

# Contingent Pacific–Atlantic Ocean influence on multicentury wildfire synchrony over western North America

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**Widespread synchronous wildfires driven by climatic variation, such as those that swept western North America during 1996, 2000, and 2002, can result in major environmental and societal impacts. Understanding relationships between continental-scale patterns of drought and modes of sea surface temperatures (SSTs) such as El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO) may explain how interannual to multidecadal variability in SSTs drives fire at continental scales. We used local wildfire chronologies reconstructed from fire scars on tree rings across western North America and independent reconstructions of SST developed from tree-ring widths at other sites to examine the relationships of multicentury patterns of climate and fire synchrony. From 33,039 annually resolved fire-scar dates at 238 sites (the largest paleofire record yet assembled), we examined forest fires at regional and subcontinental scales. Since 1550 CE, drought and forest fires covaried across the West, but in a manner contingent on SST modes. During certain phases of ENSO and PDO, fire was synchronous within broad subregions and sometimes asynchronous among those regions. In contrast, fires were most commonly synchronous across the West during warm phases of the AMO. ENSO and PDO were the main drivers of high-frequency variation in fire (interannual to decadal), whereas the AMO conditionally changed the strength and spatial influence of ENSO and PDO on wildfire occurrence at multidecadal scales. A current warming trend in AMO suggests that we may expect an increase in widespread, synchronous fires across the western U.S. in coming decades.**

Atlantic Multidecadal Oscillation | El Niño Southern Oscillation | fire history network | ocean warming | Pacific Decadal Oscillation

**W**ildfires are clearly driven by interannual variation in weather, but our understanding of the effects of multianual to multidecadal spatial variations in fire-climate patterns in western North America and their relationship to broader-scale ocean–atmosphere patterns is incomplete. Linkages between fire and climate at broad spatial scales are evident when many large fires occur synchronously across broad regions during severe and extensive droughts lasting multiple seasons, such as the recent dry spell from 1999 to 2004. Recent advances in our understanding of ocean–atmosphere patterns and their influences on climate in western North America suggest that contingent states of sea surface temperature (SST) and atmospheric pressure in both the Pacific and Atlantic Basins may synchronize drought and hence fires in the western U.S. Moreover, climate and fire in different regions (e.g., the Pacific Northwest versus the Southwest), may respond in unique ways to these ocean–atmosphere conditions and their associated circulation patterns.

Both Pacific and Atlantic conditions appear to be involved in climate teleconnections in western North America, although precise mechanisms are only beginning to be understood (1–6). Observational and modeling studies (using global circulation

models) consistently show that Pacific SSTs play an important role in driving interannual to decadal moisture and temperature patterns in this region (3, 4, 6). Dry or wet episodes are relatively stronger or weaker in particular times and regions, depending on the contingent state of El Niño Southern Oscillation (ENSO; seasonal to interannual variations in SSTs in the tropical Pacific), and Pacific Decadal Oscillation (PDO) (variations in SSTs in the north Pacific with a typical cycle of  $\approx 20$  years) (7, 8). Accumulating evidence from observations and modeling indicates that the Atlantic Multidecadal Oscillation (AMO; variations in SSTs in the north Atlantic that tend to adopt warm or cool modes at a  $\approx 60$ -year cycle) is probably also involved in North American climate patterns (1–6, 8). Contingent SST conditions in both the Pacific and Atlantic seem to be particularly important, such as the coincidence of positive phases of the PDO and AMO, that resulted in drier conditions that persisted for a decade or longer in the northern tier of western U.S. states, extending into the Great Plains, during the 1930s drought (1, 2, 5, 7). In contrast, the coincidence of positive AMO and negative PDO phases were typically associated with dry and hot conditions across the southern tier of western states, as occurred during the 1950s drought. Likewise, La Niña events (occurring at scales of seasons to years) were typically related to the strongest droughts in the Southwest during the negative phase of the PDO (occurring at scales of years to decades) (7). In some combinations, these ocean–atmosphere oscillations produce particularly strong and spatially coherent dipole patterns of opposite dry/wet conditions in the Pacific Northwest versus the Southwest (2, 7, 9, 10).

Links between contingencies of ENSO and PDO, droughts and wildfires have been noted in the western U.S. before, but only for subregions (11–13) or using 20th century data (10, 14). Furthermore, AMO–fire teleconnections and contingencies with ENSO and PDO previously have been shown for single study areas but have not been examined at regional scales (15, 16). The recent availability of multicentury tree-ring width reconstructions of ENSO (Niño-3 Pacific SST 5°N–5°S, 90–150°W) (17), PDO (standardized leading PC of monthly SST anomalies in the North Pacific poleward of 20°) (18), and AMO (10-year running mean of detrended SST anomalies averaged over the North Atlantic Basin

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Abbreviations: SST, sea surface temperature; ENSO, El Niño Southern Oscillation; PDO, Pacific Decadal Oscillation; PC, principal component; PDSI, Palmer Drought Severity Index; AMO, Atlantic Multidecadal Oscillation.

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**Table 1. Description of the North American tree-ring-based fire history database used in this study obtained from the International Multiproxy Paleofire Database, World Data Center for Paleoclimatology ([www.ncdc.noaa.gov/paleo/impd/paleofire.html](http://www.ncdc.noaa.gov/paleo/impd/paleofire.html))**

Region	Location	Number of sites	Number of fires (scars)	Number of fires (scars) by 1550 CE	Number of fires (scars) by 1700 CE
SMO	Sierra Madre Occidental, Mexico	8	231 (1,469)	0 (0)	2 (2)
AZ	Arizona	20	276 (4,785)	3 (21)	63 (605)
SNM	Southern New Mexico	37	430 (3,791)	4 (51)	58 (558)
NNM	Northern New Mexico	41	462 (6,013)	25 (120)	150 (1,147)
SCO	Southern Colorado	29	243 (2,109)	19 (105)	82 (512)
NCO	Northern Colorado	14	102 (1,155)	2 (11)	23 (129)
BHI	Black Hills, South Dakota	29	320 (1,980)	5 (26)	90 (435)
SNE	Sierra Nevada, California	54	1,220 (6,091)	26 (181)	188 (1,024)
PNW	Blue Mountains, Oregon, Washington Southern British Columbia, Canada	6	229 (5,646)	5 (25)	61 (627)
<b>Total</b>		<b>238</b>	<b>3,513 (33,039)</b>	<b>89 (540)</b>	<b>717 (5,039)</b>

from 0 to 70° N) (19), and independent networks of fire-scar chronologies enables us to evaluate continental-scale fire climatology over multiple centuries.

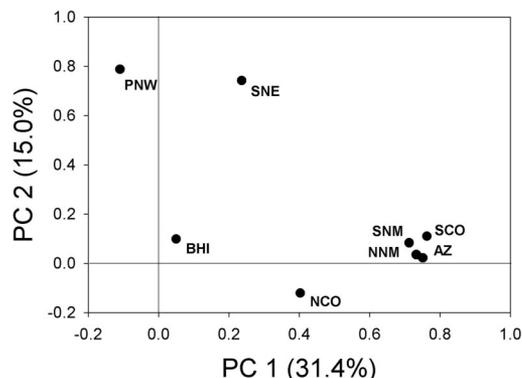
### Results and Discussion

Our data set included a total of 33,039 annually resolved fire-scar dates from >4,700 fire-scarred trees in nine regions in western North America (Table 1).

Almost half the variance in fire occurrence among the nine subregions was explained by the first two components from a rotated principal components (PCs) analysis of the annual percentage of sites recording fire (%SF; 1550–1924; PC1 and PC2, 31% and 15%, respectively). Fires were highly synchronous within the Southwest (AZ, SNM, NNM, and SCO, see Table 1) but usually asynchronous between the Southwest and the Pacific Northwest (Fig. 1).

Correlations of these components with summer Palmer Drought Severity Index (PDSI) (Fig. 2*A* and *B*) revealed broad northern and southern areas of common variation. In general, it appears that PC1 captured variations at interannual time scales, likely reflecting the influence of ENSO on fire across western North America, whereas PC2 captured variation at decadal scales, likely reflecting the influence of PDO in the Pacific Northwest.

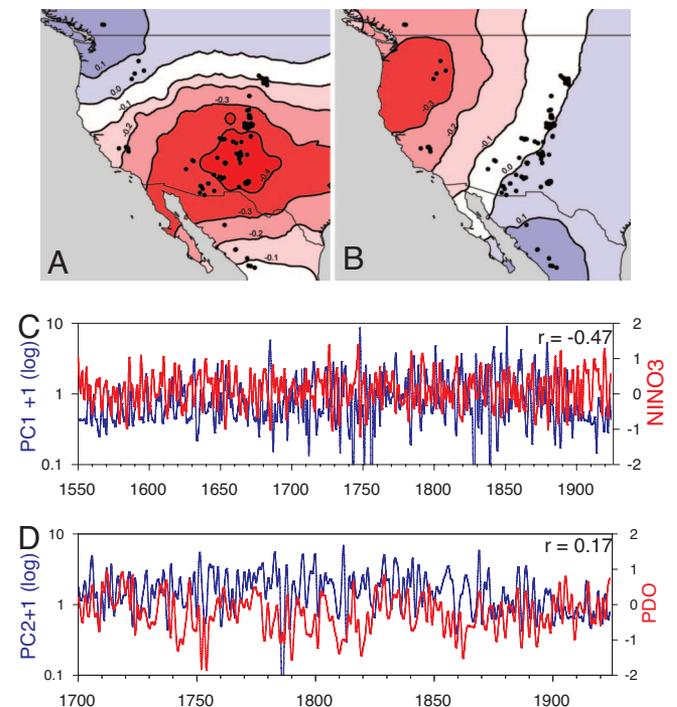
Significant correlations of the first component, PC1, and PDSI were negative in the Southwest, indicating drought ( $r < -0.3$ ,  $P < 0.0001$ ), but positive in the Pacific Northwest and southwestern Canada ( $r > 0.1$ ,  $P < 0.05$ ). This finding resembles the typical dipole pattern of precipitation and drought related to ENSO interannual variability (2, 7), (Fig. 2*A*), and, indeed, this



**Fig. 1.** Loadings of the first two PCs of a rotated principal components analysis of percentage of sites with fire scars (%SF) plotted in PC1–2 space.

component was most strongly correlated with NINO3 (Fig. 2*C*;  $r = -0.48$ ,  $P < 0.0001$ ). Although these two patterns, PC1 and PC2, account for much of the variation in fire years, fire synchrony in some years differed from these two patterns. For example, when we forced the 238 binary fire chronologies into five clusters, fires were synchronous in the Sierra Nevada, Arizona, and New Mexico or over the entire western U.S. [supporting information (SI) Fig. 6]. Wavelet spectra of the PC1 scores showed a significant global maximum at a 4- to 5-year periodicity ( $P < 0.05$ , compared with red noise spectrum, SI Fig. 7), similar to ENSO periodicity.

In the Southwest, northwestern Mexico, and the south-central Rocky Mountains, production of the fine fuels that carry forest



**Fig. 2.** Spatial and temporal patterns of fire correlations with PDSI and SST indices. (*A* and *B*) Correlations between the scores of the first two components of a rotated principal components analysis (PCA) of percentage sites with fire scars (%SF) and gridded tree-ring reconstructed PDSI in the conterminous U.S. for the period 1550–1925. Scores from the first two components of a varimax rotated PCA of the %SF (log scale, blue). (*C* and *D*) Superimposed on PC1 and PC2 scores are reconstructed NINO3 and reconstructed PDO (red line).

**Table 2. Three-way combinations of contingent states**

	SMO	AZ	SNM	NNM	SCO	NCO	BHI	SNE	PNW
SMO	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>	<i>A+P-N-</i>	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>
AZ			<b>A+P-N-</b>	<i>A-P-N-</i>	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>
SNM				<i>A-P-N-</i>	<i>A-P-N-</i>		<i>A-P+N+</i>	<i>A-P+N+</i>	<i>A-P+N+</i>
NNM			<b>A+P-N-</b>	<b>A-P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>
SCO			<i>A-P-N-</i>						<i>A-P+N-</i>
NCO				<i>A-P-N-</i>	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>	<b>A+P-N-</b>
BHI									<b>A+P-N-</b>
SNE									<i>A-P+N+</i>
PNW									<b>A+P-N-</b>

Three-way combinations of contingent states of ENSO (E), PDO (P), and AMO (A) during which observed fires were synchronous within regions (years with >5% of sites with synchronous fires, shown in diagonal cells that are enclosed in black lines) or between regions (fire years recorded at ≥1 site in each region, nondiagonal cells) above that expected by chance (bold,  $P < 0.01$ ; italics,  $P < 0.05$ ; normal,  $P < 0.10$ ,  $\chi^2$  tests); +, warm phase; -, cold phase. All phase combinations occurred during the period analyzed (1700–1900). Phase combinations during which fire synchrony was not significantly above that expected by chance are not shown. The four significant phase combinations are color coded (gold, warm AMO, cold PDO, La Niña; blue, cold AMO, cold PDO, La Niña; green, cold AMO, warm PDO, El Niño; purple, cold AMO, warm PDO, La Niña).

fires, such as grass and needle litter, is increased during wet years, which are often associated with warm ENSO events (20). When these warm events are followed by La Niña events, with their associated dry conditions, fires are synchronized across this region (21, 22).

Lagged correlations between PC1 and PDSI (SI Fig. 8) confirm the importance of prior wet years in synchronizing fire across the Southwest (10, 20, 21). PC1 was correlated with -2 year-lagged PDSI in the Southwest (AZ, SNM, NNM, NCO, SMO;  $r > 0.1$ –0.2,  $P < 0.001$ ) and with -1 year-lagged PDSI in these regions plus Colorado and northern Mexico ( $r > 0.1$ ,  $P < 0.05$ ).

In contrast to the influence of ENSO in the Southwest, warmer/drier conditions in the Pacific Northwest are associated with El Niño events, typically resulting in earlier melting of snowpack, and hence a longer fire season, leading to synchronous fires in this subregion (23, 24). Lagged correlations between PC1 and PDSI were not significant in the Pacific Northwest, where fine fuel amount apparently does not limit forest fire occurrence at these temporal and spatial scales.

Significant correlations of the second component, PC2, with PDSI were negative in the Pacific Northwest, southwestern Canada, and northern California ( $r < -0.3$ ,  $P < 0.0001$ ; Fig. 2B) and weakly positive in northern Mexico ( $r > 0.1$ ,  $P < 0.05$ ). This component was correlated with PDO ( $r = 0.17$ ,  $P < 0.05$ , 1700–1899; Fig. 2D). Furthermore, wavelet spectra of the PC2 scores show a nonsignificant peak at ≈10- to 20-year period (SI Fig. 7), similar to that for PDO. PC2 was not significantly correlated with lagged PDSI (SI Fig. 8).

In contrast to the influence of ENSO and PDO on fire synchrony, which varies among regions, positive AMO appears to synchronize fire across western North America at multidecadal time scales.

Warm AMO phases were related to higher-than-expected fire synchrony in 32 of 36 possible interregional comparisons (89%) comprising most regions of western North America (Table 2). Cool AMO produced a lower degree of synchrony (50%) over relatively smaller regions such as the Southwest (with negative PDO and La Niña conditions) and the Pacific Coast (with positive PDO and El Niño conditions; Table 2).

The degree of synchrony in fire between all pairs of regions, varied during the past 475 years, consistent with variation in AMO (19) (Fig. 3 and SI Tables 3 and 4). A smoothed time series of AMO (10-year spline) was moderately correlated with multidecadal fire synchrony variation at the continental scale ( $r = 0.50$  and 0.43, for the synchrony and dipole indices, respectively;  $P < 0.001$ ; 1550–1924; Fig. 3). In contrast, multidecadal fire synchrony variation was not significantly correlated with annual and 50-year smoothed PDO or NINO3.

AMO and multidecadal fire synchrony show similar subcontinental spatial patterns when correlated with low-frequency variations in reconstructed PDSI (Fig. 4). Multidecadal periods of synchronous fire and drought spatially mirror the broad-scale pattern of multidecadal correlation of drought with AMO (2). Drought and warm AMO are correlated from northern Mexico to the U.S. Rocky Mountains–Great Plains and in the Pacific Northwest and southwestern Canada. In contrast, southern California to south-central Canada had above average moisture during these multidecadal periods of warm AMO and synchronous fire (Fig. 4).

The association of AMO and continental-scale synchrony of fire across western North America is consistent with the role of AMO in determining patterns of drought across the western U.S. (1, 2, 5). Fire was strongly synchronous across western North America during 1650–1770 (except 1710–1725) and after 1880





