrought" has not been operationally defined, but has been used to imply a very large-scale drought more severe and sustained than any witnessed during the period of instrumental weather observations (e.g., Stahle et al. 2000). Here we use tree-ring reconstructed summer PDSI for two large spatial domains, "continental" North America and the "sub-continental West," to define the 20th century tree-ring record of decadal drought and wetness, and to then search for possible pre-instrumental megadroughts and pluvials that exceeded their 20th century counterparts in duration and magnitude. Using the consecutive time intervals when the Julian decadal filter of reconstructed summer PDSI was at or below average for North America (i.e., the 286 grid point region identified in Fig. 1a), the longest tree-ring reconstructed drought of the 20th century lasted 14 years from 1951–1964, with a cumulative summer PDSI moisture deficit of −5.262 (Table 1). Therefore, to constitute a continent-wide North American megadrought, the multi-year drought must exceed the duration and magnitude of this most extreme tree-ring reconstructed 20th century event. The worst sub-continental drought over the West in the 20th century tree-ring record also lasted from 1951–1964, with a cumulative summer PDSI deficit of −13.227 (Table 1), which sets our threshold for the definition of Western sub-continental megadroughts during the pre-instrumental period. A "pluvial" was defined in the same manner, and had to exceed the tree-ring reconstructed early 20th century wet episode (Fig. 5) in the duration and magnitude of wetness at either the continental and subcontinental scales.

Using this simple definition of megadrought, only one drought was reconstructed at the continental scale over the past 500 years that was more intense and prolonged than any evident in the reconstructed data for the 20th century (Table 1). By these criteria, the 16th century megadrought lasted 24 years from 1559 to 1582 (Table 1; Figs. 5 and 6). Three megadroughts were reconstructed at the sub-continental scale for the West, including the 16th century event (Table 1, Fig. 7). Notably, no pluvials wetter than the early 20th century pluvial were reconstructed at either the continental or sub-continental scales over the past 700 years (Fig. 5). In fact, the 20th century appears to have been relatively moist over western North America compared with the tree-ring reconstructions of drought area during the past 1,200 years (Cook et al. 2004).

5 The pattern and propagation of moisture anomalies during megadroughts

Rotated principal components analyses (RPCA) of the interannual variability of drought and wetness across the coterminus United States, based on instrumental monthly PDSIs from 1895–1981 by Karl and Koscielny (1982), identified nine regional modes of climate variability. To replicate the work of Karl and Koscielny, Cook et al. (1999) used gridded instrumental summer PDSI from 1913–1978, and tree-ring reconstructed summer PDSI

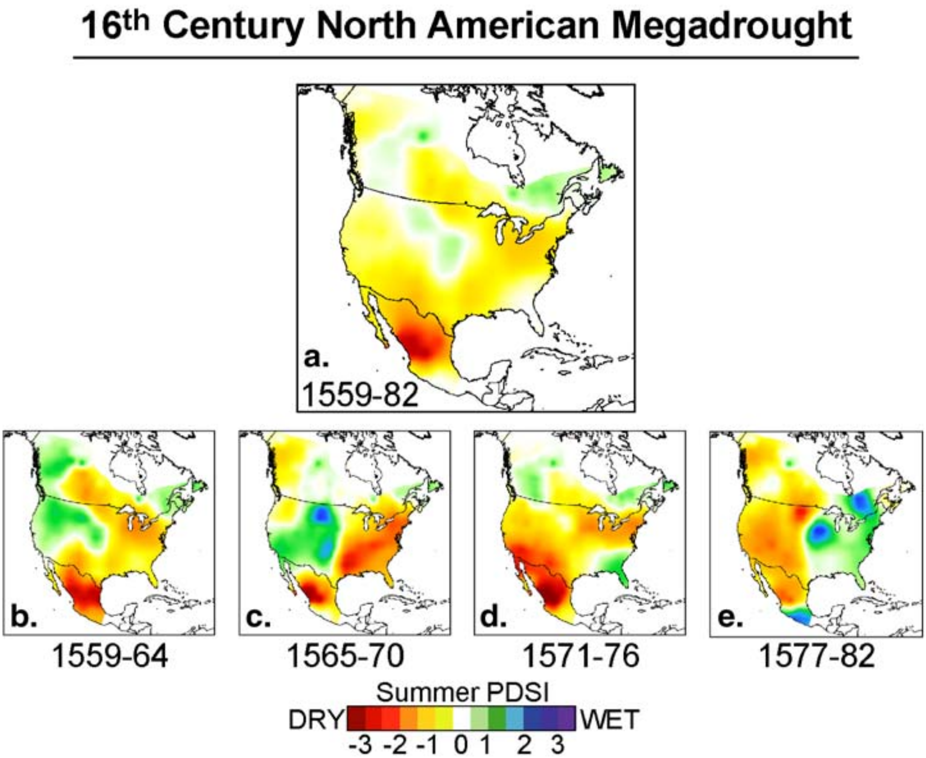

Fig. 6 Tree-ring reconstructed summer PDSI averaged and mapped from 1559–1582 during the 16th century megadrought for all 286 points across North America (a). The gridded summer PDSI were also mapped for discrete 6-year subperiods to illustrate the shifting geographical focus of drought during the late 16th century (b–d). Northern Mexico was afflicted by drought for most of this 24-year time period

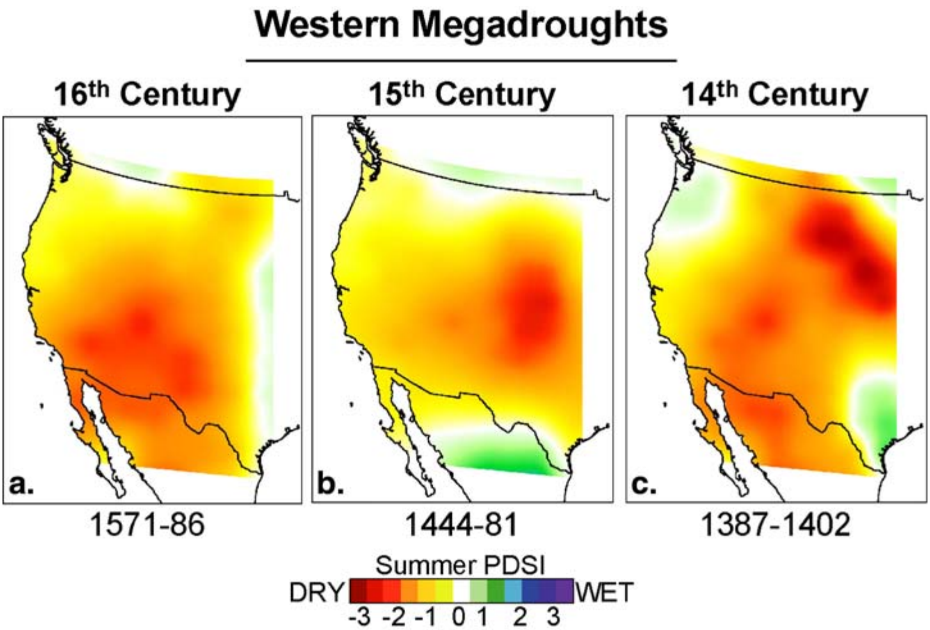

Fig. 7 Tree-ring reconstructed summer PDSI averaged and mapped over the West during the megadroughts of the 14th, 15th, and 16th centuries. The reconstructed PDSI values were averaged for the specified time periods across the entire 286 gird points, but are shown here only for the 103 western grid points. The cell of intense drought over the Northern Plains during the 14th century megadrought (c) is based on very limited tree-ring data

from 1700–1978 for the coterminus United States, and found remarkably similar regional patterns with RPCA, indicating that these spatial modes of drought and wetness have remained reasonably consistent over the past 300-years. These nine regional factor patterns differ by their unique monthly precipitation climatology, and share very little variance across the frequency spectra (Karl and Koscielny 1982). Karl and Koscielny (1982) also found that drought duration was greater over the continental interior compared with coastal areas of the United States in the monthly PDSI from 1895–1981.

Two of the leading modes of drought over the United States are the Northern Plains drought pattern and the Southern Plains pattern [respectively referred to as the "West North Central" and the "South" by Karl and Koscielny (1982), and as "Factor 4" and "Factor 7" for the 1700–1978 analyses of Cook et al. (1999)]. These particular spatial patterns of drought were expressed vividly during the prolonged 1930's Dust Bowl drought that was centered over the Northern Plains–Northern Rockies, and the persistent 1950's drought that was focused over the Southern Plains–Southwest. However, both the decadal droughts of the 1930s and 1950s appear to have evolved from two distinct and sequential regional drought patterns (Fig. 3). The decadal drought of the 1930s was the product of an intense cell of dryness centered over the Pacific Northwest and northern Rockies from 1929–1934 (the "Northwest" drought pattern of Karl and Koscielny 1982), followed by the development of severe sub-decadal drought centered over the northern Great Plains in both the instrumental and tree-ring reconstructed summer PDSI from 1935–1940 (Fig. 3; the Northern Plains pattern). The first half of the 1950s drought was most intense, with severe drought for six consecutive years (1951–1956) over the southern Great Plains and

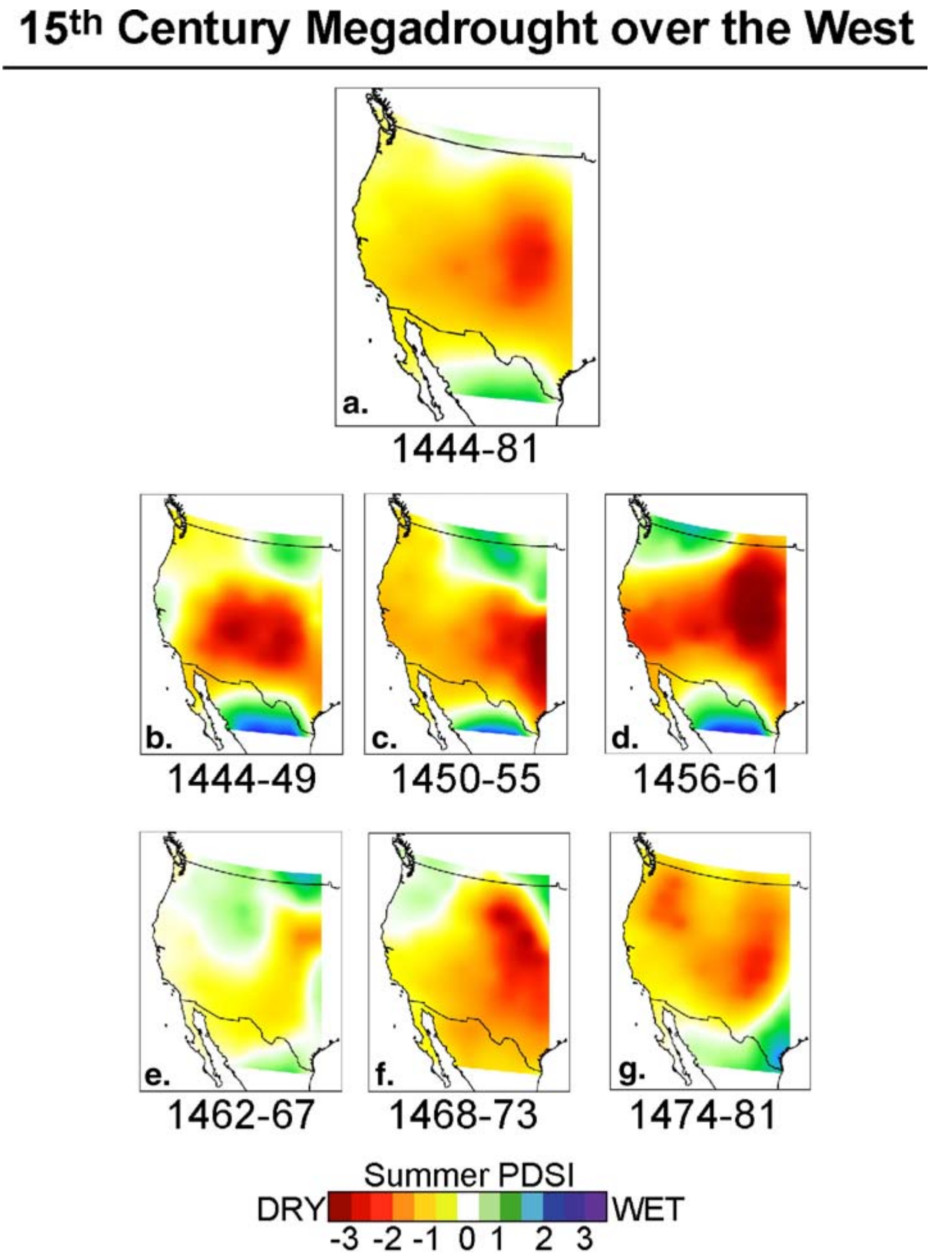

Fig. 8 (a) Same as Fig. 6 for the 15th century megadrought restricted to the West. Discrete 6-year subperiods are also mapped (b–g). Note the changing geographical epicenters of sub-decadal drought and the near normal conditions during the 1460s (e)

northern Mexico. Drought persisted over this region into the 1960s, but an area of intense drought during this 1950s event shifted into Arizona–southern California (Fig. 3), similar to the "West" drought pattern of Karl and Koscielny (1982). These leading spatial modes of drought witnessed over the United States during the 20th century can be identified during

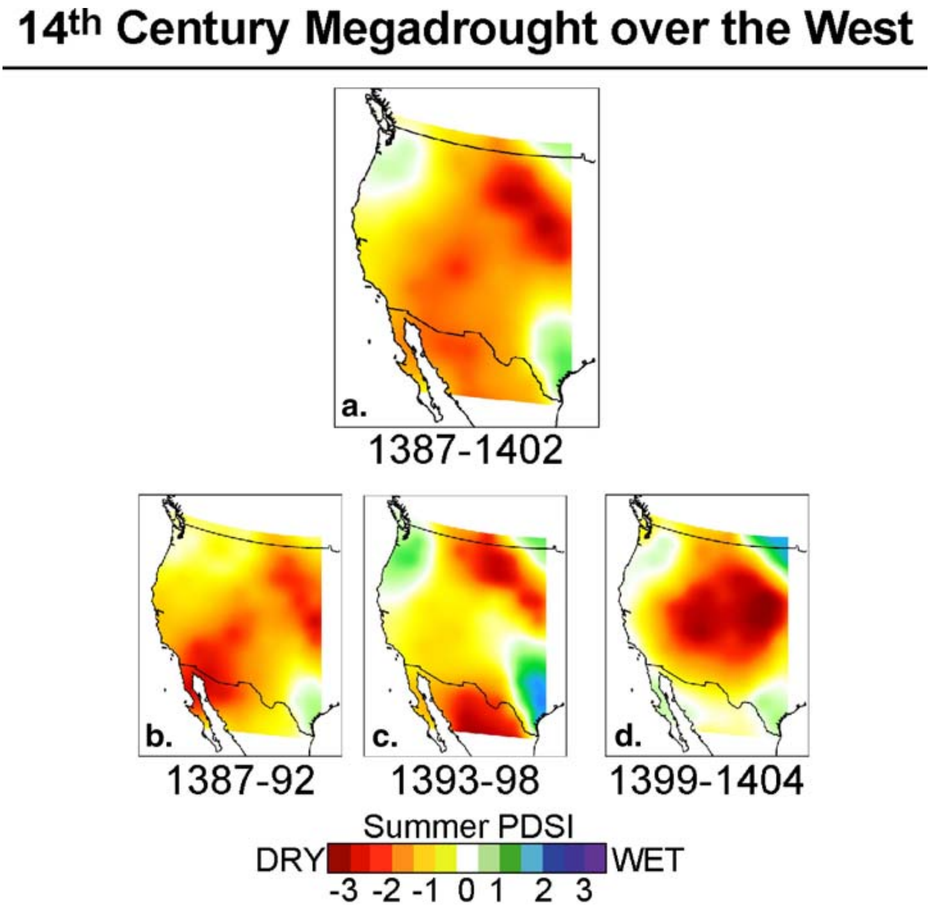

Fig. 9 (a) Same as Fig. 6 for the 14th century megadrought restricted to the West. Discrete 6-year subperiods are also mapped (b–d)

sustained droughts of the pre-instrumental era, along with drought anomaly centers in Mexico, and their sequential co-occurrence seems to have produced the extended episodes of megadrought reconstructed for North American over the past 500- to 700-years.

The 16th century megadrought was more severe and sustained than any witnessed at the continental scale during the 20th century, including the Dust Bowl based on comparisons with the instrumental and reconstructed PDSI (Table 1). Severe drought is estimated to have persisted for 24 years in northern Mexico, but included mild to moderate drought across most of the continent during this entire episode (Fig. 6a). The 16th century megadrought included several distinctive spatial modes of sub-decadal (six-year) drought that resemble the spatial patterns of drought identified in the monthly and annual PDSI data for the 20th century (Karl and Koscielny 1982; Cook et al. 1999). These regional droughts included the Southeast, Southwest, and Northern Plains drought patterns, which occurred simultaneously with the Mexican drought cell to produce the long lasting, large scale megadrought of the late 16th century (Fig. 6b–e).

We can examine the temporal and spatial history of long-term drought for a full 700-years if the analyses are restricted to western North America where the network of tree-ring chronologies at least 700-years long is more complete (Fig. 1d). Three pre-instrumental megadroughts are reconstructed for the West, including the 16th century megadrought, and two other severe sustained droughts in the 15th and 14th centuries (Fig. 5b). These western megadroughts persisted for 16 to 38 years (Table 1). The 14th and 16th century droughts both included prolonged drought over the Southwest and Colorado Plateau, but the long 15th century drought was most intense over the Central Plains and Front Range of the Rocky Mountains (Fig. 7).

Sub-decadal drought waxed and waned over the Colorado Plateau and Great Plains during the 15th century megadrought, but was most intense during the first half of this 38-year episode (prior to 1462, Fig. 8). The 14th century megadrought over the West extended from 1387–1402 and included shorter duration cells of severe drought over the Southwest, Colorado Plateau, and Northern Plains (Fig. 9), all three drought regions identified in the spatial analyses of instrumental summer PDSI by Cook et al. (1999). Persistent sub-decadal to decadal drought rarely extended to the coastal regions of the United States during any of the megadroughts of the past 500- to 700-years, consistent with the greater persistence of drought over the continental interior noted by Karl and Koscielny (1982) in their analyses of monthly PDSI during the 20th century. Northern Mexico, however, experienced coast to coast dryness during the first half of the 1950s drought (Fig. 3) and for much of the 16th century megadrought (Fig. 6).

The spatial patterns of sub-decadal drought that make up the decadal to multi-decadal droughts of the past 500- to 700-years (Figs. 6, 7, 8, 9) might be explained stochastically as the random consecutive development of regional drought, with no dynamical association among the drought epicenters. Alternatively, the decadal drought epicenters may have been linked by dynamical ocean–atmospheric mechanisms that favored the development, persistence, and spatial propagation of decadal drought regimes over the continent. The simulation of multidecadal drought over North America by coupled ocean atmospheric models (Hunt and Elliott 2002) offers an opportunity to test potential mechanisms for the development and propagation of drought regimes over the continent.

Schubert et al. (2004) and Seager et al. (2005) describe zonally-symmetric mechanisms in the upper troposphere that link cool conditions in the tropical Pacific to anomalous anticyclones and persistent drought over North America at sub-decadal timescales (>6-years). Seager et al. (2005) and Herweijer et al. (2006) reproduced the major multi-year droughts of the 19th and 20th centuries over the Great Plains and Southwest in climate model simulations involving small changes in the tropical Pacific SST field on the order of only 0.2 to 0.3°C. There is coral evidence that the tropical Pacific SSTs were persistently cooler than modern normals during the late 14th and 15th centuries (Cobb et al. 2003; Mann et al. 2005), so the extended droughts during the late 14th and mid-15th centuries may have had their origin in Pacific SSTs.

6 Conclusions

The decadal droughts of the 20th century, and the tree-ring reconstructed megadroughts dating back to A.D. 1500 and 1300 all covered large sectors of western North America, and in some cases included the Midwest and eastern United States. However, all of these persistent megadroughts appear to have resulted from shorter duration cells of regional drought that resemble the regional drought patterns identified in monthly and annual PDSI data for the 20th century. The location of intense drought seems to have shifted among these regional drought epicenters during the multi-year regimes, which served to prolong dryness over the continent and produce the large-scale and long-term megadroughts.

The tree-ring reconstructions of the temporal and spatial patterns of past drought provide an interesting framework with which to compare the evolution of the current multi-year drought over the West. The regional focus of the current Western drought shifted from the Southwest into the Northern Rockies and Pacific Northwest in 2005, and has re-intensified over the Southern Plains and Southwest in 2006 (Drought Monitor 2006), not outwardly unlike the shifting epicenters of sub-decadal drought during other modern and pre-instrumental decadal droughts of the past 700 years (Figs. 6, 8, 9). Identifying the stochastic and dynamical components of these shifting epicenters of multi-year drought would be an interesting modeling exercise. At the same time, much stronger and more persistent droughts have been reconstructed with tree rings and other proxies over North America during the Medieval era (e.g., Stine 1994; Laird et al. 2003; Cook et al. 2004). The network of long, precipitation sensitive tree-ring chronologies is very sparse during Medieval times, but 1,000- to 2,000-year long chronologies sensitive to precipitation could be developed for selected species in most, if not all of the nine drought regions identified for the coterminus United States by Karl and Koscielny (1982) and Cook et al. (2004). An effort to develop the next generation of ultra-long precipitation-sensitive tree-ring chronologies to document the temporal and spatial evolution of the potentially no-analog Medieval megadroughts should be a priority for high-resolution paleoclimatic research.

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