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MULTIDECADAL CLIMATE VARIABILITY AND CLIMATE INTERACTIONS AFFECT SUBALPINE FIRE OCCURRENCE, WESTERN COLORADO (USA)

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Abstract. This study investigates the influence of climatic variability on subalpine forest fire occurrence in western Colorado during the AD 1600–2003 period. Interannual and multidecadal relationships between fire occurrence and the El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO) were examined, in addition to the effects of phase interactions among these oscillations. Fires occurred during short-term periods of significant drought and extreme cool (negative) phases of ENSO and PDO and during positive departures from mean AMO index. At longer time scales, fires exhibited 20-year periods of synchrony with the cool phase of the PDO, and 80-year periods of synchrony with extreme warm (positive) phases of the AMO. Years of combined positive AMO and negative ENSO and PDO phases represent "triple whammies" that significantly increased the occurrence of drought-induced fires. Fires were synchronous with this phase combination over 0–30 year periods and distinctly asynchronous with the opposite phase combination. Overall, because fires are synchronous at supra-annual to multidecadal time scales with warm AMO events, particularly when combined with cool ENSO and PDO phases, this suggests that we may be entering a qualitatively different fire regime in the next few decades due to the recent shift in 1998 to a likely long-term warm AMO phase. Although uncertainty remains regarding the effects of CO_2-induced warming at regional scales, given the multidecadal persistence of the AMO there is mounting evidence that the recent shift to the positive phase of the AMO will promote higher fire frequencies in the region.

Key words: AMO; climate; ENSO; fire ecology; multidecadal; PDO; Rocky Mountains; subalpine forests.

Introduction

Characterization of trends in ecological phenomena over periods of several decades or more provides insight into the "long now" but these multidecadal trends are difficult to perceive in the absence of long-term historical analysis (Carpenter 2002). Numerous studies (see review in Holmgren et al. 2001) have linked ecological phenomena as diverse as drought (Daniels and Veblen 2000), fish abundance (Velarde et al. 2004, Funes-Rodriguez et al. 2006), mammal assemblages (Letnic et al. 2005), productivity (Peters et al. 2003), and fire (Kitzberger et al. 2001) to short-term (quasi-annual) climatic variability related to the El Niño Southern Oscillation (ENSO), while longer-term climatic trends related to the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) remain relatively unexplored. Detecting ecological relationships to low-frequency (decadal and multidecadal time periods in the current study) climatic variability and to interactions among slow and fast climatic processes is challenging, but necessary in forecasting ecological change. This study investigates the climatic mechanisms influencing subalpine forest fire occurrence in western Colorado, which provide a key to the intuitive link between drought and large, high-severity fires that are keystone disturbance processes in many high-elevation forests in the western United States.

Although the relationships between drought and fire occurrence are proximate geographically, the atmospheric mechanisms affecting patterns of drought-induced fires can be global or hemispheric in scale. Three primary broadscale climatic oscillations, the ENSO, PDO, and AMO, have distinct spatial and temporal signatures that can affect fire in distinct ways. ENSO can be characterized by an index reflecting average winter (December, January, February) sea surface temperature anomalies (SSTAs) in the equatorial Pacific Ocean, oscillating between El Niño (warmer than average SSTs) and La Niña (cooler than average SSTs) phases at 2–6 year frequencies (Diaz and Markgraf 2000). The PDO index represents variability in average summer (April, May, June, July, August) SSTAs in the North Pacific Ocean, varying between cool and warm phases at 20–30 year cycles (Mantua et al. 1997). The AMO index reflects average annual SSTAs in the North

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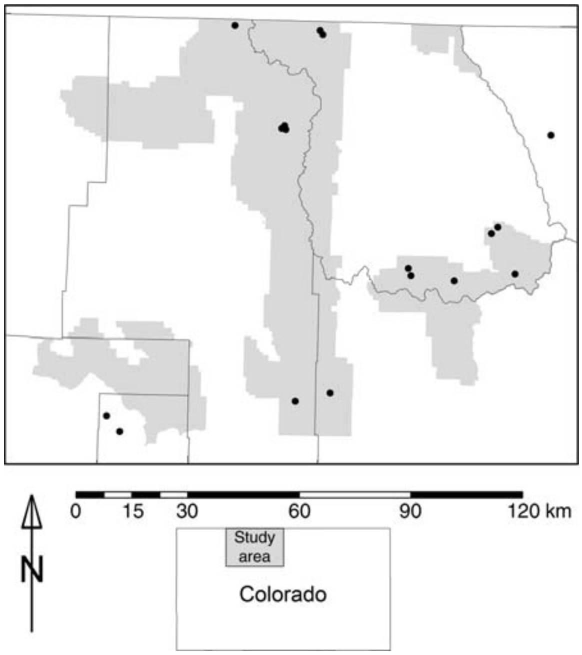

FIG. 1. Location of the study area in western Colorado, USA. Black lines represent counties, and black dots represent the 17 sites used to reconstruct tree-ring-dated fires during the 1600–1910 period. Gray shading represents the extent of the Routt National Forest, where 14 sites are located, and the Arapaho-Roosevelt (upper right) and White River (lower left) National Forests, where one and two sites, respectively, are located.

Atlantic Ocean, which cycle between warm and cool phases at 50–80 year frequencies (Kerr 2000).

Long-term records are critical in assessing the role of decadal to multidecadal climatic variation, which provides an important low-frequency context for understanding or predicting future ranges of variability. In contrast to long-term tree-ring records of wildfire activity, shorter-term documentary data (e.g., Collins et al. 2006) cannot adequately characterize multidecadal trends or determine whether climate–fire relationships observed during the 20th century reflect trends across longer time periods. Irrespective of the length of the fire record, long-term climate–fire analyses are often compromised when the temporal extent of the tree-ring-based climate reconstructions do not extend to the present; for example, some only extend into the 1970s. Such limitations curtail analysis of recent increases in wildfire activity (Westerling et al. 2006) and tests of consistent relationships across climate regime shifts, such as in 1977, when an abrupt and significant shift in North Pacific sea surface temperatures occurred (Hare and Mantua 2000) associated with an increase in El Niño events. A similar shift in North Atlantic sea surface temperatures occurred in 1998, characterized by a switch in the AMO to a predominantly positive phase, which has not been observed since the early 1960s.

Most climate–fire studies have emphasized interannual climate–fire relationships, due in part to reliance on approaches restricted to annual rather than multidecadal inference. Superposed Epoch Analysis is a common tool in climate–fire studies used to assess the interannual relationship between fire occurrence and a particular climate index. Statistically testing multidecadal relationships between fire occurrence and climate parameters is an emerging challenge. With the recent development of long-term tree-ring reconstructions of the PDO and AMO, there is growing need for suitable tools to statistically test multidecadal climate–fire relationships that also handle higher levels of serial autocorrelation inherent in PDO and AMO.

This study relies on fire history data from high-elevation subalpine forests; this has advantages over the numerous fire–climate studies conducted in lower elevation ponderosa pine–Douglas-fir forests (Swetnam and Betancourt 1990, Grissino-Mayer and Swetnam 2000, Heyerdahl et al. 2002, Hessl et al. 2004). In contrast to ponderosa pine forests, fire suppression has been minimal and fuels buildup, which might alter recent fire–climate dynamics, is essentially absent in forests characterized by stand-replacing fires (Schoennagel et al. 2004). In addition, the relationship between fire occurrence and antecedent above average moisture, which presumably increases fine fuels necessary for surface fire spread in ponderosa pine forests, is not significant in subalpine forests, where fuels generally are not considered limiting to fire occurrence or severity (Schoennagel et al. 2005, Sibold and Veblen 2006).

This study incorporates a novel analysis of a subalpine fire history in western Colorado that examines both interannual (via superposed epoch analysis) and multidecadal relationships (via bivariate event analysis) between large-fire occurrence (see Plate 1) and broad-scale climatic oscillations represented by ENSO, PDO, and AMO indexes and their phase interactions during the 1600–2003 period.

METHODS

Study area

We sampled fire history in the subalpine zone, with study sites occurring between 2700 and 3050 m. Most sites occurred in the Routt National Forest (NF), with three additional sites in adjacent Arapaho-Roosevelt NF and White River NF, western Colorado, USA (Fig. 1). In the southern part of the study area (Marvine Ranch, 2380 m), mean January temperature is −8.4°C, mean July temperature is 14.3°C, and annual precipitation is 706 mm (Western Regional Climate Center 2006). In the northern part of the area (Steamboat Springs, 2065 m) mean January temperature is −9.6°C, mean July temperature is 16.6°C, and annual precipitation is 610 mm. In summer, the Colorado Rockies are influenced by either dry continental air from the west or monsoonal air from the Gulfs of Mexico or California (Kittel et al. 2002). Forests in the study area are dominated by *Picea*

Table 1. Summary of tree-ring-dated fires in western Colorado, USA, including the number of scars recording the fire date from each site, the number of cores used to reconstruct the establishment of the postfire cohort, the period of establishment for the majority of trees cored, and estimated extent of the postfire cohort.

Site	Fire-scar date	No. scars	No. cores	Period of postfire cohort establishment	Extent of postfire cohort (ha)†
1‡	1626	2	34	1633–1675	491
2	1685	3	38	1692–1758	122
3	1714	3	23	1675–1737	66
4‡	1796	2	141	1797–1840	938
5	1846	3	47	1848–1887	863
6	1851	14	34	1852–1876	535
7	1851	2	192	1855–1872	530
8	1851	7	25	1852–1872	209
9	1851	6	55	1852–1878	558
10	1851	10	27	1854–1887	367
11	1851	6	45	1852–1881	331
12	1871	5	20	1875–1910	N/A
13	1871	5	37	1873–1888	578
14‡	1879	23	400	1880–1894	2086
15‡	1880	2	102	1882–1906	675
16	1882	**3**	21	1884–1898	1693
17‡	1910	5	42	1913–1918	80

† Size estimates from sites without a double dagger (‡) are based on the size of polygons representing age cohorts in the RIS GIS (Resource Inventory System, Geographical Information System) data that are within 5 km and 10 years of the scar date. Size estimates from sites with a double dagger are based on mapping the spatial extent of cohorts in the field.

‡ Data are from Kulakowski and Veblen (2002), Kulakowski et al. (2003).

engelmannii Parry ex Engelm. (Engelmann spruce), and *Abies lasiocarpa* (Hook.) Nutt. (subalpine fir) at the higher elevations, *Pinus contorta* Dougl. (lodgepole pine) at mid-elevations, and *Populus tremuloides* Michx. (quaking aspen) at lower elevations. Primary disturbance agents are large, infrequent stand-replacing fires, insects (spruce beetle and mountain pine beetle), and blowdown, which leave lasting evidence distinguishable through a combination of field interpretation and dendroecological techniques (Kulakowski et al. 2003).

Fire history sampling design

In stand-replacing fire systems, two primary pieces of evidence are required to establish the date of a stand-replacing fire: (1) fire dates from fire-scarred trees, which have annual resolution required for annual climate analyses, and (2) stand-origin dates from adjacent or nearby stands, which lack annual resolution but provide evidence of stand-replacement fire if a pulse of tree establishment within 10–20 years of the recorded fire is observed (Johnson and Gutsell 1994).

The sampling scheme in this study efficiently collected fire-scar and associated stand-origin dates in the subalpine zone by targeting old, scar-prone stands that have a high chance of recording fire evidence (due to site conditions) over long periods (due to age). This sampling bias facilitated efficient collection of evidence of large-fire occurrence in the region, but would be inappropriate if the goal were determining the proportion of the landscape burned by previous fires, which would require random or stratified sampling. We searched for scars in older (>80 yr) lodgepole pine stands (that appear more prone to scarring than spruce–fir), on fuel-limited rocky outcrops or dry, south-facing aspects, at the boundary between polygons of different age, located initially from the National Forest Resource Inventory System (RIS) Geographic Information System (GIS) data. RIS data depict forested polygons of similar species and age, derived from a combination of aerial photo interpretation and subsequent tree coring. We scouted potential sites identified by the RIS data, and if live fire-scarred trees were found, we removed fire-scarred wedges and cored the largest cohort of trees in adjacent stands, where evidence of stand-replacement fire (burned wood, single-age cohorts) was observed. This yielded 12 sites that met our requirements for reconstructing fire years: a minimum of two fire-scarred trees recording a date that corresponded to nearby (<500 m) establishment of an obvious cohort within 10–20 years of the fire date. We used similar data from two additional ~4500-ha study areas in subalpine forests of the Routt (Kulakowski and Veblen 2002) and adjacent White River National Forests (Kulakowski et al. 2003), which yielded five spruce–fir cohorts linked to reliable fire-scar dates, for a total of 17 tree-ring-dated fires and associated postfire cohorts used in this study (Table 1). In the laboratory, cores and wedges were processed using standard dendrochronological techniques (Stokes and Smiley 1968), which included cross-dating of fire-scarred wedges using COFECHA (Grissino-Mayer 2001).

We incorporated fires from documentary records of regional fire occurrence into our fire chronology to extend it to 2003. From GIS data sets (USDA Routt and White River Forest Service, *unpublished data*) that depict the location and size of fires between 1933 and 2003, we selected all fires that occurred in subalpine forest types (aspen, lodgepole pine, and spruce–fir) that were >200 ha, and were within 130 km of the study area center. Although the last tree-ring-dated fire scar is 1910, more recent fires could have been recorded in areas sampled for fire scars, but were not observed. Hence, the 1910–1933 period, between the last tree-ring-dated fire and the first documentary-record fire, does not reflect an artificial gap in the fire chronology.

Climate data sets

We utilized reconstructions of SSTA indexes of the AMO (Gray et al. 2004), PDO (E. R. Cook, *unpublished data*; correlation with instrumental PDO during 1900–1996 period = 0.81), and ENSO (NINO3 region; D'Arrigo et al. 2005) for the climate analysis. The period of overlap among these reconstructions ends in 1978, so we extended the climate reconstructions to 2003 by the following procedure. First, we adjusted the standard deviation and mean of the reconstruction (calculated over the period of overlap between the two time series) to reflect that of the detrended instrumental record, where the detrended values simply are the residuals from the linear regression of the annual values of the index against time. Then we replaced the reconstructed time series with the instrumental record during the 1950–2003 period, when there is relatively high correlation between the reconstructed and instrumental time series, which permits smooth splicing of the two records. The procedure above was not applied to the reconstructed drought data, gridpoint 117 (latitude 40°, longitude 107.5°) from Cook's reconstructed Palmer drought severity index (PDSI; Cook et al. 2004), which extends to 2003 and where archived instrumental data from a comparable period and region are not readily available.

Fire–climate analysis

The period of analysis was AD 1600–2003. Superposed epoch analysis (SEA; Grissino-Mayer 1995) examined short-term (interannual) relationships between subalpine fire occurrence and (1) regional drought (PDSI), and (2) individual broadscale climate anomalies represented by Pacific (PDO, ENSO) and Atlantic (AMO) SSTAs. Each SEA assessed if the mean value of the climate reconstruction was significantly different during fire events (year 0) compared to 1–6 years prior and up to two years after fire event (analysis window, 9 yr). Since the last fire considered was in 2003 and SEA examined climate trends two years after fires, we extended the climate indexes and period of analysis to 2005 for SEAs. Statistical significance was evaluated using 95%, 99%, and 99.9% confidence intervals derived from 1000 Monte Carlo simulations with block resampling, where blocks are equal to the size of the analysis window, which estimates null distributions for time series with autocorrelation (Adams et al. 2003). In cases where the serial autocorrelation is strong (e.g., >0.60) over lags greater than the analysis window, SEA may be inappropriate statistically. Autocorrelation at six-year lags for PDSI, ENSO, PDO, and AMO are: 0.025, −0.004, 0.083, and 0.468, respectively, and decline as lags increase, suggesting this application of SEA is statistically appropriate for evaluating interannual relationships between these climate indexes and fire.

To characterize lower frequency (multidecadal to centennial) relationships between subalpine fire occurrence and ENSO, PDO, and AMO, we performed bivariate event analysis (BEA) using the K1D software (D. G. Gavin, *unpublished software*). BEA is a temporal variant of spatial point pattern analysis based on Ripley's *K* function (Ripley 1977), where relationships between one-dimensional time series data rather than two-dimensional spatial data are analyzed (for equations and details see Gavin et al. 2006: Appendix B). BEA has been used to examine synchrony among fire events recorded by sedimentary records (Gavin et al. 2006) and temporal lags between drought and tree mortality events (Bigler et al. 2007). In general, BEA provides the ability to statistically test low-frequency temporal relationships not possible with SEA. BEA avoids problems of strong serial autocorrelation because particular climatic events rather than continuous time series are used.

BEA examined temporal synchrony or asynchrony between climate events (C) and fire events (F), assuming a one-directional process, where fire events only respond to previous, current, but not future climate events (see Bigler et al. 2007). After the bivariate *K* function is defined, an *L* function is calculated, where $\hat{L}_{CF}(t) = \hat{K}_{CF}(t)/2 - t$, which stabilizes the mean and variance of the *K* function, facilitating graphical interpretation. Monte Carlo simulations with 1000 replicates using randomization of the climate time series determined 95% confidence envelopes for $\hat{L}_{CF}(t)$. Values above the upper confidence limit within a window of *t* years indicate synchrony between the two time series (i.e., extreme climate events occur more often than expected *t* years before fire events), values below the lower confidence limit indicate asynchrony (i.e., extreme climate events occur less often than expected *t* years before fire events), and values between indicate independence. BEA requires identification of individual climate events (yet results in our study were robust to a range of thresholds defining climate events). This is particularly useful in examining the effect of interactions among climate indexes, which is awkward to test via SEA, where events can be selected based on the interacting phases of ENSO, PDO, and AMO.

We first examined the relationships between single climatic indexes (PDSI, ENSO, PDO, and AMO) and fire by performing SEAs for analysis of interannual variability and BEAs to examine supra-annual to multidecadal variability. In BEA, extreme climate events were defined by selecting the 50 highest or lowest annual

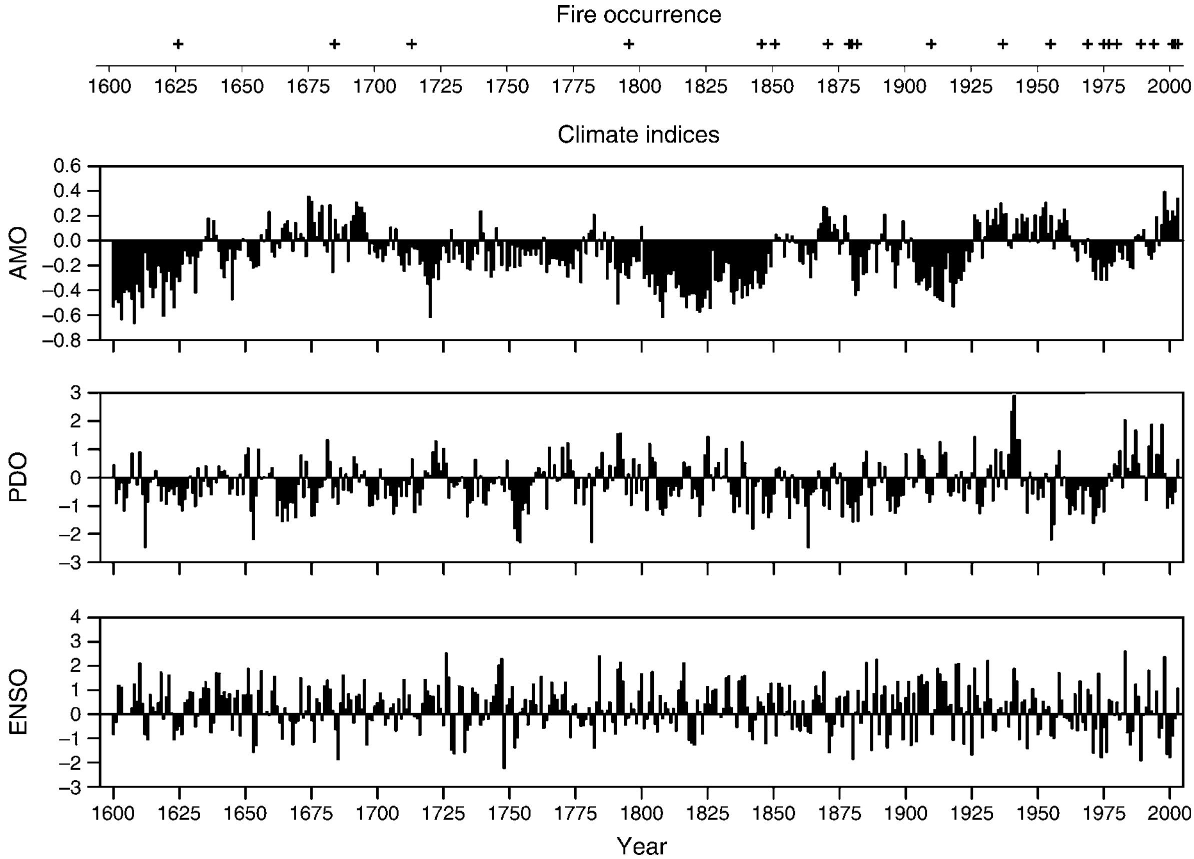

FIG. 2. Years of large-fire occurrence in subalpine forests of the study area in western Colorado, represented by + symbols. The Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), and El Niño–Southern Oscillation (ENSO) climate indexes are modified to span the 1600–2003 period (see *Methods* for details).

values (i.e., the most positive or negative 12th percentile) of the AMO, PDO, and ENSO indexes.

We next considered the influence of two-way and three-way combinations among the phases of the AMO, PDO, and ENSO on subalpine fire occurrence. At the annual scale, we relied on frequency analysis (evaluated by chi-square tests) to compare the expected fire occurrence (years during the 1600–2003 period occurring during positive and negative phase combinations of the AMO, PDO, and ENSO oscillations), to the observed fire occurrence (the number of fires occurring during these same phase combinations) to determine if fires occurred disproportionately during years of particular two-way or three-way phase combinations.

To evaluate longer-term synchronous or asynchronous relationships between fire occurrence and two-way or three-way phase combinations of the AMO, PDO, and ENSO oscillations, we again relied on BEA. Extreme climate interaction events were defined by combining the 100 and 150 highest or lowest ranked annual values (25th and 37th percentiles, respectively) to define four two-way and eight three-way phase combinations, respectively. For example, to select climate events representing years of extreme positive AMO, negative PDO, and negative ENSO phase combinations, years with the 150 highest (lowest) annual values of the AMO (PDO, ENSO) were selected independently, and from this group, only years that had been selected for each of the three indices were used to define this subset of climate events. Hence, the total number of events selected depended on the particular phase combination.

RESULTS

Fire history

We sampled 17 fire history field sites in subalpine forests across a 100 × 120 km region in northwestern Colorado (Fig. 1), from which we reconstructed 11 large tree-ring-dated fires that spanned 1626–1910 (Table 1). The Forest Service documentary record contributed 11 additional fire dates from 15 individual fires, which burned lodgepole pine, spruce–fir, and aspen stands from 1937 to 2003. In total, the fire record consists of 22 large-fire dates throughout the study area between 1600 and 2003 (Fig. 2). Just over half of the postfire cohorts and documentary-record fires were in lodgepole pine forests, while the rest were primarily from spruce–fir-dominated forests. Mean elevation of

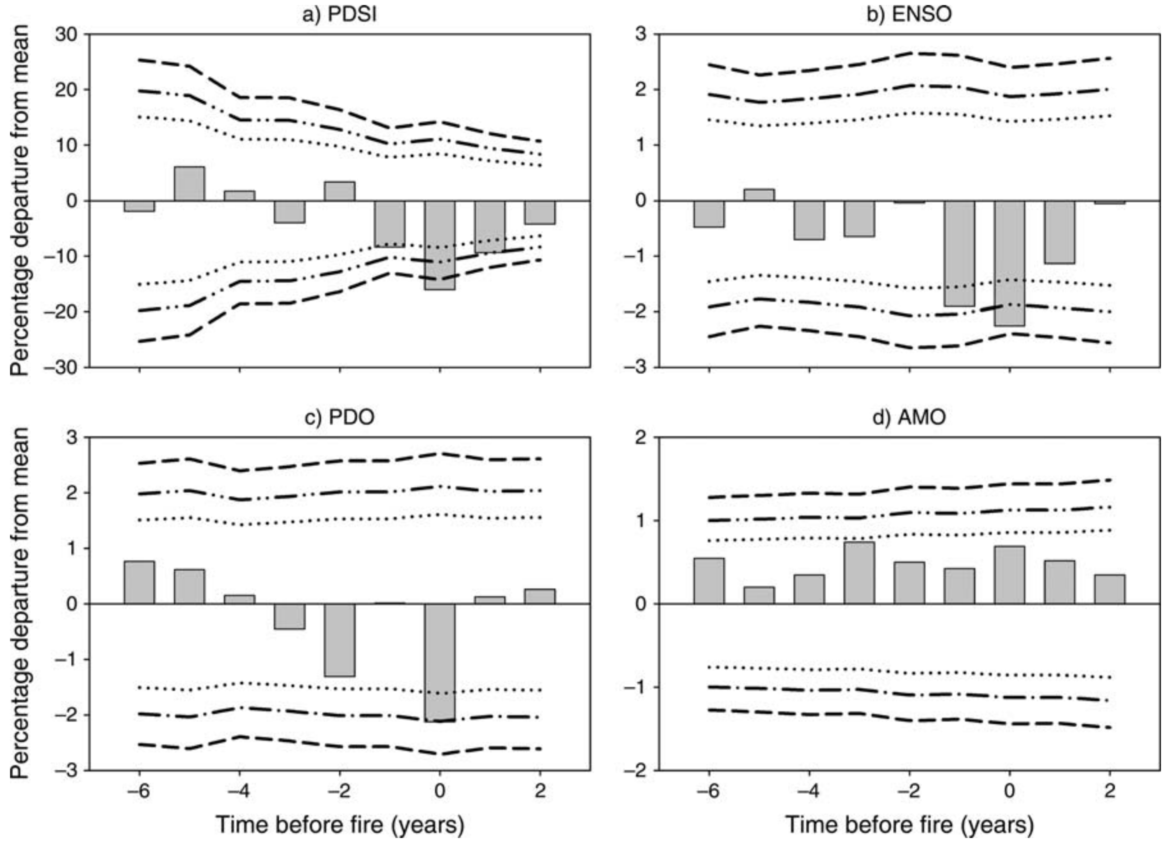

FIG. 3. Superposed epoch analyses of percentage departure from the mean (a) Palmer drought severity index (PDSI), (b) ENSO, (c) PDO, and (d) AMO reconstructions during the 1600–2005 period during large fires (year 0) relative to 1–6 years prior and two years after these events ($n = 22$ fires). Dashed lines represent 99.9% CI, dot–dash lines represent 99% CI, and dotted lines represent 95% CI derived from 1000 Monte Carlo simulations.

the predominantly south- and west-facing sites was 2880 m (2665–3060 m). On average, 75 cores (20–400 cores) were collected from the largest cohort at each stand-origin site, where more cores were collected in older or multispecies stands. On average, 2.5 years occurred between the fire-scar dates and the first observed date of tree establishment, and 63% of the trees cored were established within 20 years of the associated fire-scar date. The average minimum distance between the stand-origin and fire-scar sampling was 170 m. Cores were taken from polygons representing stands of homogenous age and species composition in the RIS data that were 24 ha on average; however, polygons with a stand age estimate within 10 years and 1 or 5 km of the sampled fire scars totaled 99 and 522 ha, respectively. In addition, almost half of the fire dates were observed at multiple sites (with 1851 being recorded at six sites), where the average minimum distance between closest sites was 9.7 km. Although the sizes of the tree-ring-dated fires are unknown, these spatial statistics indicate that the field sampling captured large subalpine fire occurrence in the region. The median size of the documentary-record fires was 725 ha (209–45 769 ha).

Fire relationships to single climatic indexes

Interannual variability.—Subalpine fires occurred during years of extreme drought ($P < 0.001$), which often coincided with periods of multiyear drought (mean PDSI the year prior, during, and after fires significantly departed from the mean, Fig. 3a). From inspection of individual fire events, numerous 2–5 year periods of low PDSI co-occur with fire occurrence throughout the period of analysis. Fires also occurred on average during years of significant negative departure from the mean SSTAs used as indexes of ENSO ($P = 0.005$) and PDO ($P = 0.005$, Fig. 3b, c). The AMO, although positive during fire years, did not depart significantly from the mean (Fig. 3d).

Multidecadal variability.—BEA corroborated short-term trends observed via SEA, where extreme drought events occurred more often than expected 0–4 years before fire and extreme cool phases of ENSO (La Niña) occurred more often than expected 0–10 years before fire (Fig. 4a, b). BEA additionally revealed decadal- to multidecadal-scale climate–fire relationships with the PDO and AMO, respectively (Fig. 4c, d). Extreme cool phases of the PDO occurred more often than expected 0–19 years before fires (but with the year before the fire

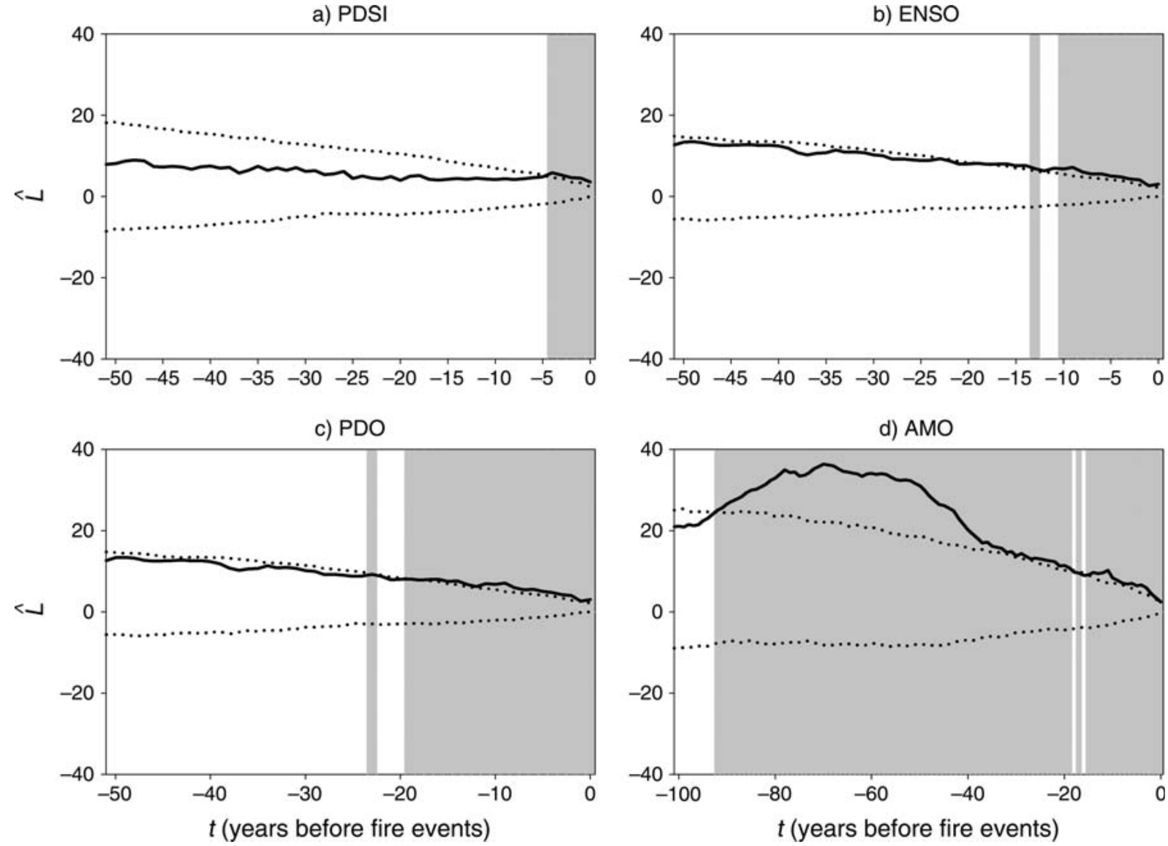

FIG. 4. Bivariate event analysis of the temporal association of extreme climate events (C, $n = 50$) before and during large-fire events (F, $n = 22$). $\hat{L}_{CF}(t)$ values (black lines) above the upper confidence limit (dotted lines) indicate synchrony between the two series of events (i.e., extreme climate events occur more often than expected t years before fire events); values below a lower confidence limit indicate asynchrony (i.e., extreme climate events occur less often than expected t years before fire events), and values between indicate independence. The 95% confidence envelopes (dotted lines) are based on 1000 Monte Carlo simulations. Years of significant (a)synchrony are highlighted with gray shading. See *Methods: Fire–climate analysis* for further explanation.

equal to the 95% CI). Fires were synchronous with extreme warm AMO events over periods of 1–92 years, with a peak in significance at 40–80 years. When BEA was used to test for relationships between 22 randomly generated years and the same climate events tested here, the results were mostly insignificant (Appendix: Figs. A1, A2), suggesting the climate–fire relationships described here do not simply reflect signatures of climate variability, irrespective of the timing of fire.

Fire relationships to combined climatic phases

Interannual variability.—Two-way phase combinations between pairwise combinations of the three climate oscillations showed that fires occurred more often than expected during years of combined cool phases of PDO and ENSO ($\chi^2 = 8.82$, df = 3, $P = 0.032$), and during the combined warm AMO and cool ENSO phases ($\chi^2 = 13.30$, df = 3, $P = 0.004$; Fig. 5a, b). Fires tended to occur during warm phases of the AMO irrespective of the combined PDO phase ($\chi^2 = 6.53$, df = 3, $P = 0.076$; Fig. 5c). Fire-frequency analysis of the three-way climate interactions at the annual scale indicates that fire occurred more often than expected when the warm AMO combined with cool phases of PDO and ENSO ($\chi^2 = 14.70$, df = 7, $P = 0.041$; Fig. 5d).

Multi-decadal variability.—The annual-scale synchronies of fire events and climate phase combinations described previously are corroborated and extended to supra-annual periods by BEA. Combined cool phases of the PDO and ENSO occurred more often than expected 0–10 years before fires (Fig. 6a), while all other PDO × ENSO combinations were nonsignificant for all time scales (results not shown). At a supra-annual to multi-decadal scales, fires were synchronous with combined warm AMO and cool ENSO events 0–38 years before fires (Fig. 6b), while all other AMO × ENSO phase combinations were nonsignificant. Fires were synchronous with extreme warm AMO and cool PDO events over the 0–16 year period, and also with warm AMO and warm PDO events during the 7–23 year period and consistently throughout the 37–99 year period (Fig. 6c, d), while all other AMO × PDO phase combinations were nonsignificant. BEA of the three-way climate interactions shows that fires were synchronous with the

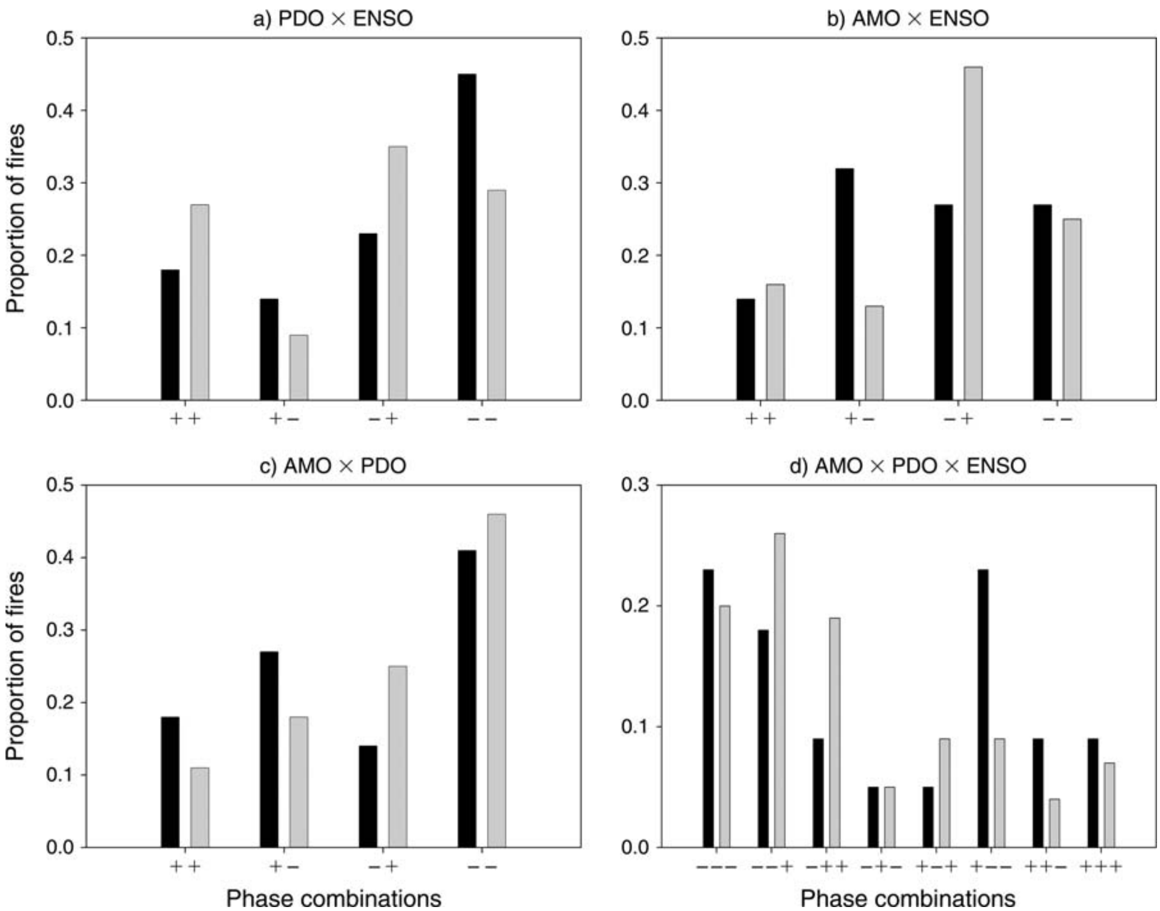

FIG. 5. Relative frequencies of fire and climate occurrences in each of the (a–c) two-way and (d) three-way combined phases of the AMO, PDO, and ENSO during the AD 1600–2003 period. Phase combinations refer to different combinations of warm and cool phases of the AMO, PDO, and ENSO in a given year. Warm (positive) phases of these oscillations are represented by + symbols, and cool (negative) phases are represented by − symbols. Black bars represent observed fire occurrence; gray bars represent expected fire occurrence. Significant departure from the expected fire occurrence was evaluated by chi-square tests (see *Results: Fire relationships to combined climatic phases*).

warm phase of the AMO and cool phases of the PDO and ENSO over 0–30 year period (Fig. 6e). Fires were distinctly asynchronous with the opposite phase combination over the 0–53 year period (Fig. 6f), while all other phase combinations were nonsignificant.

DISCUSSION

Effects of single climatic indexes on fire occurrence

This study identifies significant interannual and multidecadal relationships between large-fire occurrence in western Colorado subalpine forests and broadscale climate anomalies represented by ENSO, PDO, and AMO via superposed epoch analysis (SEA) and bivariate event analysis (BEA). Fires generally occurred during short-term periods of significant drought and extreme cool (negative) phases of ENSO. Fires tended to occur during years of extreme cool (negative) PDO phases, and also exhibited 20-year periods of synchrony with the cool phase of the PDO. The AMO showed nonsignificant positive departures from the mean 0–6 years prior to fires via SEA, while 80-year periods of synchrony between fires and extreme warm (positive) phases of the AMO were observed with BEA.

Although the numbers of climate and fire events were the same across all tests of single climate indexes, BEA revealed very different periods of climate–fire synchrony (Fig. 4a–d), which reflect the predominant frequencies of oscillation of ENSO, PDO, and the AMO. Nonsignificant results using randomly generated fire years suggest these results represent multidecadal climate–fire relationships rather than simply reflecting the signatures of climate variability. Previous studies confirm these interannual relationships between drought-induced fire occurrence in the southern Rockies and ENSO, PDO, and AMO phases. Drought and fires in the southern Rockies tend to be associated with the cool phases of ENSO (La Niña) and the PDO (Schoennagel et al. 2005, Sibold and Veblen 2006), while fires throughout much of the western United States appear to be associated with the warm phase of AMO (Kitzberger et al. 2006).

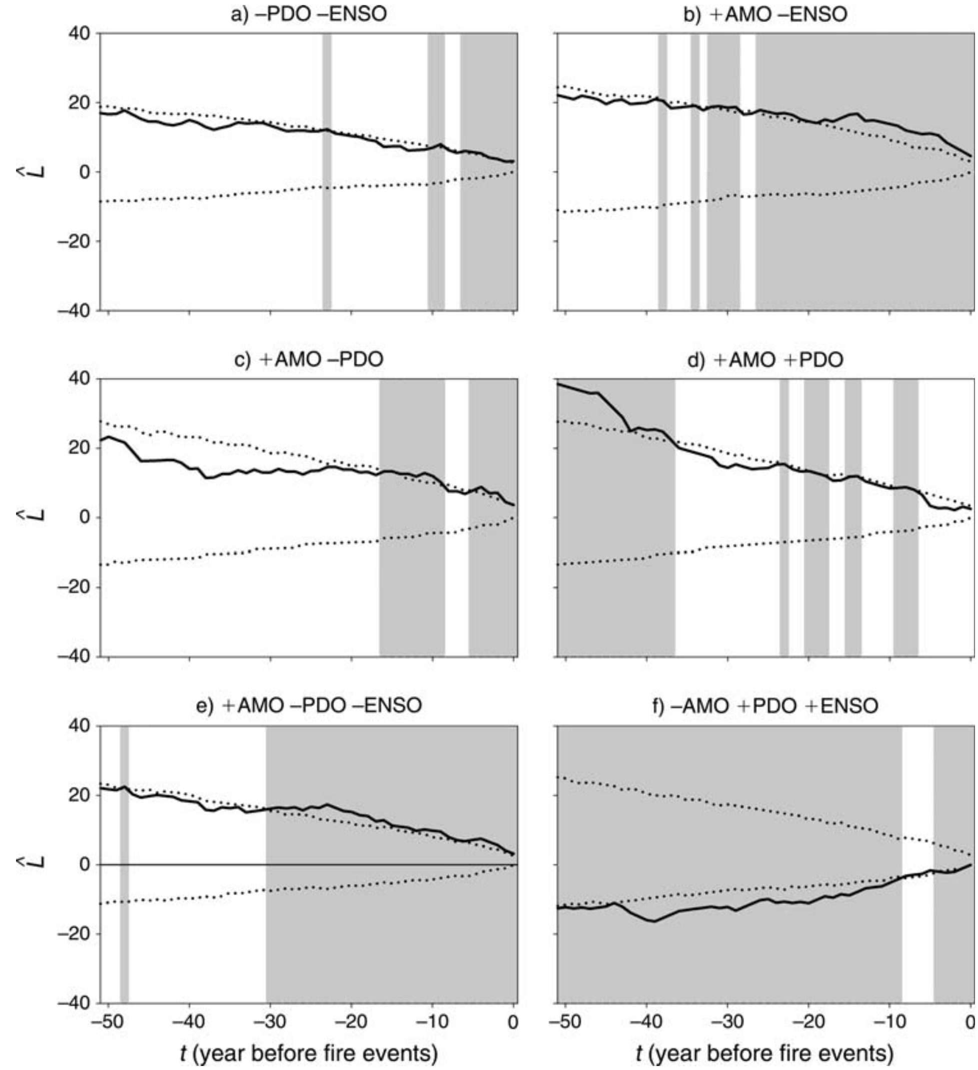

FIG. 6. Results from bivariate event analysis showing significant synchrony or asynchrony of large-fire events (F, $n = 22$) with climate events (C), which are defined by years of combined phases of (a) cool PDO and cool ENSO ($n = 44$) and (b) warm AMO and cool ENSO ($n = 26$), (c) warm AMO and cool PDO ($n = 22$), (d) warm AMO and warm PDO ($n = 24$), (e) warm AMO, cool PDO, and cool ENSO ($n = 31$), and (f) cool AMO, warm PDO, and warm ENSO ($n = 29$). Results from all other three-way phase combinations were nonsignificant. See Fig. 4 for further explanation.

Although the approaches are not directly comparable, SEA and BEA results generally were consistent at interannual timescales while BEA provides valuable additional information at longer timescales. Statistically testing multidecadal to centennial relationships between fire occurrence and climate parameters is a challenge in many fire–climate analyses. Most studies have relied on graphical comparisons of fire frequency among different time periods (Sibold and Veblen 2006), correlations among moving averages of fire and climate variables (Heyerdahl et al. 2002), or comparisons of the relative frequencies of climate and fire oscillations (Hessl et al. 2004). Each has its own strength and limitations. BEA is an alternative technique for statistically assessing patterns of synchrony or asynchrony between fire and climate at multidecadal to centennial scales, which avoids the difficulties of temporal autocorrelation and reflects emergent temporal relationships that may be difficult to discern through other techniques (Gavin et al. 2006, Bigler et al. 2007).

Effects of climatic phase interactions on fire occurrence

Interactions among broadscale climate oscillations represented by SSTAs in the Atlantic and Pacific oceans are emerging as an important predictor of significant fire activity in the western United States (Westerling and Swetnam 2003, Schoennagel et al. 2005, Kitzberger et al. 2006, Sibold and Veblen 2006). Interactions among climatic oscillations can intensify or weaken telecon-nected patterns. For example, the strength of ENSO

Plate 1. Example of large stand-replacing fire burning in subalpine forest under extreme climate conditions, Mirror Plateau, Yellowstone National Park, USA, 1988. Photo credit: NPS photo by Jim Peaco.

teleconnections to drought in the Northern Hemisphere appear to be affected by the phase of the PDO (Gershunov and Barnett 1998, McCabe and Dettinger 1999) and AMO (McCabe et al. 2004). Interactions among climate oscillations pose additional challenges in appropriately testing relationships to fire occurrence, especially at multiple time scales. Chi-square tests showed that subalpine fires in western Colorado occurred more frequently than expected during the cool phases of ENSO and PDO and warm phases of the AMO. Drought and wildfire are associated with warm phases of ENSO and PDO in the Pacific Northwest and northern Rockies while the opposite occurs in the Southwest and southern Rockies (Westerling and Swetnam 2003, McCabe et al. 2004, Schoennagel et al. 2005). PDO × AMO phase interactions reveal a similar north–south dipole relationship to drought (McCabe et al. 2004); however Colorado appears to geographically coincide with major patterns of drought associated with warm AMO phases combined with either the warm or cool phases of the PDO (McCabe et al. 2004; Fig. 6). Results from this study corroborate this spatial trend, where annual-scale frequency analyses showed greater than expected fire occurrence during the positive phase of the AMO, irrespective of the PDO phase (Fig. 5c). These phase combinations exhibited unique multidecadal periods of synchrony with fire (Fig. 6c, d).

Three-way climate phase combinations involving warm Atlantic and cool Pacific SSTAs represent triple whammies that significantly increased the probability of drought-induced fires. A disproportionately greater than expected number of fires occurred during the warm AMO combined with the cool phases of ENSO and PDO (Fig. 5d), which has also been shown in areas east of our study area in subalpine forests in the Colorado Front Range (Sibold and Veblen 2006), in ponderosa pine forests of the Front Range (R. L. Sherriff and T. T. Veblen, *unpublished manuscript*) and in the Black Hills (Brown 2006). At multidecadal scales, fires show strong 30-year periods of synchrony with these climate events and distinct asynchrony with the opposite climate condition (Fig. 6e, f).

Multidecadal relationships between fire events and climate events observed through BEA should not be interpreted as single climate events mechanistically affecting the occurrence of fire decades later, which is only plausible within short temporal windows, but that the selected climate events reflect low-frequency trends in the climate record to which fires respond. Relationships between fire occurrence and AMO × PDO × ENSO phase interactions observed through BEA may highlight possible climatic trends underlying periods of high or low fire activity in the region. For example, the 1859–1899 period, which represents 10% of the analysis period and has been documented as a period of very high fire activity in the southern Rockies, experienced 23% of the years of combined warm AMO and cool ENSO and PDO phases. In contrast, the 1790–1840 period, which represents 12% of the analysis period and is a quiescent period of fire activity throughout the southern Rockies and southwest (Grissino-Mayer and Swetnam 2000, Donnegan et al. 2001, Sibold and Veblen 2006), experienced 28% of the years of the opposite phase combination (cool AMO and warm ENSO and PDO phases).

It has been postulated that low-frequency variability in North Atlantic and North Pacific oceans modulates long-term variability in ENSO (Delworth et al. 1993, Enfield et al. 2001, Gray et al. 2003). Both Atlantic and Pacific SSTAs affect the position and persistence of the North American jet stream, which results in predictable patterns of drought across the western United States and may account for observed drought and fire responses to ENSO $\times$ PDO $\times$ AMO phase interactions. More direct mechanisms have been suggested where SSTAs in the North Atlantic represented by the AMO affect the intensity of the thermohaline circulation that may link SSTA patterns in the Atlantic and Pacific Oceans, although in complex and still poorly understood ways (Delworth et al. 1993, Schlesinger and Ramankutty 1994, Gray et al. 2003).

This study provides an important low-frequency context to recent increases in fire activity across the West, which have largely been attributed to fuels buildup due to fire suppression (Covington and Moore 1994, Covington 2000), rather than a recent significant change in the climate regime (except see Westerling et al. 2006). High-elevation subalpine forests are advantageous for climate–fire studies where there is little evidence for fuels buildup associated with past fire suppression, which is common in lower elevation ponderosa pine-dominated forests. Hence, temporal patterns in fire occurrence, which include a recent increase around 1975 in our study (Fig. 2), can largely be attributed to variation in climate rather than changes in fuels. Westerling et al.'s (2006) analysis of a large western wildfire database shows that the greatest increase in recent wildfire activity has occurred in higher elevation forests, where past land-use histories have had little effect on fire behavior.

Understanding relationships between variation in SSTAs in the Atlantic and Pacific Oceans and wildfire occurrence present useful insight into broadscale drivers of keystone ecological processes in subalpine landscapes of the western United States. Multidecadal climate–fire relationships provide ecological perspective into the long now, where low-frequency trends are difficult to perceive as they emerge in the absence of historical understanding of long-term trends (Carpenter 2002). For example, because drought-induced fires appear synchronous at multidecadal time scales with warm AMO events, particularly when combined with cool ENSO and PDO phases, suggests that we may be entering a qualitatively different fire regime in the next few decades due to the recent shift in 1998 to a likely long-term warm AMO phase (McCabe et al. 2004). Although there remains considerable uncertainly regarding the effects of CO_2-induced warming at regional scales, given the multidecadal persistence of the AMO there is mounting evidence that the recent shift to the positive phase of the AMO will promote higher fire frequencies in the region.

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Literature Cited

Adams, J. B., M. E. Mann, and C. M. Ammann. 2003. Proxy evidence for an El Niño-like response to volcanic forcing. Nature 426:274–278.

Bigler, C., D. G. Gavin, C. Gunning, and T. T. Veblen. 2007. Drought induces lagged tree mortality in a subalpine forest in the Rocky Mountains. Oikos, *in press*.

Brown, P. 2006. Climate effects on fire regimes and tree recruitment in Black Hills ponderosa pine forests. Ecology 87:2500–2510.

Carpenter, S. 2002. Ecological futures: building an ecology of the long now. Ecology 83:2069–2083.

Collins, B., P. Omi, and P. Chapman. 2006. Regional relationships between climate and wildfire-burned area in the interior west, USA. Canadian Journal of Forest Research 36:699–709.

Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle. 2004. Long-term aridity changes in the western United States. Science 306:1015–1018.

Covington, W. W. 2000. Helping western forests heal. Nature 408:135–136.

Covington, W. W., and M. M. Moore. 1994. Southwestern ponderosa forest structure: changes since Euro-American settlement. Journal of Forestry 92:39–47.

Daniels, L., and T. Veblen. 2000. ENSO effects on temperature and precipitation of the Patagonian-Andean region: implications for biogeography. Physical Geography 21:223–243.

D'Arrigo, R. D., E. R. Cook, R. J. Wilson, R. Allan, and M. E. Mann. 2005. On the variability of ENSO over the past six centuries. Geophysical Research Letters 32:L03711 [doi: 10.1029/2004GL022055].

Delworth, T. L., S. Manabe, and R. J. Stouffer. 1993. Interdecadal variations of the thermohaline circulation in a coupled ocean–atmosphere model. Journal of Climate 6: 1993–2001.

Diaz, H., and V. Markgraf, editors. 2000. El Niño and the Southern Oscillation: multiscale variability and global and regional impacts. Cambridge University Press, Cambridge, UK.

Donnegan, J. A., T. T. Veblen, and J. S. Sibold. 2001. Climatic and human influences on fire history in Pike National Forest, central Colorado. Canadian Journal of Forest Research 31: 1526–1539.

Enfield, D. B., A. M. Mestas-Nuñez, and P. J. Trimble. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. Geophysical Research Letters 28:2077–2080.

Funes-Rodriguez, R., A. Hinojosa-Medina, G. Aceves-Medina, S. Jimenez-Rosenberg, and J. Bautista-Romero. 2006. Influences of El Niño on assemblages of mesopelagic fish larvae along the Pacific coast of Baja California Sur. Fisheries Oceanography 15:244–255.

Gavin, D. G., F. S. Hu, K. Lertzman, and P. Corbett. 2006. Weak climatic control of stand-scale fire history during the Late Holocene in southeastern British Columbia. Ecology 87: 1722–1732.

Gershunov, A., and T. Barnett. 1998. Interdecadal modulation of ENSO teleconnections. Bulletin of the American Meteorological Society 79:2715–2725.

Gray, S., J. Betancourt, C. Fastie, and S. Jackson. 2003. Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains. Geophysical Research Letters 30:1316 [doi: 10.1029/2002GL016154].

Gray, S. T., L. J. Graumlich, J. L. Betancourt, and G. T. Pederson. 2004. A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D. Geophysical Research Letters 31:1–4.

Grissino-Mayer, H. D. 1995. Tree-ring reconstructions of climate and fire history at El Malpais National Monument, New Mexico. Dissertation. University of Arizona, Tucson, Arizona, USA.

Grissino-Mayer, H. D. 2001. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Research 57:205–221.

Grissino-Mayer, H. D., and T. W. Swetnam. 2000. Century-scale climate forcing of fire regimes in the American Southwest. Holocene 10:213–220.

Hare, S. R., and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103–145.

Hessl, A., D. McKenzie, and R. Schellhaas. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications 14:425–442.

Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2002. Annual and decadal climate forcing of historical fire regimes in the interior Pacific Northwest, USA. Holocene 12:597–604.

Holmgren, M., M. Scheffer, E. Ezcurra, J. R. Gutierrez, and G. M. J. Mohren. 2001. El Niño effects on the dynamics of terrestrial ecosystems. Trends in Ecology and Evolution 16: 89–94.

Johnson, E. A., and S. L. Gutsell. 1994. Fire frequency models, methods and interpretations. Advances in Ecological Research 25:239–287.

Kerr, R. A. 2000. A North Atlantic climate pacemaker for the centuries. Science 288:1984–1986.

Kittel, T. G. F., P. E. Thornton, J. A. Royle, and T. N. Chase. 2002. Climates of the Rocky Mountains: historical and future patterns. Pages 59–82 *in* J. Baron, editor. Rocky Mountain futures: an ecological perspective. Island Press, Covelo, California, USA.

Kitzberger, T., P. M. Brown, E. K. Heyerdahl, T. W. Swetnam, and T. T. Veblen. 2006. Continental-scale synchrony in wildfires and climate in western North America over the past 5 centuries. Proceedings of the National Academy of Sciences (USA) 104:543–548.

Kitzberger, T., T. W. Swetnam, and T. T. Veblen. 2001. Inter-hemispheric synchrony of forest fires and El Niño-Southern Oscillation. Global Ecology and Biogeography 10:315–326.

Kulakowski, D., and T. T. Veblen. 2002. Influences of fire history and topography on the pattern of a severe wind blowdown in a Colorado subalpine forest. Journal of Ecology 90:806–819.

Kulakowski, D., T. T. Veblen, and P. Bebi. 2003. Effects of fire and spruce beetle outbreak legacies on the disturbance regime of a subalpine forest in Colorado. Journal of Biogeography 30:1445–1456.

Letnic, M., B. Tamayo, and C. Dickman. 2005. The responses of mammals to La Niña (El Niño Southern Oscillation)-associated rainfall, predation, and wildfire in central Australia. Journal of Mammalogy 86:689–703.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069–1079.

McCabe, G. J., and M. D. Dettinger. 1999. Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States. International Journal of Climatology 19:1399–1410.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. Proceedings of the National Academy of Sciences (USA) 101:4136–4141.

Peters, A., L. Ji, and E. Walter-Shea. 2003. Southeastern US vegetation response to ENSO events (1989–1999). Climatic Change 60:175–188.

Ripley, B. D. 1977. Modelling spatial patterns. Journal of the Royal Statistical Society B39:172–212.

Schlesinger, M., and N. Ramankutty. 1994. An oscillation in the global climate system of period 65–70 years. Nature 367: 723–726.

Schoennagel, T., T. T. Veblen, and W. H. Romme. 2004. The interaction of fire, fuels and climate across Rocky Mountain forests. BioScience 54:661–676.

Schoennagel, T., T. T. Veblen, W. H. Romme, J. S. Sibold, and E. R. Cook. 2005. ENSO and PDO variability affect drought-induced fire occurrence in Rocky Mountain subalpine forests. Ecological Applications 15:2000–2014.

Sibold, J. S., and T. T. Veblen. 2006. Relationships of subalpine forest fires in the Colorado Front Range to interannual and multi-decadal scale climatic variation. Journal of Biogeography 33:833–842.

Stokes, M. A., and T. L. Smiley. 1968. An introduction to tree-ring dating. University of Chicago Press, Chicago, Illinois, USA.

Swetnam, T. W., and J. L. Betancourt. 1990. Fire-southern oscillation relations in the southwestern United States. Science 249:1017–1020.

Velarde, E., E. Ezcurra, M. Cisneros-Mata, and M. Lavin. 2004. Seabird ecology, El Niño anomalies, and prediction of sardine fisheries in the Gulf of California. Ecological Applications 14:607–615.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313:940–943.

Westerling, A. L., and T. W. Swetnam. 2003. Interannual to decadal drought and wildfire in the western United States. EOS Transactions American Geophysical Union 84:545–560.

Western Regional Climate Center. 2006. Western Regional Climate Center. Reno, Nevada, USA. ⟨http://www.wrcc.dri.edu/summary/climsmco.html⟩

APPENDIX

Bivariate event analyses of the temporal relationships between climate events analyzed in Figs. 4 and 6 and 22 randomly generated fire events (*Ecological Archives* E088-179-A1).