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Climatic Regionalization and the Spatio-Temporal Occurrence of Extreme Single-Year Drought Events (1500–1998) in the Interior Pacific Northwest, USA

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Tree-ring records from western juniper (*Juniperus occidentalis* var. *occidentalis* Hook.) growing throughout the interior Pacific Northwest identify extreme climatic pointer years (CPYs) (i.e., severe single-year droughts) from 1500–1998. Widespread and extreme CPYs were concentrated in the 16th and early part of the 17th centuries and did not occur again until the early 20th century. The 217-yr absence of extreme CPYs may have occurred during an extended period of low variance in the Pacific Decadal Oscillation. We mapped climatic boundaries for the interior Pacific Northwest based on the location of sites with similar precipitation variability indices. Three regions, the Northwest (based on chronologies from nine sites), the Southwest (four sites), and the East (five sites) were identified. Our results suggest that western juniper radial growth indices have substantial interannual variability within the northwestern range of the species (central Oregon), particularly when compared with western juniper growing in its eastern range (eastern Oregon, southeastern Idaho, and northern Nevada) and southwestern range (southern Oregon and northeast California). We suspect that the substantial differences in the variability of western juniper radial growth indices are linked to the influence of ENSO events on winter/spring precipitation amounts.

Key Words: **climatic pointer years; interior Pacific Northwest drought events; climatic regionalization.**

INTRODUCTION

The identification of climatic boundaries and the spatio-temporal occurrence of severe single-year drought events across large geographical areas are important for understanding the dynamic nature of climate and its potential future impact on human populations. Recent studies have identified possible solar-influenced centennial- and millennial-scale climatic oscillations (D'Arrigo *et al.*, 1999; Bond *et al.*, 2001), while other studies have elaborated on decadal-scale oscillations of ocean temperature (e.g., the Pacific Decadal Oscillation, or PDO) that affect climatic variability (Gershunov and Barnett, 1998; Gershunov *et al.*, 1999; Biondi *et al.*, 2001). Based on tree-ring records from southern California, USA, and northern Baja, Mexico, Biondi *et al.* (2001) reconstructed PDO indices since 1661 and found that the temporal patterns of the PDO during the 20th century were anomalous when compared with previous centuries. Their results suggest that substantial climatic variability could be modulated by the possible waxing and waning of the PDO over the past few centuries and illustrate the need to understand better the impact of these oscillations on the identification of climatic boundaries and drought frequency. This understanding, in turn, should provide a template to help gauge any expected future changes in atmospheric–oceanic circulation patterns.

Tree-ring records from the Pacific Northwest (PNW) have been used to identify climatic events, including drought occurrence (Earle, 1993), precipitation variability (Graumlich, 1987; Peterson *et al.*, 1999), temperature variability (Graumlich and Brubaker, 1986), climatic cycles (Keen, 1937; Kadonaga *et al.*, 1999), climatic boundaries (Woodhouse and Kay, 1990; Fritts and Shao, 1992), and the role of macroclimate controls on spatial patterns of radial growth (Brubaker, 1980). These studies have demonstrated that a preferred species for examining drought events and climate boundaries should have an extensive geographical range (allowing for comparative analysis throughout that region) and exhibit exceptional longevity, climatic sensitivity, and minimal biological lags.

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Western juniper (*Juniperus occidentalis* var. *occidentalis* Hook.) is a xeric tree species with a wide geographic range, growing in California, Idaho, Nevada, Oregon, and Washington, typically occurring in regions receiving less than 35 cm annual precipitation. It exhibits exceptionally high sensitivity to climatic variability (mean sensitivities can reach 0.70; Knapp *et al.*, 2001a) and on fire-protected sites individuals can exceed 1600 yr in age (R. F. Miller, personal communication, 2001). Western juniper radial growth is largely dependent on winter/spring precipitation and does not appear to be affected by biological lags (Knapp *et al.*, 2001b). Further, although decadal (and longer) scale trends in reconstructed climate have been used to help isolate climatic boundaries (e.g., Woodhouse and Kay, 1990; Dean and Funkhouser, 1995), we observed considerable spatial variation in the ability of western juniper trees to record single-year extreme drought events and hypothesized that this variability was due to spatiotemporal regionalization of climate. Given these combined characteristics, western juniper should be an ideal species to help identify regional-scale single-year drought events that might designate climatic boundaries.

Our study makes extensive use of "pointer years" found in the tree-ring record to identify single-year drought events. Pointer years are characterized by tree rings that are particularly narrow and occur in the majority of trees sampled within a site (Schweingruber, 1988). These rings are most often used to ensure precision during crossdating. The use of pointer years for crossdating was first established in Europe (e.g., Schweingruber *et al.*, 1990; Bridge *et al.*, 1996; Meyer, 1999) where temperate climates often cause tree growth that is less variable from year to year when compared to more arid regions, such as the southwestern United States. The analysis of pointer years has only sparingly been used in the United States (e.g., Hughes and Brown, 1992; Shortle *et al.*, 2000) but could provide additional information on (spatial) regional-scale climatic patterns above that provided by sole inspection of (temporal) short- or long-term trends in tree-ring-derived reconstructions.

In this paper, we first develop a method to highlight single-year drought events for the interior PNW from 1500 to 1998 that uses a climatic pointer year index (CPYI). Subsequently, we develop a method to define climatic boundaries based on a precipitation variance index (PVI). Our objectives in this study are to use these indices to (1) provide spatial guides to years that reflect large-scale unfavorable growing conditions, (2) reveal radial growth patterns that are distinctly regional and thus serve as a proxy means to identify climatic boundaries, and (3) discuss possible synoptic-scale controls that account for both the climatic boundaries and the frequency of single-year drought events.

METHODS

Selection of Chronologies

We selected 18 chronologies developed from western juniper trees throughout the Pacific Northwest (Fig. 1). Seven chronologies (BNU, GMU, HBU, HRN, IRN, PBU, STU; see Table 1) were developed by Knapp *et al.* (2001b). The remaining eleven chronologies were developed by Holmes *et al.* (1986) and were obtained from the International Tree-Ring Data Bank (Grissino-Mayer and Fritts, 1997). Because too few chronologies extended prior to 1500, we selected the period 1500–1998 as a common period where over half of the chronologies were represented.

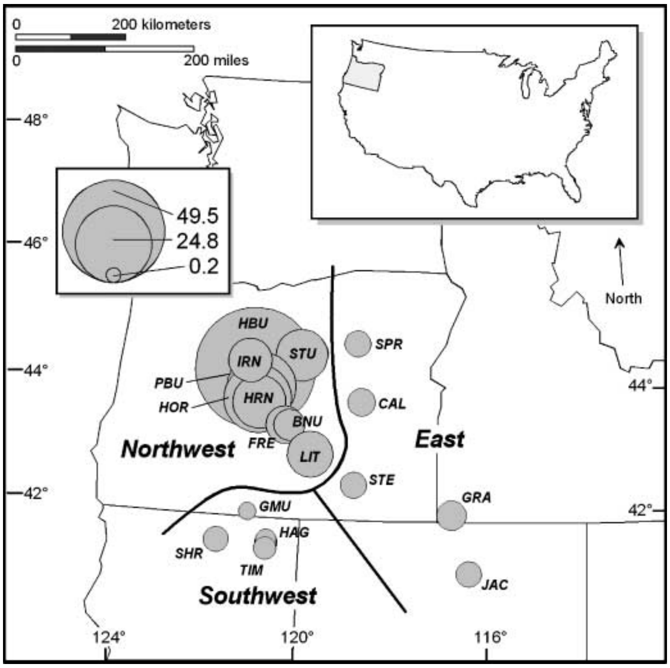

FIG. 1. Subregional divisions based on a precipitation variability index. Circles indicate both location of chronologies and magnitude of the index. Bold line indicates approximate climatic boundary between subregions.

Development of a Climatic Pointer Year Index

Previous studies (Hughes and Brown, 1992; Schweingruber *et al.*, 1990) have used threshold values (e.g., years with ring width index values in the lowest decile) for establishing pointer years. We were concerned, however, about establishing *a priori* threshold values as certain periods could be well below this value in general (i.e., long-term trends). We employed a different method that includes the preceding and following years to calculate the CPYI. We selected this technique because we believe it is intuitive and mimics the visual method of crossdating, whereby a moving "window" of years is established when attempting to identify particularly narrow rings (i.e., pointer years). Our technique uses three consecutive tree rings. This short "window" could result in the discrimination against dry years embedded in extended droughts (such as the 1930s), because the middle pointer year may not show up if the previous year was also a narrow ring. Our focus, however, is on identifying *single*-year drought events to help us learn about extreme climatic events (and to gain more information about crossdating), and we found the 3-year "window" to be more effective.

TABLE 1
General Characteristics for Each Chronology

Site name	Site code	Latitude °N	Longitude °W	Elevation (m)	Chronology period	1734–1979 CPYI variance	Matched climate station ID	Monthly Ppt. variance	PVI	Division
Haystack Butte PRNA	HBU	44.45	121.15	1185	1596–1998	2.97	357062	0.06	49.50	NW
Powell Butte RNA	PBU	44.15	121.00	1220	1665–1998	0.76	357062	0.06	12.67	NW
Horse Ridge	HOR	43.97	121.07	1109	1281– 1982	0.84	351067	0.07	12.00	NW
Horse Ridge RNA	HRN	43.92	121.03	1300	1613–1996	0.44	351067	0.07	6.29	NW
Sutton Mountain PRNA	STU	44.68	120.23	800	1709–1998	0.51	355641	0.09	5.67	NW
Little Juniper Mountain	LIT	43.13	119.87	1524	1377–1982	0.36	356302	0.07	5.14	NW
The Island RNA	IRN	44.57	121.27	730	1733–1996	0.44	355515	0.13	3.38	NW
Frederick Butte	FRE	43.58	120.45	1433	1097–1982	0.21	358029	0.11	1.91	NW
Benjamin RNA	BNU	43.58	120.35	1510	1682–1998	0.11	358029	0.11	1.00	NW
Grasshopper Trail	GRA	42.22	116.80	1689	1492–1984	0.09	102444	0.10	0.90	E
Calamity Creek	CAL	43.98	118.80	1433	1396–1982	0.09	357675	0.13	0.69	E
Steens Mountain	STE	42.67	118.92	1625	1501–1982	0.07	356853	0.11	0.64	E
Spring Canyon	SPR	44.9	118.92	1340	1405–1982	0.05	350417	0.09	0.56	E
Jackson Mountains	JAC	41.3	116.43	2024	1267–1984	0.07	262189	0.14	0.50	E
Sharp Mountain	SHR	41.73	121.82	1335	1548–1982	0.08	045941	0.17	0.47	SW
Hager Basin	HAG	41.77	120.75	1518	1310–1980	0.05	040161	0.21	0.24	SW
Timbered Mountain	TIM	41.72	120.75	1555	1654–1980	0.05	040161	0.21	0.24	SW
Goodlow Mountain RNA	GMU	42.2	121.18	1555	1285–1998	0.05	357354	0.39	0.13	SW
Northwest sites						0.74				
Northeast sites						0.07				
Southwest sites						0.06				
All sites						0.41				

Note. CPYI = Climatic pointer year index.

To create a CPYI for each year in the chronology, we divided the annual radial growth index by the average of the growth indices from the previous and following years. Thus, for any given year, the magnitude of the CPYI would be lower (or higher) if that year's growth index was less than (or greater than) the mean of the two adjacent years. Because the prior and following years were necessary for the development of the CPYI, the earliest CPYI was calculated for 1501 and the latest for 1997.

Development of a Precipitation Variability Index (PVI)

Winter/spring precipitation (October–June total) is the climatic variable that most influences radial growth of western juniper throughout a large portion of the species' range in the Pacific Northwest (Knapp *et al.*, 2001a, b). Climate records for nearby stations, however, indicate substantial variability in the amounts of winter and spring precipitation that could affect variability in growth rates of western juniper. For example, rainfall at the IRN site is largely concentrated during the winter months, while rainfall at the HAG and TIM sites is spread evenly throughout the winter and spring months. Hence, a dry winter will have differential effects (i.e., intraannual variability) throughout the range of our study sites and therefore affect the interannual variability of western juniper tree growth. To account for the possible effects of this intraannual variability, we first calculated the CPYI variance for the common interval period of 1734–1979 for each of the 18 chronologies. We then divided the CPYI variance by the variance in mean monthly precipitation (i.e., monthly precipitation from January through December) obtained from the climatic station closest to the site from where the trees were collected (Table 1). This second index we call the precipitation variability index, or PVI. The PVI therefore contains information on the CPYI, but accounts for variability in both intraannual and interannual precipitation amounts. The PVI should assist in the identification of climatic boundaries. We omitted including a measure of temperature variance because our previous studies have shown that temperature has only a minor influence on radial growth (Knapp *et al.*, 2001a, b).

Climatic Regionalization

We used two methods to search for spatial patterns in climate as identified by the CPYI and the PVI. First, we mapped the PVI for each of the 18 chronologies. We then identified distinct clusters of sites (PVI values of 0–0.49, 0.50–0.99, and >1.0) with similar values of the index.

Second, we used s-mode principal components analysis (PCA) on the CPYI values from a common interval period 1734–1979 to confirm the validity of the regionalization based on spatial coherence of PVI values. S-mode PCA is a proven technique for climate regionalization (e.g., Dyer, 1975; Karl and Koscielny, 1982; Eder *et al.*, 1987; Soulé, 1990; Leathers *et al.*, 1993; Acker and Soulé, 1995). The input data set consisted of 18 columns representing the individual chronologies and 246 rows containing

TABLE 2
Comparison of Drought Years (All Sites) Defined by Actual Mean Radial Growth Index Data and CPYI Data for All Sites

Year	Mean CPYI	CPY rank	Rank of year based on mean radial growth index
1924	0.37	1	3
1800	0.42	2	6
1931	0.43	3	1
1632	0.44	4	7
1992	0.45	5	16
1703	0.46	6	24
1968	0.48	7	28
1532	0.48	8	2
1600	0.48	9	30
1626	0.49	10	11
1518	0.49	11	18
1955	0.50	12	35
1939	0.55	13	20
1783	0.56	14	23
1595	0.57	15	9
1657	0.58	16	40
1529	0.58	17	19
1565	0.59	18	93
1721	0.60	19	10
1788	0.60	20	32
1934	0.60	21	4
1829	0.60	22	13
1717	0.61	23	21
1987	0.61	24	109
1959	0.61	25	64
1994	0.61	26	175
1926	0.61	27	42
1880	0.62	28	92
1735	0.62	29	27
1807	0.63	30	36
1639	0.63	31	45
1729	0.63	32	22
1502	0.64	33	118
1686	0.65	34	69
1714	0.66	35	84
1695	0.66	36	39
1655	0.66	37	90
1966	0.67	38	208
1831	0.67	39	54
1652	0.67	40	15
1554	0.68	41	50
1563	0.68	42	114
1706	0.68	43	46
1609	0.68	44	292
1804	0.68	45	189
1922	0.69	46	149
1667	0.70	47	151
1744	0.70	48	211
1598	0.70	49	202
1933	0.71	50	5

Note. Super-regional CPYs, shown in bold face, do not exist post-1983 because no chronology in the East subregion had an ending date later. CPY = climatic pointer year; CPYI = CPY index.

yearly values of the CPYI. Using the FACTOR procedure of the Statistical Analysis System (SAS, 1985), we first conducted an unrotated PCA to determine the number of principal components (PCs) to retain for rotation. A scree test (Cattell, 1966) suggested that three PCs be retained for rotation. We then used the Varimax orthogonal rotation to search for spatial clusters of stations. Specifically, we examined the pattern of the PC loadings for each of the three PCs to see if spatially homogeneous regions could be identified.

Identifying Common Extreme Years

We averaged the CPYI from all sites within a given region to acquire a regional value for each year. We then ranked these CPYI values from lowest to highest. For example, the CPYI for the year 1800 for the Northwest group (mean of nine chronologies) was 0.09 and represented the lowest index value for the entire region. We repeated this process for the East and Southwest groups. When the mean regional CPYI value fell within the top 10% (i.e., lowest CPYI values) of all years, we labeled that year an extreme climatic pointer year (CPY). The years meeting these criteria were identified as "super-regional" years if the extreme CPY occurred in all three regions, "regional" if the extreme CPY was present in two of the regions, and "subregional" if the extreme CPY occurred in only one region. To confirm that CPYs with high rankings (i.e., low CPYI values) accurately reflected extreme single-year drought events, we compared those years with high CPY rankings with rankings derived by averaging the mean yearly radial growth index values for all 18 sites (i.e., super-regional) and for each region. For example, we compared the rank for the year 1924 based on the CPY (rank = 1) with the rank based on the average radial growth from all sites (rank = 3; Table 2).

RESULTS

Climatic Regions

We identified three spatially coherent regions (Table 1, Fig. 1): a Northwest region (NW) that included nine chronologies (BNU, FRE, HBU, HRN, HOR, IRN, LIT, PBU, STU), an East region (E) with five chronologies (CAL, GRA, JAC, SPR, STE), and a Southwest region (SW) with four chronologies (GMU, HAG, SHR, TIM). These regions were differentiated by the variability in either the CPY indices or monthly precipitation. The Northwest region was characterized by high CPYI variance but low monthly precipitation variance. The East and Southwest regions both had low CPY variances but were differentiated by the variance of the monthly precipitation totals for the nearby climatic stations.

The PC loadings pattern for the 18 chronology locations closely matched the regionalization identified by the PVI map (Table 3, Fig. 1). Eight of the nine chronologies grouped into the Northwest region using the PVI all load most highly on PC1, the five East region chronologies plus GMU and HAG load most highly on PC2, and SHR, TIM, and BNU load most highly on

PC3. Thus, PC1 is most closely aligned with our Northwest region chronologies, PC2 with the East region, and PC3 with the Southwest region. Two of the chronology locations that differ on the regionalization methods, BNU and HAG, actually load highly on two PCs. For example, the PC1 loading for BNU was 0.58 and for PC2 it was 0.59, suggesting that BNU has experienced conditions (as identified by the CPYI) common to these two groupings. As indicated by the PC loadings, only one location, GMU, is clearly more aligned with chronology locations outside the region (SW) identified using the PVI. Despite the more objective classification offered by PCA, we selected the more intuitive PVI method for our climatic regionalization because the placement of chronologies within a region was more spatially consistent (e.g., HAG and TIM, only a few km apart, fell within the same region using the PVI, but were separated by PCA).

Extreme Climatic Pointer Years

Eleven years met the criteria for super-regional extreme CPYs (Fig. 2). Of these extreme CPYs, seven occurred between 1502 and 1657, while only 2 yr occurred after 1717. There were 18, 15, and 26 regional extreme CPYs for the NW × E, NW × SW and E × SW regions, respectively (Table 4, Fig. 2). For the NW × E, and NW × SW combinations, again the extreme CPYs were concentrated in the early years with only 1 yr in the 1800s being an extreme CPY. Conversely, for the E × SW region, extreme CPYs were much more evenly distributed over the approximate 500-yr period.

TABLE 3
Loadings Pattern from a Varimax Orthogonal Rotation with Three Principal Components (PC) Retained

Site	PC1	PC2	PC3
STU	**0.74**	0.31	−0.14
IRN	**0.73**	0.11	0.36
HBU	**0.74**	−0.04	0.08
PBU	**0.87**	0.21	0.22
HOR	**0.86**	0.10	0.19
HRN	**0.77**	0.25	0.29
FRE	**0.73**	0.15	0.55
BNU	0.58	0.26	**0.59**
LIT	**0.59**	0.20	0.47
SPR	0.05	**0.79**	0.03
CAL	0.19	**0.76**	0.29
STE	0.30	**0.79**	0.15
GRA	0.21	**0.82**	0.14
JAC	0.16	**0.55**	0.44
GMU	0.05	**0.80**	0.29
HAG	0.02	**0.64**	0.55
SHR	0.39	0.32	**0.71**
TIM	0.26	0.43	**0.72**

Note. Highest loadings for each principal component are in bold, with loadings measuring the degree of relationship between each variable (chronology, as measured by the CPYI) and the associated principal component. CPYI = climatic pointer year index.

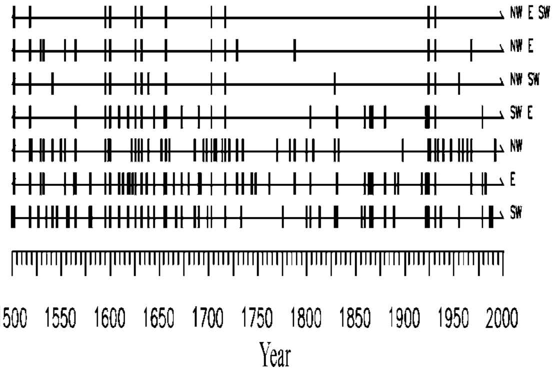

FIG. 2. Temporal occurrence of extreme climatic pointer years by super-region (NW E SW), region (NW E, NW SW, and SW E), and subregion (NW, E, and SW).

For the subregions, the occurrence of extreme CPYs varied considerably (Tables 4 and 5) and each subregion had one unusual century. The 1800s in the Northwest subregion were unusual in that only five extreme CPYs occurred in comparison to the nearly even distribution in the four other centuries. Similarly, there were only four extreme CPYs during the 1700s for the Southwest subregion. For the East subregion, the 1600s were unusual in that 17 extreme CPYs occurred, suggesting that this was a century of repeated extreme single-year droughts.

DISCUSSION

Climatic Boundaries and Climatic Forcing

Two of the three climatic regions that we identified based on the PVI closely approximate those of Mitchell (1976; see Fig. 3 in Mitchell), who used equivalent potential temperature (a function of water vapor and temperature) as a delimiting factor for regions of the western United States. Specifically, Mitchell (1976, p. 925) identified two PNW climatic regions, “II,” and “V,” which are similar to our East and Southwest subregions, respectively. Conversely, the sites that fall within our Northwest region all occur along the transition boundary between Mitchell’s regions “I” and “II.” The Northwest subregion, which was characterized by the sites having high variances in the CPYI, was the most distinct of our three regions. Mitchell’s transition boundary between regions “I” and “II” was based on region “I” having “frequent intrusions” of marine air in the summer (as opposed to “interior air”), although both regions are impacted by marine air in the winter. Because of the high correlation between winter/spring precipitation and radial growth of western juniper (and only minor influences from temperature variability), we suspect that the high CPYI variances of our nine sites within the Northwest subregion may be caused by their location on the seasonal marine/interior air mass boundary. Additional possible causes could be the influence of El Niño/Southern Oscillation (ENSO) events that promote above-average winter/spring precipitation in much of the PNW during positive Southern Oscillation Index

(SOI) phases and below-average precipitation during negative SOI phases (Redmond and Koch, 1991). The nine Northwest subregional sites, however, all fall within a region (i.e., climatic division) that has a positive, but not significant, correlation with SOI events. Thus, this relationship is unclear.

TABLE 4
Extreme Climatic Pointer Years (Top 50 Years for Each Subregion Based on CPYI)

Year	NW	Year	NE	Year	SW
1800	0.09	1924	0.45	1924	0.40
1532	0.10	1600	0.46	1703	0.46
1529	0.13	1657	0.54	1581	0.49
1632	0.16	1518	0.55	1595	0.51
1968	0.17	1626	0.56	1579	0.52
1931	0.18	1632	0.57	1609	0.53
1934	0.20	1831	0.58	1989	0.57
1652	0.24	1563	0.59	1733	0.57
1518	0.24	1532	0.59	1626	0.58
1939	0.26	1804	0.60	1500	0.58
1955	0.27	1565	0.60	1686	0.61
1829	0.27	1623	0.60	1937	0.61
1695	0.28	1865	0.60	1558	0.64
1550	0.29	1735	0.60	1829	0.64
1924	0.30	1982	0.61	1717	0.65
1783	0.32	1922	0.61	1655	0.66
1598	0.32	1703	0.63	1667	0.66
1600	0.33	1609	0.63	1859	0.67
1703	0.35	1680	0.64	1639	0.67
1626	0.36	1931	0.65	1502	0.69
1959	0.39	1620	0.66	1776	0.69
1721	0.39	1554	0.66	1535	0.69
1926	0.39	1863	0.67	1987	0.69
1992	0.40	1655	0.67	1618	0.69
1706	0.40	1859	0.68	1546	0.69
1639	0.41	1692	0.68	1800	0.70
1788	0.42	1595	0.68	1632	0.70
1622	0.43	1618	0.68	1565	0.70
1714	0.44	1645	0.69	1955	0.71
1595	0.44	1673	0.70	1556	0.71
1947	0.45	1917	0.70	1880	0.71
1554	0.46	1880	0.70	1699	0.71
1565	0.46	1744	0.71	1645	0.72
1833	0.46	1893	0.72	1831	0.72
1698	0.47	1613	0.72	1979	0.73
1502	0.47	1717	0.72	1867	0.73
1770	0.47	1529	0.73	1690	0.73
1660	0.47	1890	0.73	1657	0.73
1729	0.47	1729	0.73	1600	0.73
1807	0.48	1502	0.73	1518	0.73
1629	0.48	1979	0.73	1931	0.73
1964	0.48	1968	0.74	1527	0.74
1657	0.49	1637	0.74	1541	0.74
1520	0.49	1665	0.74	1813	0.75
1708	0.49	1580	0.74	1673	0.75
1686	0.50	1867	0.74	1865	0.75
1898	0.50	1762	0.74	1889	0.75
1717	0.51	1690	0.75	1804	0.75
1735	0.52	1748	0.75	1856	0.76
1541	0.53	1788	0.75	1922	0.76

TABLE 5
Occurrence of Extreme Climatic Pointer Years by Subregion and Century

	Subregion			
Century	NW	E	SW	Total
1500s	11 (3)	9 (5)	13 (2)	33 (10)
1600s	12 (4)[a]	17 (5)	14 (3)	43 (12)
1700s	11 (5)	8 (5)	4 (4)	23 (14)
1800s	5 (9)	9 (5)	11 (4)	25 (18)
1900s	11 (9)	7 (5)[b]	8 (4)[c]	26 (18)

Note. Numbers shown in parentheses indicate number of chronologies represented per century.

[a] Includes one chronology that began in 1613.

[b] All chronologies ended by 1983. Thus, this number may *underestimate* the total number of climatic pointer years for the 1900s.

[c] Only one chronology from 1981–1997.

The consistency of CPYI variances of the East and Southwest subregions suggests that the synoptic controls influencing winter/spring precipitation are more spatially homogeneous. Winter/spring precipitation amounts are not significantly correlated with SOI values (Redmond and Koch, 1991), and thus radial growth of western juniper in these regions is unlikely severely impacted by the waxing and waning of El Niño/La Niña events. In fact, a remarkable characteristic of the East and Southwest subregions is the lack of truly severe droughts. A comparison of the top 50 CPYIs for each of the subregions (Table 4) shows that the most extreme CPYI (lowest index value) for the East and Southwest subregions would have ranked 31st and 25th, respectively, to the lowest CPYI for the Northwest subregion. We also explored the possibility that the lower CPYI variances for the East and Southwest subregions were related to elevation of the collection sites. The Northwest subregion is substantially lower (mean elevation of nine sites was 1120 m), while the mean of the East and Southwest sites are 1622 m and 1490 m, respectively. There is, however, no significant correlation between CPYI variance and elevation.

Occurrence of Extreme CPY Events

Use of the CPYI identified 11 years that were common for all three subregions and thus suggests that a synoptic-level climatic control was operative during these events. It is noteworthy that, following the 1717 event, no CPYs were concurrently extreme in all three subregions until 1924, suggesting that both the 18th and 19th centuries were largely characterized by a paucity of drought events that were severe and widespread, but of short duration. These results are in close agreement with the spatial and temporal changes of the winter air-mass boundary (Woodhouse and Kay, 1990) that affects the interior PNW. Using eleven tree-ring chronologies growing near the air mass boundary defined by Mitchell (1976), Woodhouse and Kay (1990) determined that substantial temporal variability occurred in the location of this boundary during the past four centuries, with a meridional

TABLE 6
Variability of the PDO Index Compared with Variability in CPYs

PDO phase	Phase type	Percentage of years $\lvert\Sigma\mathrm{PDO}_t\rvert \geq 5$[a]	PDO average by phase[b]	PDO variance by phase	Extreme CPYs per year	CPY variance
1900–1924	cold	0%	0.11	0.27	0.08	0.08
1925–1946	warm	23%	0.50	0.35	0.23	0.66
1947–1976	cold	37%	−0.78	0.60	0.20	0.17
1977–1997	warm	24%	0.48	0.65	0.14	0.20

Note. PDO = Pacific Decadal Osullation; CPY = climatic pointer year.

[a] November–March monthly PDO summed. PDO values of ±1 in each month would therefore give a summed value of ±5.

[b] Based on November–March monthly PDO Index.

orientation during the 1600s, early 1700s and 1900s, and a zonal orientation during the remaining 1700s and 1800s. Changes in the degree of meridionality of the winter air-mass boundary is likely the result of a wintertime blocking high positioned over Vancouver Island, which steers midlatitude cyclones substantially north of their average storm track (Fritts *et al.*, 1979; Namias, 1983). In an assessment of winter precipitation variability in the Columbia Basin and California since the early 1600s, Fritts *et al.*, (1979) suggested a greater frequency of this pattern during the 1600s compared to the following centuries was likely responsible for the highest concentration of drought events during their study period.

The extended period without an extreme CPY also may have been caused by a potential relationship between the CPYI and another oscillatory climatic pattern. The PDO, (sometimes called the North Pacific Oscillation or NPO) shifts between warm and cool phases that bring below and above average precipitation, respectively, to the Pacific Northwest (Mantua *et al.*, 1997; Gershunov and Barnett, 1998; Gershunov *et al.*, 1999). This oscillation appears to operate over decadal timescales, at least during the 20th century, with cool phases occurring between 1900 and 1924 and 1947 and 1976, and warm phases occurring from 1925 and 1946 and again from 1977 to 1996. The variability of the PDO is low during the 1900–1924 period and increases substantially after 1924. We also observed that CPYs became more numerous during the 20th century (beginning with the severe drought year of 1924) after a long absence of severe regional drought years between 1717 and 1923 (Fig. 2). To test this possible association, we summed November–March monthly PDO indices (months used to derive the PDO) and recorded the percentage of years with extreme values ($\lvert\Sigma\mathrm{PDO}_t\rvert \geq 5$). No extreme PDO years occurred between 1900 and 1924, a period that had no extreme CPYs (Table 6). Furthermore, both the frequency and variance of PDO increase beginning with the 1925–1946 period, concurrent with an increase in the frequency and variance of CPYs (Table 6). CPYs as recorded in tree growth therefore appear to reflect intensification of the PDO during the 20th century. This relationship possibly suggests that the influence of the PDO was nonexistent or minimal during the period 1717–1923, a period with few regional drought years as recorded in the tree-ring record. Biondi *et al.* (2001) also observed that the variability of the PDO during the 1900s was anomalous compared to reconstructed indices for the three previous centuries. In addition, Kadonaga *et al.* (1999) found "unusual year groupings" in the period 1924–1946 during their inspection of tree-ring records back to 1650 for the Pacific Northwest, suggesting a significant change in climate variability.

CONCLUSIONS

Use of tree-ring records from a species with a wide geographical range may be advantageous for reconstruction of extreme single-year drought events and the subsequent mapping of potential climatic boundaries. Western juniper, because of its widespread distribution throughout the interior PNW, strong correlation between growth and current year winter/spring precipitation, and interannual radial growth variability, is thus an excellent species to examine. Our results suggest that the frequency of severe and widespread, but short-term drought events in the interior PNW has significant temporal and spatial variability and that the occurrence of these drought events during the last 500 yr was concentrated in the 16th and 17th centuries. Further, the number of extreme CPYs within these centuries exceeded the combined total for the following three centuries, indicating that overall, the last 300 yr have been unremarkable from a drought-frequency perspective, but noteworthy in terms of drought intensity. Examination of the interannual variability in western juniper growth indices suggests that in addition to being an excellent indicator of subtle climatic boundaries, this species could be used to reconstruct variability in these boundaries for the past half-millennium.

Development of extreme CPYs may also provide a beneficial side effect in that these years can be used in the crossdating of future chronologies. The consistency of extreme CPYs, particularly those that are super-regional, indicate that these years should also be easily identified in other western juniper chronologies collected throughout the interior PNW. Further, this method of identifying extreme CPYs is simple and could be applied to other species.

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