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ENSO AND PDO VARIABILITY AFFECT DROUGHT-INDUCED FIRE OCCURRENCE IN ROCKY MOUNTAIN SUBALPINE FORESTS

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Abstract. Understanding the effect of variation in climate on large-fire occurrence across broad geographic areas is central to effective fire hazard assessment. The El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) affect winter temperature and precipitation regimes in western North America through mid-latitude teleconnections. This study examines relationships of ENSO and the PDO to drought-induced fire occurrence in subalpine forests of three study areas across the Rocky Mountains: Jasper National Park (JNP, northern Rockies), Yellowstone National Park (YNP, central Rockies) and Rocky Mountain National Park (RMNP, southern Rockies) over the 1700–1975 period. Large-scale climatic anomalies captured by ENSO (NIÑO3) and PDO indices had differential effects on large-fire occurrence across the study areas. Superposed epoch analysis (SEA) showed that large fires in RMNP occurred during extreme La Niña years, while the PDO, although predominantly negative during fire years, did not depart significantly from the mean. In YNP and JNP, neither ENSO nor PDO indices were significantly different from the mean during large-fire years, although fires tended to occur during El Niño and positive PDO years. Constructive phases (years of combined warm [positive] or cool [negative] phases) of ENSO and the PDO were significantly associated with large-fire occurrence across the Rockies, even though these large-scale climatic anomalies were not significant when considered singly in SEAs. Combined warm phases (positive PDO during El Niño) co-occurred with large fires in the central and northern Rockies, while the combined cool phases (negative PDO during La Niña) appeared to promote large fires in the southern Rockies. Almost 70% of large fires in RMNP burned during La Niña events that coincided with a negative PDO, although these phases co-occurred during only 29% of the 1700–1975 period. Spatial teleconnection patterns between drought, PDO and ENSO across western North America independently support the sign and strength of relationships between these climatic anomalies and subalpine fire occurrence along a broad north–south gradient of the Rockies. Forecasts of ENSO that are dependent on the expected PDO phase suggest promise for fire hazard prediction across the West.

Key words: climate; drought; El Niño–Southern Oscillation; fire ecology; Pacific Decadal Oscillation; subalpine forests.

INTRODUCTION

Understanding the effect of variation in climate on large-wildfire occurrence across broad geographic areas is central to effective wildfire management and planning. Although the relationship between drought and fire is intuitive, mechanisms underlying regional patterns of drought are much more complex. Drought-induced wildfires have been associated with global circulation anomalies such as the El Niño–Southern Oscillation (ENSO; Swetnam and Betancourt 1990, 1998; Heyerdahl et al. 2002) and more recently the Pacific Decadal Oscillation (PDO; Westerling and Swetnam 2003, Hessl et al. 2004). This previous work has been conducted primarily in ponderosa pine forests of the southwestern and northwestern United States, while climate–fire relationships in Rocky Mountain subalpine forests have remained relatively unexplored. Extending our understanding of these climate–fire relationships to the Rockies may improve forecasts of fire activity across western North America and projections of region-specific responses to expected climate change.

ENSO and the PDO represent variation in sea surface temperatures (SSTs) and sea-level atmospheric pressure in the equatorial and northern Pacific Ocean, respectively, that primarily affect winter temperature and precipitation regimes in the western United States and Canada through mid-latitude teleconnections (Cayan et al. 1998, Diaz and Markgraf 2000). Teleconnections are simultaneous variations in climate observed over distant areas. The effect of these two ocean–atmosphere oscillations on drought in western North America is generally consistent within regions but opposed be-

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PLATE 1. Subalpine forest fire in Grand Teton National Park, 2000. Photo credit: T. Schoennagel.

tween the Pacific Northwest (PNW) and Southwest (SW). El Niño (La Niña) coincides with warmer, drier (wetter, cooler) winters in the PNW, while each of these phases produces the opposite effect in the SW. Similarly, negative (positive) phases of the PDO coincide with cooler, wetter (warmer, drier) winters in the PNW, while these phases result in the opposite response in the SW. The location of the switch in this north–south dipole pattern has been estimated to be around 40–45° N latitude (Dettinger et al. 1998, Westerling and Swetnam 2003); however, it is likely not stationary through time. Moreover, the phase of the PDO appears to affect the strength of ENSO events and associated drought teleconnections (Gershunov and Barnett 1998, McCabe and Dettinger 1999, Westerling and Swetnam 2003). Hence, the temporal and spatial variation in ENSO and PDO teleconnections may be nonlinear (Rajagopalan and Cook 2000) and warrant further exploration for effective application to fire forecasting in the Rocky Mountain West.

Despite broad similarities in the teleconnection patterns of ENSO and the PDO to drought across the western United States, there are important spatial and temporal differences between these two oscillations. The climatic imprint of the PDO is most evident in the North Pacific/North American sector, with secondary signatures in the tropics, whereas the opposite occurs with ENSO. ENSO is characterized by interannual variability, with irregular two- to six-year cycles between warm (El Niño) and cool (La Niña) phases (Diaz and Markgraf 2000), whereas the PDO varies decadally, cycling between warm (positive) and cool (negative) phases every 20–30 years (Mantua et al. 1997). The PDO has experienced only two full cycles during the last century. A possible reversal to the negative PDO in the coming years could initiate a multidecadal climate pattern not experienced since the 1970s.

Previous work examining climate–fire relationships in western North America is based primarily on dendrochronological evidence of fire occurrence (fire scars) from dry, low-elevation ponderosa pine forests. Fuel and weather conditions in these dry, low-elevation ponderosa pine forests allow surface fires to recur at a few years to several decades in stands of a few dozen to approximately 100 ha (Swetnam and Baisan 1996, Grissino-Mayer et al. 2004). In such ecosystems, years of widespread fire are inferred from synchronous fire-scar dates on widely separated surviving trees, but actual extent or severity of fires remain ambiguous. In contrast, the current study relies on fire evidence from more mesic subalpine forests of Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine (*Pinus contorta* var. *latifolia*). The evidence used in this study includes fire scars dated to corresponding cohorts of tree establishment, which identify the predominant fire type in these forests as severe and stand replacing and provides estimates of relative fire size. In subalpine forests, severe fires kill most or all of the trees over areas of hundreds to many thousands of hectares at long but varying intervals within the range of 100–400+ years (Romme and Despain 1989, Kipfmueller and Baker 2000, Schoennagel et al. 2003, Buechling and Baker 2004; Sibold et al., *in press*). Because these events are rare but large and extreme, forecasting is especially desirable and the ecological impacts are widespread. Furthermore, because fire intervals are long relative to the short fire suppression period, and high-elevation, remote locations

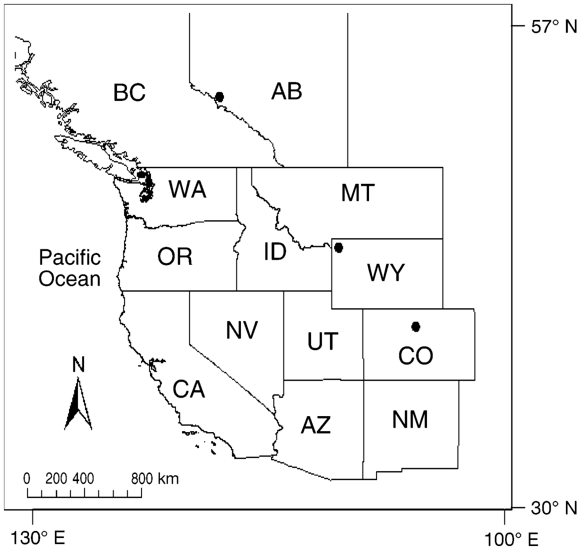

FIG. 1. Location of the three fire history study areas in the Rocky Mountains (solid circles). From north to south, they are: Jasper National Park, Alberta, Canada (53° N, 118° W); Yellowstone National Park, Wyoming, USA (44° N, 110° W); and Rocky Mountain National Park, Colorado, USA (40° N, 105° W).

make access a challenge, the effects of fire suppression in subalpine forests are less than in ponderosa pine, where the fire suppression period spans the length of many expected fire intervals and low-elevation locations are more accessible (Romme and Despain 1989, Johnson et al. 2001, Schoennagel et al. 2004).

In order to assess the effect of large-scale climatic anomalies on fire occurrence in high-elevation subalpine forests across a broad latitudinal gradient of the Rockies, we addressed the following questions in three study areas: (1) What are the temporal relationships between large-fire occurrence, drought (Palmer Drought Severity Index, PDSI), ENSO, and the PDO? (2) How do these relationships vary spatially across the Rocky Mountains? (3) How do drought and fire respond to interactions between the PDO and ENSO across the Rockies?

STUDY AREAS

The Rocky Mountains extend between 35° and 65° N in western North America. This study relies on dendrochronogical fire history data over the last 300 years from three study areas in the northern Rockies (Jasper National Park [JNP]; 419 800 ha), the central Rockies (Yellowstone National Park [YNP]; 128 842 ha) and the southern Rockies (Rocky Mountain National Park [RMNP]; 27 592 ha; Fig. 1). Fire data from each study area are from high-elevation subalpine forests (~1000–3000 m) dominated by Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine (*Pinus contorta* var. *latifolia*) (Peet 2000; see Plate 1). All study areas lie on the continental divide, with elevations ranging from 910–2150 m in JNP, 2080–2990 m in YNP, and 2650–3450 m in RMNP.

Regional weather patterns vary across the extent of the Rockies (Table 1). In winter, storms entering the northern Rockies from the Pacific Ocean are generally wet, while storms in the central and southern Rockies are relatively dry, having lost much of their moisture crossing the Cascades or Sierra Nevada and the Intermountain West (Kittel et al. 2003). However, masses of drier polar continental cold air can also enter from the north, while warm moist air from the Gulf of Mexico can generate precipitation as it moves up the eastern front of the Rockies (Kittel et al. 2003). In summer, the northern Rockies generally receive moist Pacific air, while the central and southern Rockies are influenced either by dry continental air from the west or monsoonal air from the Gulfs of Mexico or California (Kittel et al. 2003). SSTs in the Pacific Ocean affect the N–S position of the jet stream, which in turn influences the predominance of wet or dry regional weather patterns in western North America.

METHODS

Data sets

Fire history.—In each of the study areas, similar methods were used for determining fire history by following the stand-origin procedure (Heinselman 1973) in combination with fire-scar dates (Tande 1979,

TABLE 1. Average summer (June–August) maximum temperature and average winter (December–March) minimum temperatures, average yearly precipitation, and snowfall for three Rocky Mountain weather stations.

Weather stations	Average summer maximum temperature (°C)	Average winter minimum temperature (°C)	Average yearly precipitation (cm)	Average yearly snowfall (cm)
Jasper Townsite	21.0	−13.0	23.2	15.2
Old Faithful	21.7	−13.9	4.4	76.7
Allens Park	22.5	−7.4	3.0	41.2

Notes: In vertical order, the stations are near Jasper National Park (1100 m above sea level; data from 1850 to 2000), Yellowstone National Park (2237 m above sea level; 1978–2003), and Rocky Mountain National Park (2590 m above sea level; 1948–1999). Weather data for Old Faithful and Allens Park weather stations are from the Western Regional Climate Center; data for Jasper Townsite are from Environment Canada.

TABLE 2. A comparison of fire history data sets from the three study areas over the 1700–1975 period.

Parameter	Rocky Mountain National Park (RMNP)	Yellowstone National Park (YNP)	Jasper National Park (JNP)
Study area (ha)	27 592	128 842	419 800
No. large fires/ha†	0.0014 (0.0008)	0.0011 (0.0002)	0.0004 (0.00008)
Percentage of study area where fire-origin dates relied on fire-scarred trees	100%	15%	65%
No. fire-scarred cross-sections	676	108	910
Documentary period (years)	1872–2000	1881–2003	1900–2000
Documentary data sources	RMNP GIS Program	YNP GIS Lab	JNP GIS Center
Reconstructed fire history source	Sibold et al. (*in press*)	Romme and Despain (1989), Tinker et al. (2003)	JNP GIS Center (10% based on data from Tande [1979])

Note: In each data set, fire dates during this period are from reconstructed fire histories and documentary sources.
† Large fires are defined for each study area as ≥0.5% of the area burned over the 1700–1975 period.

McBride 1983, Tinker et al. 2003, Sibold et al., *in press*; Table 2). Patches of homogeneous forest structure were identified from aerial photos to develop preliminary cohort maps. In the field, each patch (presumed cohort) was visited. Small cohorts (<10 ha), which constitute a small percentage of subalpine forests, were not sampled. Each patch was searched for fire-scarred trees, focusing on patch boundaries, steep slopes, and rocky outcrops where fire scars are more likely to be preserved. Full and partial cross sections of fire-scarred trees provide fire dates with annual resolution (McBride 1983). To corroborate that the fire detected from fire-scarred tree wedges reflected a large stand-replacing fire, fire-scar dates were linked to the stand age of an adjacent fire-initiated patch on the landscape. Within each patch, at least 10 of the largest and presumably oldest trees were cored at dispersed sampling points to estimate the stand-origin date of the patch. Trees were cored 10 cm above the ground. At some sites, seedlings from open stands were destructively sampled to determine the average age at 10 cm, providing a correction for rings missed by sampling above the root–shoot interface. More sampling points were located in larger patches. Adjacent patches of similar age were aggregated, while single patches with multiple cohorts were divided. When fire scars were not found, fire-origin dates were estimated by the age of the oldest trees in the stand, which introduces greater uncertainty. These procedures resulted in maps of polygons depicting fire origin dates across each study area. Accuracy of the fire dates varies among study areas, primarily due to the number of fire scars found within the study areas (Table 2), which was lowest for YNP, presumably due to the flatter topography. Gently rolling plateaus present fewer fire breaks and rock outcrops where fire scars are commonly formed. Inaccuracies can also arise due to the insensitivity of lodgepole pine tree rings to annual climate variation, which made cross-dating difficult in many cases.

In addition to these field data, we also included more spatially extensive documentary data from Park records that report the size and date of fires in subalpine areas over the period of record. Because the study areas varied in size, large fires were defined by postfire patches ≥0.5% of the total area burned (≥100 ha, 1000 ha, and 2500 ha for RMNP, YNP, and JNP, respectively). Inevitably, more recent fires burn over portions of older fires. However, no trends of increasing fire size with time were evident in the three data sets considered, suggesting that patch size can be used as a coarse proxy for defining fire size thresholds. The fire history data sets used in this study identified years of large-fire occurrence in each of the study areas over the 1700–1975 period.

Palmer Drought Severity Index (PDSI).—Instrumental PDSI values are standardized measures derived from a combination of current and prior precipitation, air temperature, and local soil moisture with values ranging from −6.0 (extreme drought) to +6.0 (extreme wet conditions). Characterization of historical patterns of drought relied on reconstructions of the summer PDSI for the western United States over the 1700–1975 period across a regular grid ($2° \times 3°$) of 74 points (Cook et al. 1996, 1999), which explains 50–70% of the variation in the instrumental summer PDSI. An additional 24 points of PDSI data from Canada relied on the instrumental period only (1900–1975), for a total of 98 PDSI grid points across western North America. The Canadian PDSI reconstructions correlated less well with the instrumental period than the PDSI data for the western United States (1928–1978), where the median calibration r^2 was 0.478 for Canada and 0.591 for the western United States. Spatial correlation maps also revealed distinct drops in correlation coefficients between PDSI and the climate indices tested across the U.S.–Canada border, while correlations with instrumental PDSI did not reveal such abrupt spatial disjunctions across political boundaries. Hence, we relied on gridded instrumental PDSI data for the southern Alberta and British Columbia and reconstructed PDSI data for the 1700–1975 period across the western United States. The local PDSI time series used in superposed epoch analysis of large-fire occurrence in JNP (see *Methods: Analyses: Temporal variation: superposed epoch analysis*) relied on reconstructed PDSI values for the full 1700–1975 period from a grid point directly south of JNP, which explained the greatest proportion of the variation in the instrumental PDSI among the Canadian grid points (calibration $r^2 = 0.634$). Characterization of drought in YNP and RMNP similarly relied on tree-ring reconstructed PDSI values from local grid points for the full historical period.

El Niño-Southern Oscillation (ENSO).—To characterize ENSO variability, we relied on a tree-ring based reconstruction of winter (December–February) sea surface temperatures from the NIÑO3 region of the equatorial Pacific (5° S–5° N, 150° W–90° W), which covers the period 1408–1978 AD (Cook 2000). The NIÑO3 region of the Pacific captures the greatest interannual variability in SSTs representing ENSO. This ENSO reconstruction captures 62% of the variance in NIÑO3 region SSTs in the instrumental record during the overlapping 1950–1978 period. When the NIÑO3 index is positive (negative) it reflects El Niño (La Niña) conditions.

Pacific Decadal Oscillation (PDO).—We relied on D'Arrigo et al.'s tree-ring reconstruction of the PDO (D'Arrigo et al. 2001), which explains the most variance in the instrumental record (53% of the variance in the annual PDO over the 1900–1979 period) compared to other published reconstructions (Biondi et al. 2001, Gedalof et al. 2002). It also accurately replicates the spatial correlation structure between the instrumental PDO and the North Pacific SSTs (D'Arrigo et al. 2001). Positive (negative) PDO values produce relatively similar climate and circulation patterns to El Niño (La Niña) conditions, although the periodicity is decadal.

Analyses

The goals of the analyses are to initially examine and compare the temporal relationships of large-fire occurrence with drought, ENSO and the PDO at each of the three study areas via superposed epoch analysis (SEA). This analysis tests whether large fires coincide with drought and how these ''drought-induced fires'' are associated with variability in ENSO and the PDO. To independently corroborate the variability in relationships of drought-induced fires to ENSO and the PDO across the three study areas, and to provide further evidence that ENSO and the PDO represent important mechanisms controlling drought throughout the west, we develop teleconnection maps. These maps provide independent evaluation of the spatial trends and suggested mechanisms observed through SEAs.

Temporal variation: superposed epoch analyses.—To examine the temporal relationship between large-fire occurrence, drought, and large-scale climatic anomalies we relied on superposed epoch analysis (SEA; Grissino-Mayer 1995). SEA is often applied to fire history data to characterize variability in a particular independent climatic parameter prior to, during, and after fire events. We ran separate SEAs to assess if mean values of PDSI, ENSO, and PDO were significantly different during fire years relative to one to four years prior to a fire event (4-yr lag) and two years after. Ninety-five percent, 99%, and 99.9% confidence intervals were determined from a simulated distribution of means of the climatic parameter via bootstrapping, where fire years were randomly selected from 1000 simulated runs, and means were calculated for years -4 to 2, where 0 is the fire year.

To assess the effect of ENSO × PDO interactions, we separately selected large-fire years during which both indices were positive, both were negative, or one was negative while the other was positive. We calculated the proportion of all large fires from each study area that occurred during each of the four ENSO × PDO phase combinations, and compared this to the proportion of years that fell within each phase combination during the complete 1700–1975 period to determine if fires occurred disproportionately during a particular phase combination. We used chi-square tests to assess departure from expected large-fire frequencies under each of the four phase combinations. We ran additional SEAs of large-fire events occurring during combinations of the PDO and ENSO for which fire frequencies were higher than expected, using PDSI, ENSO, and PDO as the independent climate variables.

SEA evaluates current-year and lagged responses of fire events to climatic variables (Haurwitz and Brier 1981, Prager and Hoenig 1989), and is a standard statistical analysis for examining nonlinear relationships between fire events and short-term variability in drought and ENSO (e.g., Swetnam and Betancourt 1990). We were primarily interested in detecting which short-term climatic signals trigger annual fire events, rather than understanding relationships of overall fire frequency or periodicity to long-term climatic variability. Although the PDO generally exhibits decadal variability, significant temporal autocorrelation is much shorter: four years ($P = 0.005$) in the D'Arrigo reconstruction. So for SEA analyses of the PDO, we also considered 10-year lags prior to fire to permit detection of significant departures from the mean. In all cases, however, there was no difference in overall significance of the PDO between the 10- and 4-yr lag analyses. So, for consistency and brevity, we only report results from SEAs with 4-yr lags.

Spatial variation: teleconnection patterns.—Spatial analysis was used to corroborate the variation in climate–fire relationships observed across study areas through SEAs. We first determined how large-fire occurrence in each study area related spatially to patterns of drought (PDSI) across western North America. We then independently assessed the spatial relationship of ENSO and PDO to drought across the same region. These teleconnection patterns were derived from maps showing a relationship between two variables of interest such as patterns of drought in the western United States and indices of ENSO or PDO variability over a certain period (Stenseth et al. 2003).

The first map defined regional patterns of drought (PDSI) associated with large-fire occurrence in each study area. For each study area, we selected years in which large fires occurred, then calculated the frequency of those years experiencing extreme drought at each of the 98 grid points. Extreme drought was defined by PDSI values in the lowest quartile over the 1700–1975 period across all grid points (≤ -1.087). This metric, ''extreme-drought frequency,'' reflects the degree of association between a categorical variable (the binomial variable large-fire occurrence in this case and combined phases of PDO–ENSO below) and PDSI, adopted from McCabe et al. (2004). This metric is used in place of correlation coefficients between continuous variables to produce teleconnection maps that incorporate categorical variables. This resulted in separate maps that depict spatial patterns of extreme-drought frequency occurring during large-fire years in each of the three study areas.

To characterize ENSO and PDO teleconnection patterns, we correlated the PDSI at each of the 98 grid points with the instrumental ENSO and PDO values using Spearman rank correlations over the 1900–1990 period. To assess teleconnection patterns associated with ENSO $\times$ PDO interactions, we divided the 1700–1975 period in four categorical combinations of years (where both indices were positive, both were negative and either one was negative while the other was positive). We calculated extreme-drought frequency, as above, for each subset of years reflecting the four categorical combinations of ENSO and PDO phases.

Each of these maps was interpolated to a contour surface using the inverse distance weighted method in ArcGIS 8.3 (ESRI, Redlands, California, USA). Maps of climatic teleconnections (spatial patterns of climate-fire or climate-drought relationships) provide independent support for the possible climate mechanisms underlying spatial patterns of drought-induced fire across the Rockies observed through SEAs in the three study areas.

Results

Climatic anomalies and fire: temporal variation

Large fires occurred during years of extreme drought (negative PDSI) in the 1700–1975 subalpine fire history record from JNP, YNP, and RMNP (Fig. 2). In each of the study areas, the fire years (year 0) experienced significantly negative departures from mean PDSI ($P < 0.05$). None of the four years prior to fire were significantly different from average PDSI, indicating that antecedent conditions do not affect fire occurrence in these high-elevation subalpine forests.

Large-scale climatic anomalies captured by ENSO and PDO indices had differential effects on large-fire occurrence across the study areas (Fig. 2). In RMNP, the NIÑO3 index of ENSO was significantly negative during large-fire years ($P < 0.001$), meaning that fires occurred during extreme La Niña years at this southern Rocky Mountain subalpine forest. The PDO index, although predominantly in its negative phase during fire years in RMNP, did not depart significantly from the mean. In contrast to RMNP, mean ENSO and PDO indices tended to be positive but were not significantly different from the mean ($P < 0.05$) during large-fire years in YNP and JNP. At YNP the NIÑO3 index was significantly positive three years prior to large fires and coincided with a nonsignificant tendency toward higher PDSI.

Climatic anomalies and fire: spatial teleconnections

The regional extent and location of extreme drought associated with large fires varied among the three study areas (Fig. 3). During large-fire years in RMNP, the frequency of extreme drought was highest (74–84%) in the southwestern United States (Four Corners region). High extreme-drought frequencies (55–74%) also extended throughout Colorado, Utah, Arizona, and New Mexico (Fig. 3c). Large fires in YNP were associated with the high extreme-drought frequencies (39–45%) southwest of the park (southeastern Idaho and northeastern Utah), and relatively high extreme-drought frequencies (32–39%) extending over a larger swath of Utah, southern Idaho, western Wyoming, and Montana (Fig. 3b). Large-fire years in JNP were associated with high extreme-drought frequencies (54–59%) northwest of the park, with relatively high frequencies (44–54%) throughout Alberta and eastern British Columbia (Fig. 3a). Overall, the frequencies of extreme drought associated with large-fire occurrence reflect the location of the study areas but are higher in the southern Rockies and SW due to the generally warmer and drier conditions.

Correlation maps between drought and instrumental records of ENSO and PDO corroborate trends observed in the SEAs in the three study areas (Fig. 4). The drought–ENSO correlation map shows that drought (negative PDSI) is relatively highly correlated with La Niña conditions (negative NIÑO3), resulting in positive Spearman rank correlation values (ranging from 0.121 to 0.378) in the southwestern United States (Fig. 4a). In contrast, drought in the central and northern Rockies is negatively but relatively weakly correlated with the NIÑO3 index (-0.137 to -0.055) indicating that drought is weakly associated with El Niño conditions in this region. In terms of the PDO, rather similar patterns were observed where drought is relatively strongly correlated with the negative phase of the PDO in the SW, represented by relatively high, positive correlations (ranging from 0.164 to 0.308). In the central and northern Rockies, drought is negatively correlated with the PDO index (-0.270 to -0.018), indicating that drought tends to occur during the positive phase of the PDO in this region (Fig. 4b). Overall, the relationship between drought and ENSO is relatively weak in the northern and central Rockies compared to

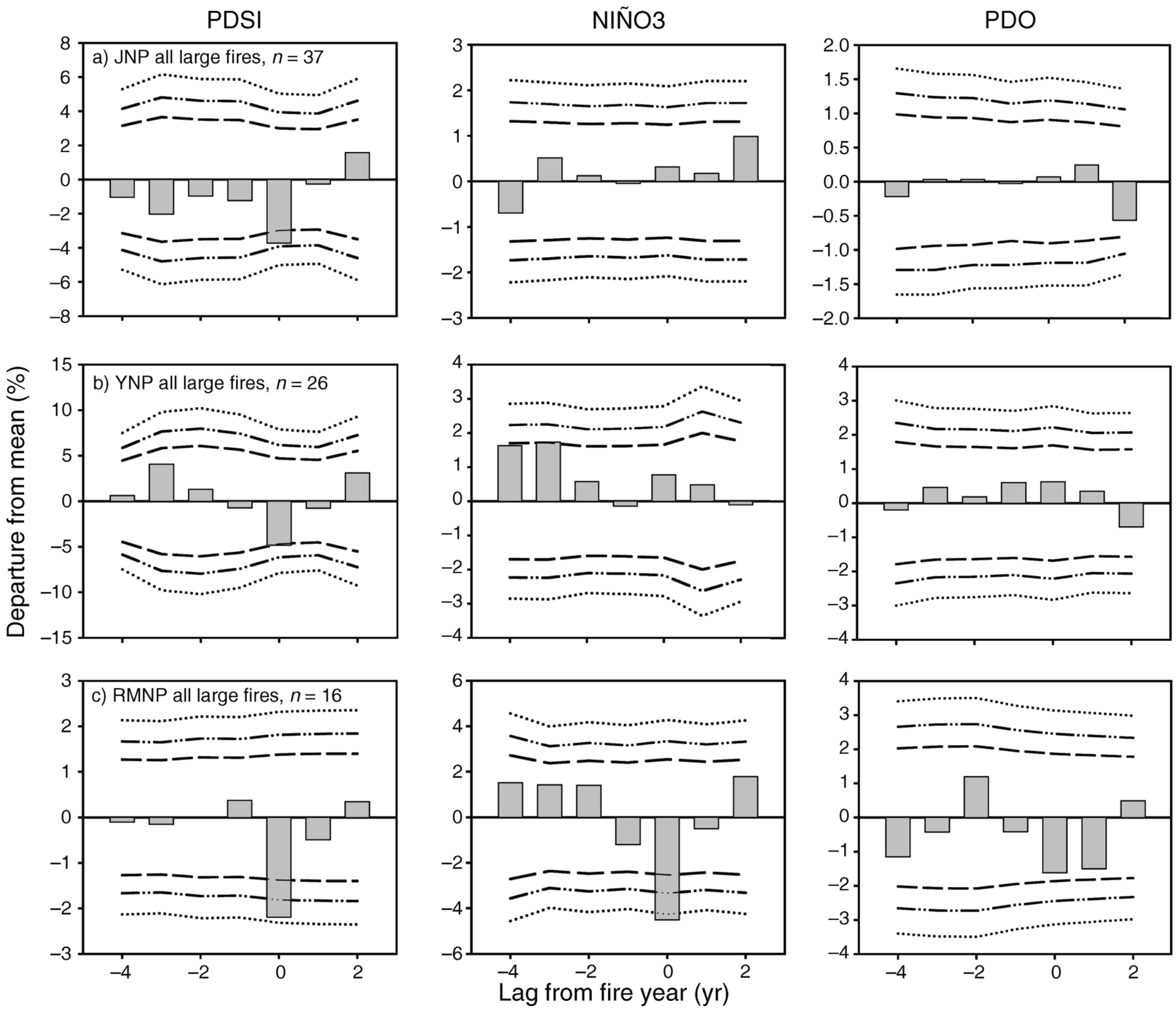

FIG. 2. Superposed epoch analyses of percentage departure from the mean Palmer Drought Severity Index (PDSI), El Niño–Southern Oscillation (NIÑO3), and Pacific Decadal Oscillation (PDO) reconstructions during the 1700–1975 period during large-fire years (year 0) relative to 1–4 years prior to a fire event and two years after from (a) Jasper National Park (JNP), (b) Yellowstone National Park (YNP), and (c) Rocky Mountain National Park (RMNP). Dotted lines represent 99.9% CI, dot-dash lines represent 99% CI, and dashed lines represent 95% CI derived from 1000 Monte Carlo simulations; *n*, number of fire years.

the southern Rockies, while PDO effects on drought appear to be strongest in the northern and southern Rockies.

PDO-ENSO interactions: temporal variation

The frequency of large fires at different study areas was dependent on different combined phases of PDO and ENSO indices (Fig. 5). Large fires in RMNP occurred more frequently (69%) during years of negative PDO–negative NIÑO3 (La Niña), although these phases co-occurred only 29% of the 1700–1975 period ($\chi^2 = 12.52$, $P = 0.006$). In RMNP, when large fires burned during these cool phases of the PDO and ENSO, all three indices (PDSI, PDO, and NIÑO3) departed significantly from the mean (Fig. 6c). In contrast, when all fire years were analyzed regardless of the ENSO or PDO phase, PDO did not depart significantly from the mean (Fig. 2c). A very high proportion of the fires in RMNP occurred during the combination of La Niña years with a negative PDO, but only 3% occurred during the combination of La Niña years with the positive phase of the PDO (Fig. 5). This indicates that the phase of the PDO augments the favorable influence of La Niña on fires in the southern Rockies.

In contrast to RMNP, large fires occurred more frequently during years of positive PDO and positive NIÑO3 (El Niño) in YNP and JNP, although this was not significantly different from expected ($\chi^2 = 1.12$, $P = 0.772$; $\chi^2 = 2.08$, $P = 0.556$, respectively; Fig. 5). In YNP and JNP 35% and 41% of fires occurred, respectively during these combined warm phases, which occurred 30% of the 1700–1975 period. In YNP and

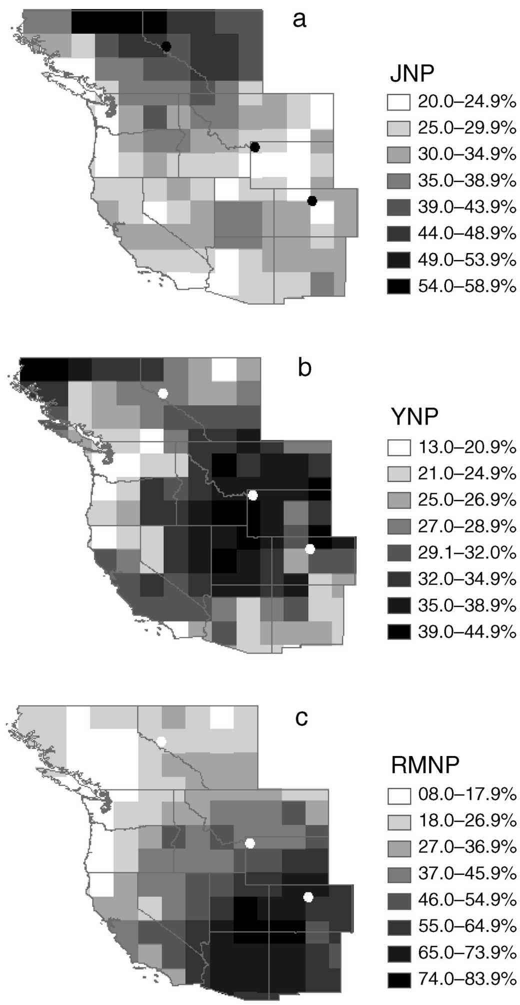

FIG. 3. Maps depicting the percentages of large-fire years occurring during extreme drought (first quartile PDSI in 2° × 3° grids) across the western United States and Canada in (a) Jasper National Park (JNP, n = 37 fire years), (b) Yellowstone National Park (YNP, n = 26 fire years), and (c) Rocky Mountain National Park (RMNP, n = 16 fire years) over the 1700–1975 period. The three study areas are represented by circles.

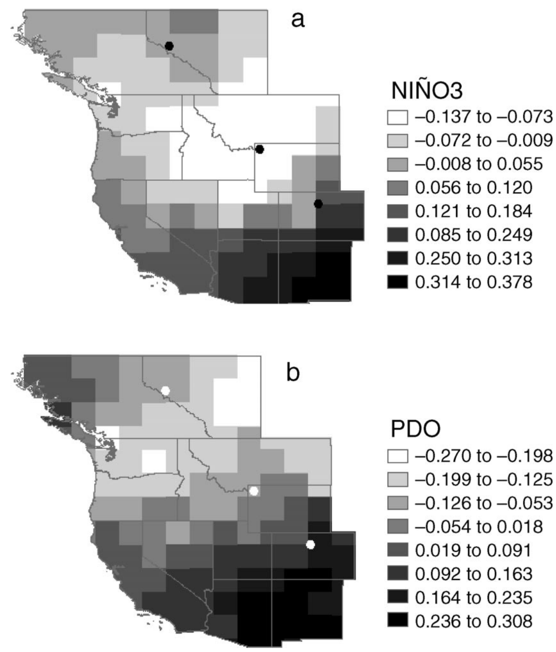

FIG. 4. Maps depicting correlations (Spearman rank) of drought (PDSI) across the western United States and Canada to (a) the NIÑO3 index (Cook 2000) and (b) the PDO index (D'Arrigo 2001) for the instrumental period 1900–1990. High positive correlations represent drought (PDSI) associated with negative phases of the PDO or NIÑO3 (La Niña) indices, and high negative correlations represent drought associated with positive phases of the PDO and NIÑO3 (El Niño) indices. The three study areas are represented by circles.

JNP, SEAs showed that drought and the climate reconstructions departed significantly from the mean in fire years occurring during the positive PDO–NIÑO3 combination (Fig. 6a, b). None of the other PDO–ENSO phase combinations appeared to increase the occurrence of drought-induced fire at YNP or JNP, however. Although some significant departures in NIÑO3 and PDO occurred during fire years under other combinations, they were not associated with significant drought during fire years. Compared to SEAs of all fire years (Fig. 2a, b), where the PDO and ENSO indices were not significant in YNP and JNP, these results suggest that the combined positive PDO and El Niño conditions can affect the occurrence of large drought-induced fires in the central and northern Rockies (Figs. 5, 6a, 6b).

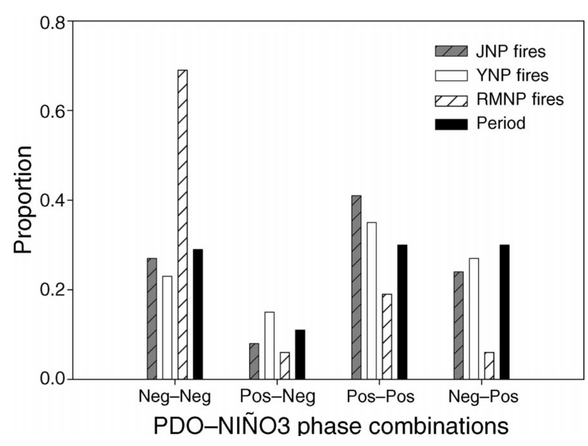

FIG. 5. The proportion of total number of fires at each study area relative to the total proportion of years during the 1700–1975 period (black bars) in each PDO–ENSO phase combination. Chi-square tests show that the fires occurred more often than expected in RMNP during negative PDO–La Niña conditions (P = 0.006). The frequency of fires in YNP and JNP did not differ significantly from expectations, although fires occurred most often during the positive PDO–El Niño conditions.

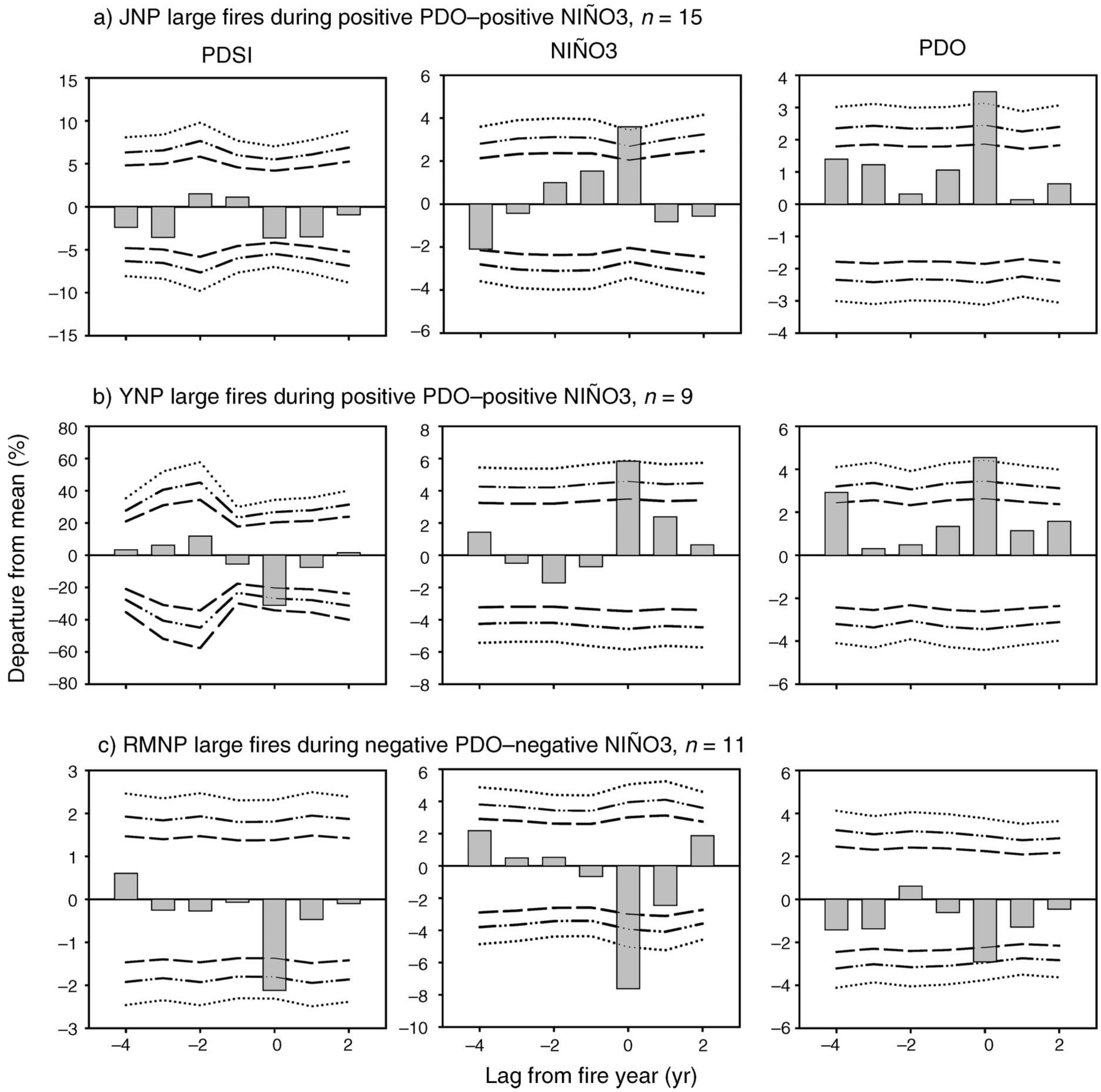

FIG. 6. Results from superposed epoch analyses performed on years of large fires occurring during combinations of the PDO and ENSO for which fire frequencies were highest at each site (Fig. 5): the positive PDO and positive NIÑO3 (El Niño) phases in (a) Jasper National Park (JNP) and (b) Yellowstone National Park (YNP), and the negative PDO and negative NIÑO3 (La Niña) phases in (c) Rocky Mountain National Park (RMNP). Graphs represent the percentage departure from the mean PDSI, ENSO, and PDO reconstructions during large-fire years occurring during the PDO–ENSO phase described above (year 0) relative to 1–4 yr prior to a fire event and 2 yr after for each of the study areas. Dotted lines represent 99.9% CI, dot-dash lines represent 99% CI, and dashed lines represent 95% CI derived from 1000 Monte Carlo simulations.

PDO–ENSO interactions: spatial teleconnections

During the negative PDO and negative NIÑO3 (La Niña) phases, the southwestern United States experienced the highest frequency of extreme drought (52–68%; Fig. 7a). In contrast, the positive PDO and the positive NIÑO3 (El Niño) phases are associated with the relatively high frequency of extreme drought (26–38%) in the northern Rockies, northern Intermountain region, and PNW (Fig. 7b). Although YNP falls between these two poles of high drought frequency, on average fires appear to have been more influenced by the positive PDO–positive NIÑO3 drought pattern over the 1700–1975 period (Figs. 5, 6). The positive PDO–negative NIÑO3 (La Niña) combination co-occurred with relatively high frequency of extreme drought (36–54%) in southern California and parts of the SW (Fig. 7c). Although this combined phase did not appear to influence the occurrence of large drought-induced fires at any of the study areas in the Rockies, the occurrence of fires in southern California may be higher during

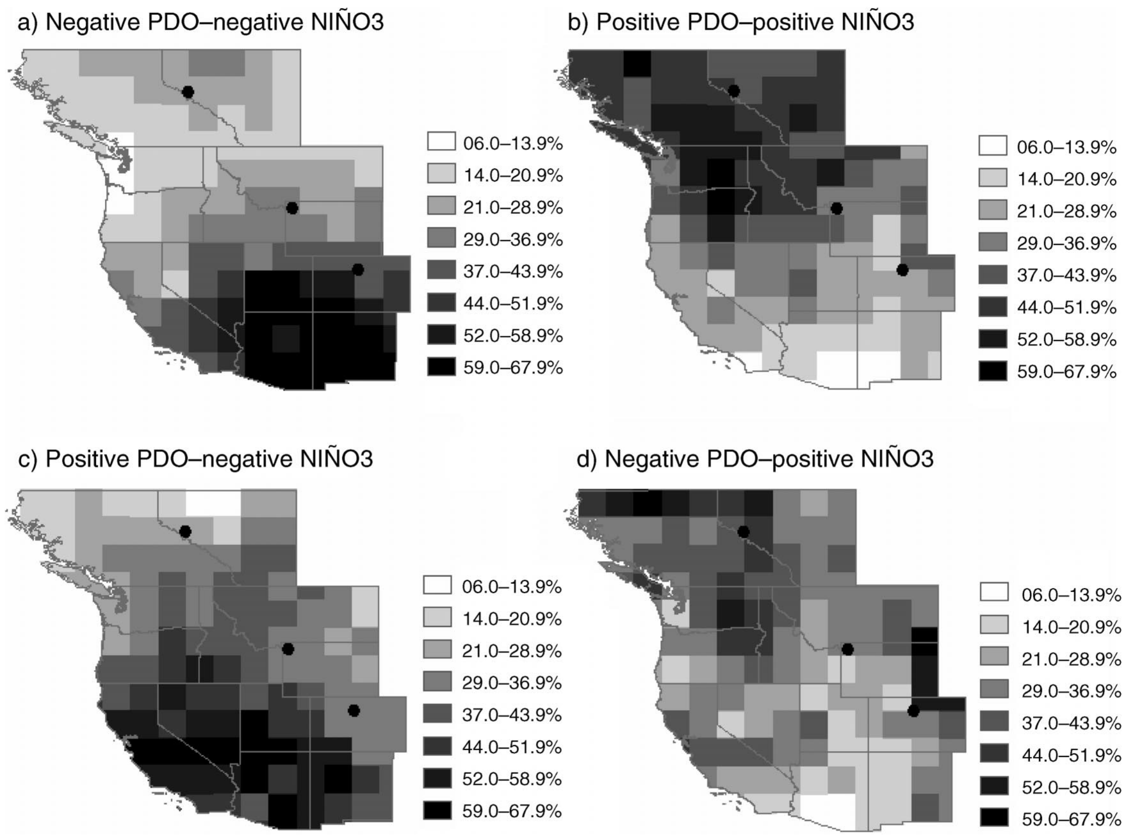

FIG. 7. Maps depicting the percentages of years classified as extreme drought (first-quartile PDSI) during the four categorical combinations of the PDO and ENSO phases across the western United States and Canada. The three study areas are represented by solid circles.

this relatively infrequent PDO–ENSO phase combination (10% of the 1700–1975 period). Comparing Fig. 7a and 7c indicates that the effect of ENSO on drought may be less dependent on the phase of the PDO in New Mexico, AZ and southern UT, compared to the southern Rockies of central CO. The negative PDO–positive NIÑO3 (El Niño) combination had the weakest and least spatially coherent influence on drought across western North America (Fig. 7d).

DISCUSSION

Drought–fire relationships in subalpine forests

Large fires in the subalpine forests of this study coincided with drought during the fire year and antecedent conditions appeared unimportant (Fig. 2). These results agree with other subalpine studies (Kipfmuller and Swetnam 2000, Westerling et al. 2003*a*, Sibold et al., *in press*), and with low-elevation ponderosa pine studies in the PNW that are snow covered in winter (Heyerdahl et al. 2002, Westerling et al. 2003*a*, Hessl et al. 2004). In contrast, wet antecedent conditions when followed by a dry summer are conducive to widespread fires in low-elevation, snow-free ponderosa pine forests of the SW and southern Rockies, perhaps due to an increase in fine fuels such as grasses during the wet year that, when desiccated during the following dry year, carry large surface fires (Swetnam and Baisan 1996, Veblen et al. 2000, Rollins et al. 2002, Westerling et al. 2003*a*, Grissino-Mayer et al. 2004). In general, frequent low-severity surface fires historically dominated dry, warm, low-elevation ponderosa pine forests (Brown and Seig 1996, Swetnam and Baisan 1996, Veblen et al. 2000). Most summers tended to be sufficiently dry to promote low fuel moistures and permit ignition in dry low-elevation ponderosa pine forests, but the abundance and continuity of fine surface fuels apparently had a significant influence on the occurrence and spread of surface fires, historically (Swetnam and Baisan 1996). In contrast, high-elevation subalpine forests typically experience high-severity crown fires. In these moist, cool forests the climate is rarely conducive to ignition, and fine fuels are consistently abundant throughout the dense canopy (Schoennagel et al. 2004). As a consequence, current-year drought is the most important trigger of large crown fires in subalpine forests.

Fire, ENSO, and PDO relationships

Sea-surface temperatures in the Pacific Ocean varied with the occurrence of drought-induced wildfires in subalpine forests across the Rockies from 40° to 53° latitude, but the sign and strength of these relationships varied spatially. Large, high-elevation, stand-replacing forest fires occurred in RMNP (southern Rockies) during extreme La Niña events over the 1700–1975 period. Fire occurrence during droughts associated with La Niña events has been observed in previous work in low- and high-elevation forests in central and northern Colorado (Veblen et al. 2000, Donnegan et al. 2001, Sherriff et al. 2001). Major fire years associated with La Niña events are also characteristic of Southwestern ponderosa pine ecosystems (Swetnam and Betancourt 1990, 1998, Swetnam and Baisan 1996, Westerling and Swetnam 2003).

When analyzed independently of the PDO, ENSO did not significantly affect large-fire occurrence in the central (YNP) and northern (JNP) Rockies study areas. The data for YNP (and possibly JNP) likely have poorer annual resolution relative to RMNP given the lower proportion of dates linked to fire scars at these sites (see Table 2). This could account for the insignificance of ENSO, which varies interannually, at these sites. Our results, however, are consistent with variable to no significant association of fire years with ENSO (as judged by SEAs) in ponderosa pine forests at higher latitudes in northern California and the PNW (Heyerdahl et al. 2001, Norman and Taylor 2003, Hessl et al. 2004). Correlations between ENSO and drought also appear to be weaker in the central and northern Rockies during the instrumental period (Fig. 4). Despite weak correlations of fires with ENSO in YNP and JNP, fires tended to occur during El Niño years, similar to results in the PNW and northern California (Heyerdahl et al. 2001, Norman and Taylor 2003, Hessl et al. 2004)

In our study, large-fire years in the southern and central-northern Rockies were associated with the negative PDO and positive PDO phases, respectively, but the PDO alone was not statistically significant in SEAs. SEAs may not fully capture the influence of low-frequency climate variation, however. In the PNW, decadal variation in fire extent in dry ponderosa pine forests is hypothesized to correlate positively with the PDO (Heyerdahl et al. 2002), and large, regional fire events have been shown to occur more often during the positive PDO phase (Mote et al. 1999, Hessl et al. 2004). Climatic variation tied to the PDO has also been linked to fire activity in the SW (Westerling and Swetnam 2003).

Analyses of combined PDO and ENSO phases clearly revealed intensifications and contingencies in their effects on fire. Interactions between the phases of ENSO and the PDO were significantly associated with large-fire occurrence across the Rockies, even when these large-scale climatic anomalies were not significant when considered singly in SEAs. Gershunov and Barnett (1998) define constructive (same-sign) phases of the PDO and ENSO when both oscillations are simultaneously in the cool phase (negative PDO, La Niña) or the warm phase (positive PDO, El Niño), while destructive (opposite) phases occur when a warm (cool) PDO and a cool (warm) ENSO co-occur. Constructive phases of the PDO and NIÑO3 exerted the strongest influence on large-fire occurrence across the Rockies. The warm phases co-occurred with large drought-induced fires in the central and northern Rockies, while the cool phases appeared to promote extreme drought and large fires in the southern Rockies. The effect of the PDO–ENSO interaction was more pronounced in the southern Rockies, resulting in a marked increase in the frequency of large fires during the cool-phase combination.

A number of climatological studies suggest that the phase of the PDO strengthens or weakens ENSO teleconnections (Gershunov and Barnett 1998, McCabe and Dettinger 1999, Biondi et al. 2001, Gray et al. 2003), although others have questioned this relationship (Rajagopalan and Cook 2000). In northeastern California, fires were most widespread during El Niño years when the PDO was in the positive phase (Norman and Taylor 2003). In a spatially extensive study, Westerling and Swetnam (2003) developed a statistical reconstruction of area burned by region based on PDSI across the western United States. Their statistical model of area burned (validated using fire-scar data from ponderosa pine stands in Arizona and New Mexico) indicates that when the negative PDO phase coincides with La Niña, the SW and southern Rockies (Arizona, Nevada, Utah, Colorado, and Wyoming) experience greater area burned (Westerling and Swetnam 2003). In contrast, higher fire activity is expected during the positive PDO phases during El Niño events in the PNW (Westerling and Swetnam 2003). Our empirical results corroborate these expected relationships of higher fire activity during negative PDO phases and La Niña conditions in Colorado (Westerling and Swetnam 2003). However, in contrast to Westerling and Swetnam's (2003) model predictions, our results from YNP suggest that the occurrence of high-elevation fires in northwestern Wyoming may increase under El Niño and positive PDO conditions. Their model did not extend into the northern Rockies, but their results from the PNW corroborate ours for the northern Rockies.

ENSO has been shown to be a weak influence on drought and fire at higher latitudes (40–45° latitude; Norman and Taylor 2003, Hessl et al. 2004), but our analysis indicates that the influence of El Niño on drought-induced fire is significant in the central and northern Rockies when coupled with positive phases of the PDO. Conversely, the influence of La Niña on drought-induced fire has been well established on the basis of fire-scar data from high- to low-elevation forests on relatively dry sites in the southern Rockies and SW (Swetnam and Betancourt 1990, 1998, Swetnam and Baisan 1996, Veblen et al. 2000, Donnegan et al. 2001, Sherriff et al. 2001, Westerling and Swetnam 2003). However, our current study shows that the relative effect of La Niña on fire occurrence depends on the phase of the PDO for large, severe fires in more mesic subalpine forests in the southern Rockies (Fig. 5). Further studies are needed on the synergy of ENSO and the PDO. Specifically, is the strength of La Niña reported in previous studies of fire occurrence in ponderosa pine forests in the SW due primarily to its co-occurrence with the negative phase of the PDO?

Regional patterns of fire and drought

The dipole or seesaw teleconnection pattern, where drought in the PNW co-occurs with wet conditions in the SW during warm phases of ENSO and PDO, has been previously observed in western North America (Dettinger et al. 1998, Gershunov and Barnett 1998, Rajagopalan and Cook 2000, Gray et al. 2003). The pivot point in this dipole pattern has been identified around 40° N (Dettinger et al. 1998), and has been suggested to be rather stable through time (Cayan et al. 1998, Dettinger et al. 1998). However, fire occurrence in the Sierra Nevada (~40° N) is sometimes synchronized with Washington and Oregon, while at other times with the SW (Westerling et al. 2003*a*, Westerling and Swetnam 2003). Based on these previous studies and the spatial correlation patterns of drought with ENSO and the PDO (Fig. 4), we expected fires in YNP to relate ambiguously to ENSO and PDO, reflecting this low-correlation zone and/or a possible shift in the pivot position through time. However, our results indicated that fire history in YNP and JNP responded similarly to the PDO and ENSO (and their phase interactions), suggesting that the central Rockies may be more influenced by weather patterns of the PNW than the SW on average over the 1700–1975 period. However, these relationships may not be stable over longer or shorter periods, and fire hazard may indeed be less predictable in the central Rockies. These spatially opposing effects of ENSO and the PDO are only recently being discovered by fire ecologists and managers, yet may provide important information to regional fire planning across the western United States and Canada.

Climatic mechanisms promoting drought patterns in the West

Regional weather patterns in western North America relate to broad-scale climatic teleconnections with the Pacific Ocean and are most pronounced during constructive phases of ENSO and the PDO. Phases of the PDO and ENSO affect the track of the winter jet stream, which can explain the response of drought-induced fire across the West to these combined oscillations (Gershunov and Barnett 1998). In general, variability in SSTs in the North Pacific Ocean affects the strength of air flows from the Pacific into the northern and central Rockies, while SSTs in the subtropical and tropical Pacific Ocean primarily influence weather patterns in the southern Rockies. The positive PDO is associated with warmer SSTs along the Pacific Coast and a deep Aleutian low that shifts storm tracks southward, resulting in drier conditions in the PNW, western Canada and northern Rockies and wetter conditions in the southern Rockies (Gershunov and Barnett 1998, Gray et al. 2003). A coincident El Niño enhances the moisture of the eastern tropical Pacific, resulting in wetter conditions in the SW and southern Rockies, while a ridge of high pressure in central Canada enhances drying in the PNW and northern Rockies. Such persistent high-pressure blocking ridges promote prolonged dry periods that have been linked to large areas burned in the PNW and the northern Rockies, in association with below-normal SSTs in the North Pacific Ocean (Johnson and Wowchuk 1993, Gedalof et al. 2005). In contrast, during cool, constructive phases the negative PDO is associated with a weak Aleutian low that steers storms farther north, resulting in a wet PNW, western Canada, and northern Rockies. Meanwhile, La Niña events associated with low SSTs in the eastern tropical Pacific result in less frequent, dry storms resulting in dry conditions over the SW and southern Rockies (Gershunov and Barnett 1998, Gray et al. 2003).

Destructive phases of ENSO and the PDO are predicted to result in spatially incoherent, unstable, precipitation patterns (Gershunov and Barnett 1998). The negative PDO, by pushing storms to the north, combined with El Niño, by increasing the southerly storm moisture, may result in more spatially homogeneous conditions across the western United States. Indeed, the negative PDO–El Niño combination reflected relatively incoherent spatial variation in extreme drought frequency across the western United States (Fig. 7d). In contrast, however, high drought frequencies in southern California and the SW occurred during the positive PDO–La Niña combination (Fig. 7c). Although this phase combination is relatively rare (10% of the 1700–1975 period), if this teleconnection pattern is persistent, it may indicate a relatively good forecasting tool for this region. Keeley (2004), however, notes that synoptic weather conditions promoting drought are less important than seasonally occurring ''Santa Ana'' winds in generating extreme fire weather conditions in southern California. The strength of this particular teleconnection to fire activity in southern California requires further investigation.

Forecasting and management applications

Forecasts of ENSO that are linked with the expected PDO phase suggest a promising aid to fire forecasters and fire managers across the West. Statistical forecasts of regional area burned often rely on antecedent PDSI values (typically up to two years) (Westerling et al. 2002, 2003*a*, *b*). However, as shown in this study and others (Kipfmuller and Swetnam 2000, Sibold et al., *in press*), antecedent PDSI is not significantly correlated with the occurrence of large fires in Rocky Mountain subalpine forests, whereas PDSI during the summer of fire is. Indeed, antecedent PDSI has been shown to be a relatively weak predictor of area burned in subalpine forests (Westerling et al. 2002, 2003*a*, *b*).

Because ENSO in constructive phase with the PDO tends to be associated with extreme summer drought, forecasts of ENSO, which can be predicted relatively well three to 12 months in advance, can provide a useful aid to forecasting fire activity in subalpine zones in place of antecedent PDSI. Although the mechanisms controlling the PDO are currently not well understood, and prediction of phase shifts of the PDO is weak (Mantua and Hare 2002), skill in forecasting the PDO is relatively strong given its multidecadal persistence. Therefore, stratifying ENSO forecasts by PDO phase, could improve the forecasting of fire hazard in subalpine forests (Gershunov and Barnett 1998, Mantua and Hare 2002). Previous researchers have recommended such categorical probability forecasts of ENSO (Rajagopalan and Cook 2000). Because the relationship between ENSO and PDSI appears to be nonlinear, drought may be best predicted by ENSO events that exceed a threshold (Rajagopalan and Cook 2000), as occurs during constructive phases with the PDO (Gershunov and Barnett 1998). Decreased amplitude of ENSO and PDO, as experienced during the 19th century (Grissino-Mayer 2000, Gedalof et al. 2002), may affect the sensitivity of fire to constructive phase combinations and attenuate teleconnections to fire over longer time scales, however. Additional investigation is needed of significant North Atlantic Oscillation (NAO) excursions that may co-occur with destructive PDO–ENSO combinations (Gershunov and Barnett 1998). Other work has suggested significant interactions between the PDO and variability in SSTs in the North Atlantic captured by the Atlantic Multidecadal Oscillation (AMO; McCabe et al. 2004), which may also aid fire forecasting across the western United States and Canada.

Fire planning organizations and forest management agencies currently do not rely on climate indices for planning or implementation. Even without the aid of sophisticated statistical forecasts of fire activity, information provided by ENSO and PDO forecasts could prove very useful, the former being readily available and the latter changing infrequently. Fire planners and managers could prepare for high fire activity in the PNW and northern and central Rockies when El Niño was expected during a positive PDO, and in the SW and southern Rockies when La Niña was expected during a negative PDO. This information could also inform managers whose experience during one ENSO phase may not be consistent from one year to another, depending upon the phase of the PDO. Overall, attention to climate–fire teleconnections outlined in this study should aid near-term fire management and planning efforts by facilitating better assessment of the risks associated with projected climate conditions.

Ecologists' recognition of the importance of large-scale ocean-atmosphere anomalies to fire and other ecological processes has grown substantially over the past 20 years (Swetnam and Betancourt 1990, 1998, Kitzberger et al. 1997, 2001, Daniels and Veblen 2000, Heyerdahl et al. 2002, Norman and Taylor 2003, Westerling and Swetnam 2003, Hessl et al. 2004). The recent history of research on the ecological consequences of such climatic anomalies reveals a growing sophistication in understanding both atmospheric and ecological processes (Stenseth et al. 2002, Gedalof et al. 2005, Hessburg et al. 2005). For example, an early study of fire occurrence during the 20th century found no associations with ENSO events for the Rocky Mountain region (Simard et al. 1985) but the geographical aggregation of fire data in that study did not reflect known spatial patterns of climate or ENSO influences on climate. In contrast, recent ecological research has been designed to detect and reflect geographical variation in ENSO and PDO influences on regional climatic variation (Kitzberger et al. 1997, Daniels and Veblen 2000, Westerling and Swetnam 2003). Earlier studies of climatic anomalies on wildfire tended to stress relationships with ENSO almost exclusively (Swetnam and Betancourt 1990) whereas more recent studies, including the present one, have recognized important interactions between tropical and high-latitude teleconnections affecting wildfire activity in the temperate latitudes (Veblen et al. 1999, Norman and Taylor 2003, Westerling and Swetnam 2003).

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