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Drought frequency in central California since 101 B.C. recorded in giant sequoia tree rings*

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Abstract. Well replicated tree-ring width index chronologies have been developed for giant sequoia at three sites in the Sierra Nevada, California. Extreme low-growth events in these chronologies correspond with regional drought events in the twentieth century in the San Joaquin drainage, in which the giant sequoia sites are located. This relationship is based upon comparison of tree-ring indices with August Palmer Drought Severity Indices for California Climate Division 5. Ring-width indices in the lowest decile from each site were compared. The frequency of low-growth events which occurred at all three sites in the same year is reconstructed from 101 B.C. to A.D. 1988. The inferred frequency of severe drought events changes through time, sometimes suddenly. The period from roughly 1850 to 1950 had one of the lowest frequencies of drought of any one hundred year period in the 2089 year record. The twentieth century so far has had a below-average frequency of extreme droughts.

Introduction

The potential of the annual rings of giant sequoia [*Sequoiadendron giganteum* (Lindl.) Bucholtz] as a source of well-dated information on past environments was recognized early in the twentieth century by Douglass (1919, 1928). It was already known that not only did this species contain the largest trees in the world, but also some of the oldest. Douglass used his newly developed technique of crossdating to assign each annual ring to a specific calendar year. He then combined measurements of the width of such dated rings from a number of long-lived trees from several locations in a 3200 year-long chronology.

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Crossdating in giant sequoia depends upon the presence of "signature" years. These are narrow rings which are often easily noted in a sequence of relatively uniform ring widths. The occurrence of consistent signature years throughout much of the 250 km range of giant sequoia indicates there was a common climatic factor controlling the formation of small rings, even if that same climatic factor may not have influenced growth in other years to any great extent. Douglass, working in the early twentieth century, had only one or two signature years to compare with the instrumental records available at the time. These were from meteorological stations in the Central Valley and coastal areas of California, commencing in the mid-nineteenth century or later. Efforts by Douglass and others (Huntington 1914; Antevs 1925) to relate giant sequoia ring widths to temperature and precipitation records by graphical, correlation and superposed epoch analyses met with little success.

Recently, new attention has been paid to giant sequoia as an excellent recorder of fire. Sequences of fire-scars are recorded in wood near the bases of the trees. A program of research into past fire history of giant sequoia groves using Douglass' original chronology for crossdating (Swetnam et al. 1990) also led to a new effort to determine what climate factor or factors were responsible for controlling yearly growth in giant sequoia. The results of preliminary work showed that extreme low-growth years for giant sequoia in the twentieth century correspond to intense drought events in the San Joaquin drainage (Hughes et al. 1990). The giant sequoia groves referred to in this report are found in this drainage, on its eastern margin.

We report the results of a comparison of August Palmer Drought Severity Indices (PDSI: Palmer 1965; Alley 1984; Karl and Koscielny 1982) for California State Climate Division 5 (the San Joaquin basin) and low-growth events in giant sequoia chronologies from three sites, viz. Camp Six, Giant Forest, and Mountain Home (Fig. 1). Low values of August PDSI were found to have the best correspondence with extreme low-growth years. The frequency of these low-growth events

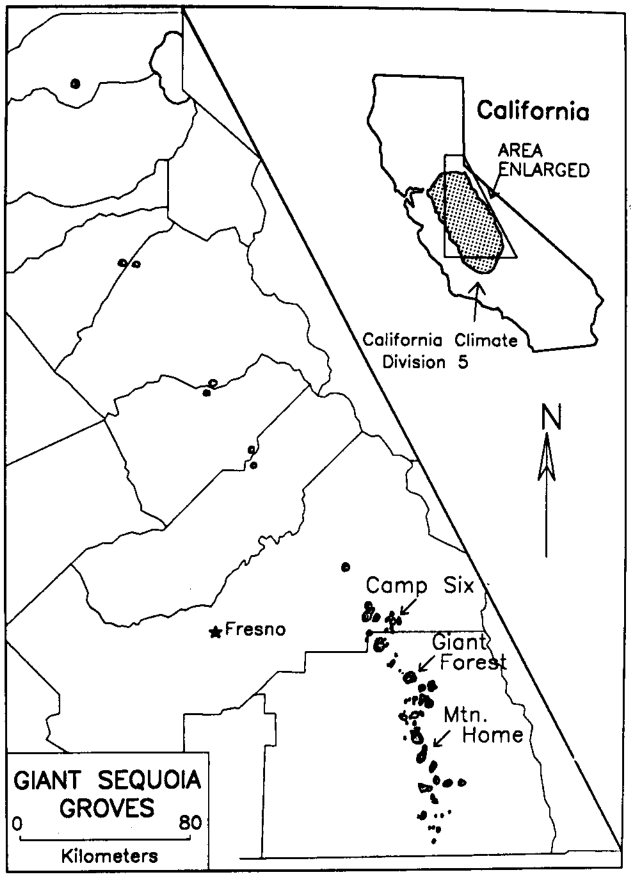

Fig. 1. Locations of giant sequoia chronologies. Irregular *gray areas* are giant sequoia groves. The *hatched area* in the insert map of California is California State Climate Division 5, the San Joaquin drainage

was then examined for a 2089 year-long period common between the three chronologies and interpreted as a record of the frequency of extreme droughts in Central California since 101 B.C.

Methods

Radial samples were removed from giant sequoia stumps and logs in conjunction with the fire history study (Swetnam et al. 1990). Many trees sampled were remnant stumps of extensive logging that took place between the late 1800s and early 1900s. Samples were removed from as far above ground level as possible to minimize the effects of healing surges associated with fire scarring. Radii with the least evidence of fire scars or related growth surges were chosen for sampling. Most samples were cut from the tops of stumps at least 2 to 3 m above present ground surface, while samples for fire history were taken at ground level. Other radii included in the final chronologies for Camp Six and Mountain Home were collected by Douglass in the late 1910s and early 1920s. Living trees in the same stands or adjacent unlogged stands were cored with increment borers to extend the chronologies to the present, overlapping the remnant material by between 200 and 700 y.

Radial samples were surfaced, crossdated and measured according to standard procedures (Stokes and Smiley 1968; Robinson and Evans 1985). Ring widths were detrended into dimensionless indices to stabilize mean and variance between trees of differing ages and to remove non-climatic growth trends (Fritts 1976; Cook et al. 1990). Giant sequoia ring widths may exhibit growth responses to fire events, referred to as "growth releases". Growth releases range from very subtle to, in at least one instance, quite dramatic increases in ring widths after fire. Ring widths recorded at Mountain Home after a fire in A.D. 1297 were an order of magnitude larger than before the fire (Stephenson et al. in press). These larger ring widths persisted for several decades before gradually declining to widths comparable to those found before 1297. Such abrupt growth releases following fires may be due to the combined effects of an ecosystem nutrient surge and a reduction in competing understory species killed by fire. It is highly problematic in giant sequoia series to determine whether low frequency fluctuations in ring widths are due to climate or fire events. In order to minimize the influence of fire releases on the high frequency signal, a very flexible 40-year cubic smoothing spline was employed in the detrending procedure (Cook and Peters 1981). Ring-width series from Mountain Home were separated into pre- and post-1297 segments before detrending in an attempt to eliminate the effects of the growth release from this one event.

After detrending, a time series model was fitted to the individual series and residuals calculated. Parsimoniously chosen AR(1) models were fitted (Box and Jenkins 1970; Meko 1981; Cook 1985). This step had the effect of removing persistence form the ring-width index time-series and further insured that only the high frequency signal was retained. Prewhitened residual series were combined into a mean chronology for each of the three sites using a bi-weight robust mean (Cook et al. 1990). Eighty of the longest series from all three sites were also combined into a regional giant sequoia chronology. Detrending, autoregressive modeling, and calculation of the mean value function for each of the four chronologies were accomplished using the program ARSTAN (Cook 1985).

Subsample signal strength (Wigley et al. 1984) was calculated for each chronology and used to assess the effect of sample depth (number of samples per year) on the chronology signal. Simple correlation coefficients for 100 y periods lagged by 50 y were also calculated between chronologies. This aided estimation of an optimal period for in-common analysis between the three sites. Once an in-common period was determined, separate percentiles of lowest index values for all three sites were identified and compared year by year. Frequencies of low-growth years were then determined for the entire length of the common period.

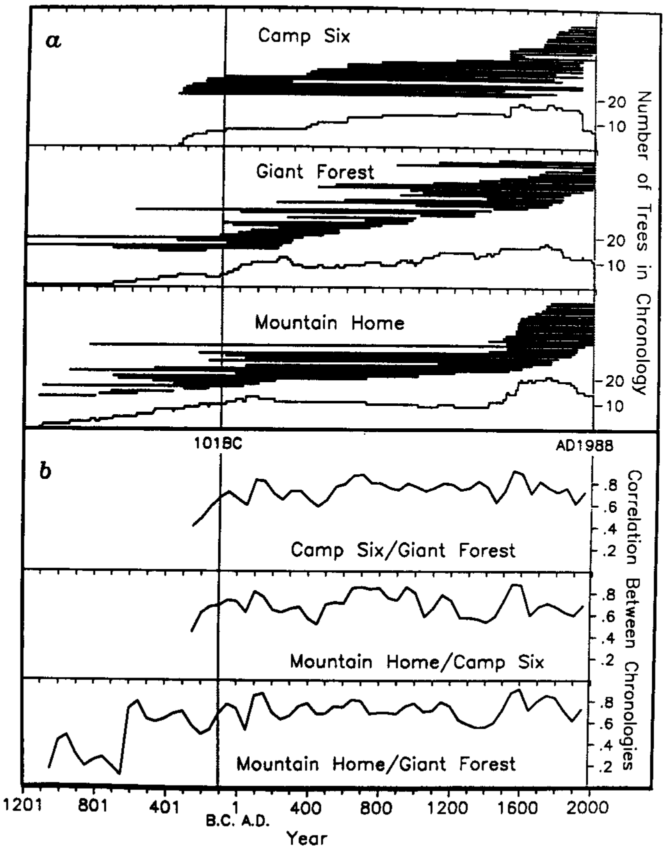

Fig. 2. a Time spans of individual radii (*horizontal lines*) and sample depth (*irregular line*) for three sequoia sites. **b** 100-year correlations between sequoia chronologies computed every 50 y. Note the dip in correlation between Mountain Home and the other two chronologies around A.D. 1300 due to the large fire in 1297 at Mountain Home and its associated growth releases

Results

Tree-ring series

Sample replication for chonologies at Camp Six (368 B.C. to A.D. 1989), Giant Forest (1268 B.C. to A.D. 1988), and Mountain Home (1127 B.C. to A.D. 1989) is shown in Fig. 2a. Note that trees living two thousand or more years were not uncommon, resulting in very few problems of homogeneity in the resulting chronologies. Correlations between pairs of chronologies suggest a similar response to climate at each site (Fig. 2b). This is particularly significant considering that these are correlations between essentially white noise series (when $r > = 0.332$, $p < 0.001$). Based upon subsample signal strength (Wigley et al. 1984) and the drop in both correlation between Camp Six and the other two chronologies (Fig. 2b) and sample depth at Camp Six (Fig. 2a), it was decided that the common period used for comparison of low-growth years would be limited to a 2089 year period from 101 B.C. to A.D. 1988.

Representative segments of the three chronologies from A.D. 800 to 1000 show correspondence between ring-width indices, particularly of low-growth years (Fig. 3). The years marked by the dashed lines are those in which all three chronologies show a ring-width index in the lowest decile calculated from the 2089 year common period. This class of years (lowest decile ring width index at all three sites) will be the focus of the remainder of this report, since such years represent probable regional scale extreme events in giant sequoia growth.

Giant sequoia tree-ring growth and extreme droughts

The most extreme droughts of the twentieth century in the San Joaquin drainage, in order of decreasing magnitude, occurred in 1977, 1976 and 1924. These are

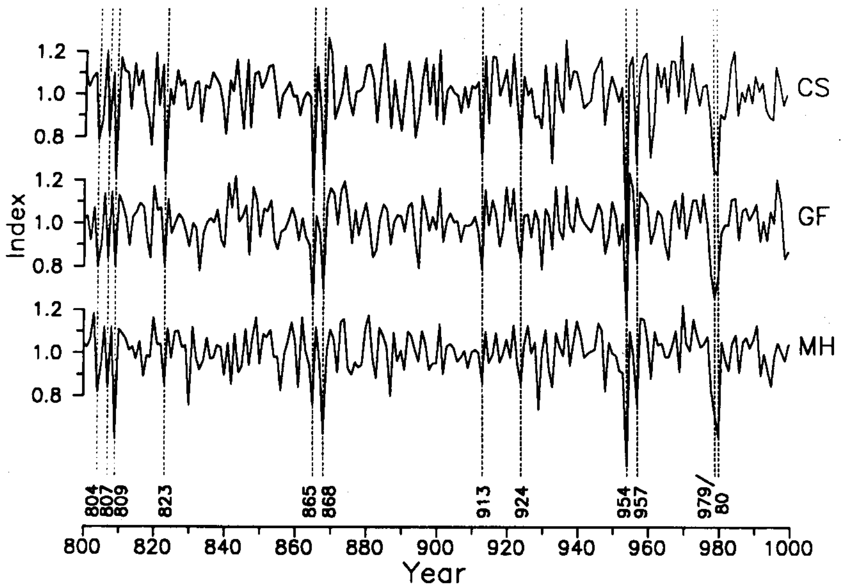

Fig. 3. Dimensionless ring-width indices for Camp Six (*CS*), Giant Forest (*GF*), and Mountain Home (*MH*) for A.D. 800–1000. Years marked are lowest decile years in-common at all three sites

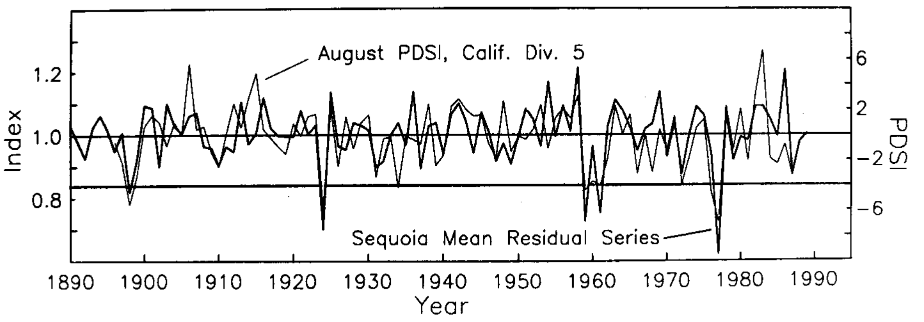

Fig. 4. August Palmer Drought Severity Index for California Division 5 (San Joaquin drainage) for 1895–1987 (*light line*) and sequoia mean residual series for 1890–1988 (*heavy line*). Simple correlation between series is 0.625 ($p<0.001$)

years in which the lowest values of August Palmer Drought Severity Index in the San Joaquin drainage were recorded (Fig. 4). 1977 and 1924 were also classified as three site low-growth years (as already defined), as were the drought years 1959 and 1961. The years 1898, 1934 and 1976 are those in the instrumental record during which August PDSI was below - 4.0 but a three-site low-growth year did not occur. Two sites record low-growth in 1898 and one site in 1976. No site records the 1934 drought. The three-site low-growth criterion scores four hits out of a possible seven as an indicator of extreme San Joaquin droughts defined by August Divisional PDSI below −4.0. No false hits occurred.

Correlations between the three separate site chronologies and California Division 5 monthly PDSI consistently showed the best relationship with August PDSI (correlations with August PDSI: Camp Six 0.536; Giant Forest 0.550; Mountain Home 0.499: $p<0.001$ in each case). The correlation was slightly better ($r=0.625$; $p<0.001$) between August PDSI and the mean giant sequoia chronology made up of ring-width series from all three sites (Fig. 4). It is clear the correlation is substantially, but not exclusively, determined by the coincidence of extreme droughts and years of very low growth. A survey of multiple correlations between August PDSI for California Division 5 and various combinations of 28 moisture sensitive tree-ring chronologies from California, Oregon and the Intermountain West yielded none as strong as with the mean giant sequoia chronology.

Characteristics of three-site low-growth years in the instrumental record

The giant sequoia groves experience a mediterranean climate in which the greater part (90%) of precipitation falls in the late autumn, winter and spring (November through April), much of it as snow. Summers are dry, resulting in soil moisture deficits from June through September (Stephenson 1988). Mean annual (August to July) precipitation for a 52 y record from stations within the groves at Sequoia National Park was 1045 mm. Mean annual precipitation for the four extreme drought years in the Giant Forest instrumental record (1959, 1961, 1976 and 1977) was 588 mm. December, January and February accounted for 314 mm

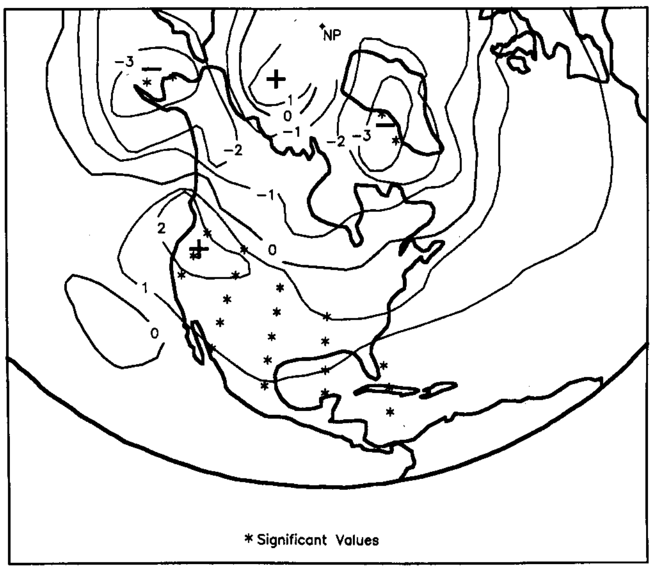

Fig. 5. Map of mean sea level pressure anomaly patterns during winters (December, January, February) preceeding Augusts of extreme drought in California State Climate Division 5 (that is when August PDSI < -4.0). *Figures* are anomalies from the 1951–1980 mean in millibars. *Asterisks* (*) indicate 5° latitude by 10° longitude grid points at which the anomaly is significant at $p<0.05$. Calculations by P. M. Kelly

of the 457 mm mean deficit, the rest contributed by November, March and April. An analysis of winter sea-level pressure anomalies for these years (Fig. 5) reveals a characteristic hemisphere-scale circulation pattern associated with these precipitation-deficient winters. A ridge of high pressure over central and northern California diverts snow-bearing winter storms away from the central Sierra Nevada, typified by conditions during the winter of 1976–1977 (Namias 1978).

Giant sequoia tree-ring formation occurs in the summer months, ending in late September (L. Mutch, personal communication 4 February 1991). Soil water availability to these plants during their growing season is determined in part by winter moisture supply and in part by actual evaporation in dry summer months. This is consistent with the observation that August PDSI is a better predictor of giant sequoia ring-width index than is any combination of monthly temperatures and precipitation (Hughes et al. 1990). The Palmer Drought Severity Index was designed empirically to measure departures from average soil-water balance conditions, weighted for conditions over a number of months according to the presumed water storage capacity of local soil (Palmer 1965). It appears that only in the case of extreme drought (August PDSI < -4.0) is the soil water deficit sufficient to produce a ring-width index in the lowest decile for each series at all three sites.

Frequency of inferred extreme droughts since 101 B.C.

Given the strong coincidence of three-site low-growth years and years of extreme drought in the San Joaquin drainage, it seems reasonable to interpret the occurrence of such low-growth years in pre-instrumental times as a record of extreme droughts. This is made possible by the threshold nature of the relationship between drought intensity and ring-width index. During the 2089-year common period, 95 y were found to have ring-width indices in the lowest decile for all three series (Table 1a). This compares with an expectation of 2.1 y in common if low-growth years were occurring as random, independent events at all three sites. Three-site low-growth years are not distributed evenly through the two millenia (Fig. 6a). In particular, there are periods of frequent three-site low-growth events from A.D. 700 to 850, 250 to 350, and 1480 to 1580, in general order of decreasing intensity (Fig. 6b, upper plot). These are interpreted as periods of frequent extreme droughts, as many as 12/100 y period. Similarly, there were periods marked by a relative absence of three-site low-growth events, notably from 100 B.C. to A.D. 100, 400 to 500, 1300 to 1450, 1600 to 1700, and from 1850 to 1950. We interpret one of these, the minimum between A.D. 1300 and 1450, as an artefact of the very major fire at Moun-

Table 1.

a Low-Growth Years common to all three sites

B.C.:	84	63	10						
A.D.:	15								
	100	109	169	189					
	236	256	271	274	292				
	305	313	333	344	369	377	386		
	442	497							
	518	539	553	554	570				
	629	640	659	664	699				
	707	728	742	751	762	781	786	788	797
	804	807	809	823	865	868			
	913	924	954	957	979	980			
	1025	1052	1072	1082	1090	1098			
	1126	1152	1156	1183					
	1218	1227	1264	1292					
	1352	1377							
	1410	1468	1479	1499					
	1500	1510	1529	1532	1548	1571	1579	1580	
	1653	1654							
	1703	1721	1729	1765	1777	1795			
	1822	1841							
	1924	1959	1961	1977					

b Low-Growth years common to Camp Six and Giant Forest

B.C.:	84	63	10								
A.D.:	15										
	100	109	115	168	169	189					
	226	236	256	271	274	292					
	305	306	313	333	339	344	349	369	377	386	
	424	442	497								
	518	539	553	554	557	570					
	629	640	659	664	676	677	691	699			
	707	719	728	742	751	762	781	786	788	797	
	804	807	809	819	823	847	865	868			
	913	924	930	954	957	979	980				
	1025	1052	1059	1072	1082	1090	1092	1098			
	1126	1152	1156	1170	1183						
	1218	1227	1231	1263	1264	1284	1285	1292	1296		
	1335	1351	1352	1358	1377	1390					
	1410	1413	1426	1468	1479	1499					
	1500	1510	1515	1518	1529	1532	1548	1571	1579	1580	
	1637	1653	1654								
	1703	1706	1721	1729	1739	1748	1756	1765	1777	1782	1795
	1818	1822	1829	1841	1843	1898					
	1924	1959	1961	1977							

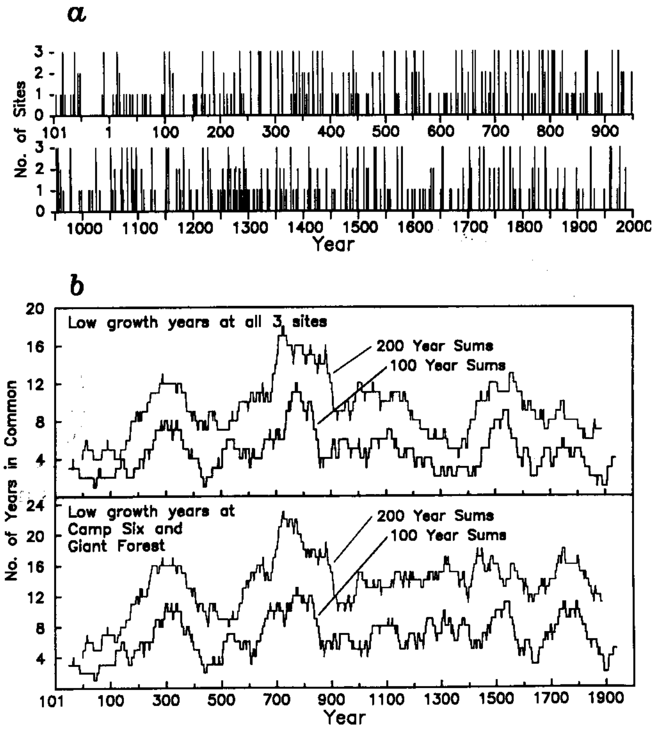

Fig. 6. a Occurrence of lowest decile years in the ring-width index chronologies at one, two, or three sites. **b** 200-year and 100-year sums of low decile years computed every year. *Upper plot* - three-site lowest decile growth years. *Lower plot* - lowest decile growth years at both Camp Six and Giant Forest

tain Home in A.D. 1297 and the resultant changes in the stand dynamics at this site. It is probable that this fire killed a substantial proportion of understory trees and perhaps overstory giant sequoia which resulted in reduced competition for moisture and other resources. This interpretation is supported by a comparison with the series of frequencies of low-growth events common only to the other two sites, Camp Six and Giant Forest (Fig. 6b, lower plot). Low growth years common to these two sites are listed in Table 1b. The shape of the frequency plot of low growth events at these two sites is similar to that for three-site events until the 1300s. Hence, with the exception of the A.D. 1300–1450 minimum, the periods of minima in the upper plot of Fig. 6b are interpreted as periods of few extreme droughts in the San Joaquin drainage, as few as one or two per hundred year period. It is evident from Fig. 6a that the transition from almost drought-free periods to those of very frequent extreme droughts has, on occasion, occurred almost as a step-function, for example at around A.D. 700.

Discussion

Evidence from the instrumental period links three-site low-growth events with extreme droughts in the San Joaquin drainage as indicated by August PDSI values of -4.0 or less. It has already been shown that giant sequoia low-growth years are also years of drought inferred from low growth in moisture sensitive tree-ring chronologies across much of California and the interior West between 1601 and 1963 (Hughes et al. 1990). This supports the hypothesis that the extreme drought/giant sequoia low growth link is stable in time and not limited to the twentieth century. Further evidence in support of this comes from comparison with a tree-ring based reconstruction of precipitation in the region around Santa Barbara on the California coast (Michaelsen et al. 1987). Seven of the ten driest years identified in the Santa Barbara region from approximately 1600 to 1985 are also three-site low-growth years in the giant sequoia chronologies. The tree-ring chronologies on which the Santa Barbara reconstruction was based were not included in the network referred to by Hughes et al. (1990).

Treating the three-site, low-growth events as extreme droughts in the San Joaquin drainage, the frequency of such droughts has varied between 1 and 12/100 y since 101 B.C. There have been 4 such events in the twentieth century through 1989, three since 1958. The mean for the full 2089-year period was 4.5/100 y. Hence the twentieth century has, so far, had a slightly below-average incidence of such droughts, whilst the period between 1850 and 1950 had one of the lowest frequencies i.e. 1, in the whole record. The previous inferred minimum in extreme drought frequency was from 1600 to 1700, none being recorded between 1580 and 1653. Enzel et al. (1989) report permanent water in Lake Mohave, 200 km south, at a roughly corresponding period, resulting from especially high winter precipitation in the San Bernardino Mountains of southern California. This is of interest, although there may be no relationship between the frequency of occurrence of extreme droughts and extreme high precipitation events. There were several periods since 101 B.C. during which extreme droughts were much more frequent than during the twentieth century. The most notable were from A.D. 699 to 823, when there were 14 droughts in a period of 125 years, from A.D. 236 to 377 with 11 droughts in 142 years, and A.D. 1468 to 1580 with 11 droughts in 113 years. Two consecutive drought years were reconstructed on 5 occasions, and two droughts within three years on a further 3 occasions.

No similarities between this reconstructed history of extreme drought frequency and other late-Holocene paleoclimate information for this and neighboring regions (LaMarche 1974; Scuderi 1987a, b) have been noted. This may change as a larger set of high-temporal resolution climate records is established for western North America. On the other hand, it may be that the frequency of these relatively rare single year events is independent of longer-term changes in the climate system, at least within the framework of the climate regime of the last two millennia. Indeed, changes in drought frequency may be intrinsically unpredictable under these circumstances. Notwithstanding this, changes in drought frequency as great as those recorded in the annual rings of giant sequoia have considerable significance for human society and ecological systems in the region. It should be noted that there have been times when drought-free decades have been followed by multi-decade periods of very frequent extreme drought.

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References

Alley WM (1984) The Palmer Drought Severity Index: limitations and assumptions. J Clim Appl Meteor 23:1100–1109

Antevs E (1925) The big tree as a climatic measure. Carnegie Inst Washington 352:115–153

Box GEP, Jenkins GM (1970) Time series analysis: forecasting and control. Holden-Day, San Francisco USA

Cook ER (1985) A time series analysis approach to tree-ring standardization. PhD diss, University of Arizona, Tucson USA

Cook ER, Peters K (1981) The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree-Ring Bull 41:45–54

Cook ER, Briffa K, Shiyatov S, Mazepa V (1990) Tree-ring standardization and growth-trend estimation. In: Cook ER, and Kairiukstis LA (eds) Methods of dendrochronology: applications in the environmental sciences. Kluwer Academic Publishers, Dordrecht, The Netherlands

Douglass AE (1919) Climatic cycles and tree-growth: a study of the annual rings of trees in relation to climate and solar activity. Carnegie Inst Washington Vol. 289

Douglass AE (1928) Climatic cycles and tree growth: Vol. II. Carnegie Inst Washington Vol. 289

Enzel Y, Cayan DR, Anderson RY, Wells SG (1989) Atmospheric circulation during Holocene lake stands in the Mojave Desert: evidence of regional climate change. Nature 341:44–47

Fritts HC (1976) Tree rings and climate. Academic Press, London, UK

Huntington E (1914) The climatic factor as illustrated in arid America. Carnegie Inst Washington Vol. 192

Hughes MK, Richards BJ, Swetnam TW, Baisan CH (1990) Can a climate record be extracted from giant sequoia tree rings? Proc of 6th Ann PACLIM Wkshp, Mar. 5–8, 1989. Calif Dept Water Res, Interagency Ecol Stud Prog Tech Rep pp 111–114

Karl TR, Koscielny AJ (1982) Drought in the United States: 1895–1981. J Climatol 2:313–329

LaMarche VC, Jr. (1974) Paleoclimatic inferences from long tree-ring records. Science 183:1043–1048

Meko DM (1981) Applications of Box-Jenkins methods of time series analysis to the reconstruction of drought from tree rings. PhD dissertation University of Arizona, Tucson, USA

Michaelsen J, Haston L, Davis FW (1987) 400 years of central California precipitation variability reconstructed from tree-rings. Water Res Bull 23:809–818

Namias J (1978) Multiple causes of the North American abnormal winter 1976–77. Mon Weather Rev 106:279–295

Palmer WC (1965) Meteorologic drought. US Weather Bureau Res Pap No. 45

Robinson WJ, Evans R (1980) A microcomputer-based tree-ring measuring system. Tree-Ring Bull 40:59–64

Scuderi LA (1987a) Late-Holocene upper treeline variation in the southern Sierra Nevada. Nature 325:242–244

Scuderi LA (1987b) Glacier variations in the Sierra Nevada, California, as related to a 1200-year tree-ring chronology. Quat Res 27:220–231

Stephenson NL (1988) Climatic control of vegetation distribution: the role of the water balance with examples from North America and Sequoia National Park, California. PhD dissertation, Cornell University, New York, USA

Stephenson NL, Parsons DJ, Swetnam TW (in press) Restoring natural fire to the sequoia-mixed conifer forest: should intense fire play a role? Tall Timbers Fire Ecol Conf Proc Tallahassee, Fla., May 18–21, 1989

Stokes MA, Smiley TL (1968) An introduction to tree-ring dating. University of Chicago Press, Chicago, USA

Swetnam TW, Baisan CH, Brown PM, Caprio AC, Touchan R (1990) Late Holocene fire and climate variability in giant sequoia groves. Bull Ecol Soc Amer, Prog Abstr, 75th Annual ESA Meeting, 29 July–2 August, 1990. 71:342

Wigley TML, Briffa KR, Jones PD (1984) On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J Clim Appl Meteor 23:201–213