CSIRO PUBLISHING

International Journal of Wildland Fire **2013**, *22*, 588–598
http://dx.doi.org/10.1071/WF12064

Historical fire–climate relationships of upper elevation fire regimes in the south-western United States

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Abstract. Understanding relationships between variability in historical fire occurrence and ocean–atmosphere oscillations provides opportunities for fire forecasting and projecting changes in fire regimes under climate change scenarios. We analysed tree-ring reconstructed regional climate teleconnections and fire–climate relationships in upper elevation forests (>2700 m) from 16 sites in eight mountain ranges in the south-western USA. Climate teleconnections were identified by testing for associations between regional Palmer Drought Severity Index (PDSI) and individual and combined phases of El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) indices for both the fire exclusion (1905–1978) and reconstructed fire periods (1700–1904). Fire–climate relationships were identified by comparing reconstructed fires (84 fire years) in three classes (all, synchronous and stand-replacing fires) with PDSI, precipitation, temperature, and individual and combined phases of ENSO, PDO and AMO indices. Individual and phase combinations of ENSO, PDO and AMO were associated with variability in regional PDSI. Upper elevation fire occurrence was related to variability in regional drought, ENSO phase and phase combinations of ENSO and PDO. We conclude that ENSO most consistently influenced variability in moisture and upper elevation fire occurrence, including stand-replacing fires, but this relationship was potentially modulated by phases of the PDO.

Additional keywords: Arizona, Atlantic Multidecadal Oscillation, El Niño–Southern Oscillation, high-severity fire, New Mexico, Pacific Decadal Oscillation, stand-replacing fire, tree ring.

Received 21 April 2012, accepted 27 November 2012, published online 25 March 2013

Introduction

Fire is arguably the most important disturbance process in the western United States, affecting both ecosystems and societies. Identifying the drivers of variability in fire occurrence benefits both natural resource management and fire hazard planning. An intuitive, inverse relationship between inter-annual moisture levels and fire occurrence is well established (i.e. drought promotes more fire). However, more complex relationships with antecedent wet years have been demonstrated for some ecosystems (Norman and Taylor 2003; Stephens *et al.* 2003; Swetnam and Baisan 2003; Crimmins and Comrie 2004; Skinner *et al.* 2008). Upper elevation, stand-replacing (high-severity) forest fire regimes are consistently associated with severe drought during the fire year, which is necessary to sufficiently dry the abundant fuels and allow fire spread in these relatively cool, mesic and productive forests (Schoennagel *et al.* 2005; Sibold and Veblen 2006; Margolis *et al.* 2007). Although drought–fire relationships are fairly well documented and understood at inter-annual time scales (Veblen *et al.* 2003), less is known about decadal to multi-decadal variability in fire occurrence and the factors controlling climate variability (e.g. ocean–atmosphere oscillations) that ultimately drive mesoscale variability in fire occurrence (but see Trouet *et al.* 2010; Marlon *et al.* 2012; Roos and Swetnam 2012).

Climate variability in the south-western USA (Arizona, New Mexico and adjacent areas) at inter-annual to multi-decadal scales is associated with modes of variability in both the Pacific and Atlantic Oceans. Tropical Pacific ocean–atmosphere variability at 2–7-year time scales (El Niño–Southern Oscillation, or ENSO) is the best understood driver of North American climate variability (Diaz and Markgraf 2000). La Niña-like (cool equatorial Pacific sea surface temperature) conditions have been associated with drought in the south-western USA in the instrumental and pre-instrumental periods (Seager *et al.* 2005; Cook *et al.* 2007). Extra-tropical ENSO teleconnections can strongly affect winter moisture variability, which is a primary factor in determining spring and early-summer fire risk in the south-western USA (Westerling *et al.* 2002; Crimmins and Comrie 2004).

Multi-decadal variability in the northern Pacific Ocean (Pacific Decadal Oscillation, or PDO) affects the western North American climate at bi-decadal to penta-decadal time scales (Mantua *et al.* 1997; Mantua and Hare 2002). Interactions between phases of the equatorial and northern Pacific Ocean oscillations can amplify or diminish the effects on the western North American climate (Gershunov and Barnett 1998; McCabe and Dettinger 1999; Brown and Comrie 2004). In addition to the Pacific Ocean, multi-decadal variability in the north (0–70°)

Atlantic Ocean (Atlantic Multidecadal Oscillation, or AMO) has been associated with North American climate variability at ~60-year timescales (Enfield *et al.* 2001). Mechanisms of this association are not clear, but both modelling and observational studies independently strengthen interpretations that the teleconnection is genuine (Hidalgo 2004; Sutton and Hodson 2005; Dong *et al.* 2006). Phase combinations of PDO and AMO can strengthen or weaken the teleconnections and enhance or reduce the effect on regional climate variability, such that the most severe North American 20th century droughts (1930s – Great Plains, Pacific Northwest; 1950s – south-west) have been associated with warm phase AMO coincident with cool (1950s) and warm (1930s) phases of the PDO (McCabe *et al.* 2004). Although associations between ocean–atmosphere variability and climate have been identified in the 20th century, it is important to remember that the teleconnections are not necessarily stable in time or space. For example, multi-decadal variability associated with the PDO may not have been a primary mode of climate variability during much of the 19th century (Gedalof *et al.* 2002).

The understanding of links between variability in ocean–atmosphere oscillations, local climate teleconnections and fire occurrence across the western USA has evolved in recent decades (Swetnam and Anderson 2008). Simard *et al.* (1985) first identified significant ENSO–fire associations for the south-eastern USA, but their analysis of the western USA was too coarse, including all Rocky Mountain states in one sub-region, and Pacific Coast states in another sub-region. They found no significant associations in the western USA, because their over-broad sub-regions (north–south) confounded the 'dipole' (inverse pattern) of ENSO–climate and ENSO–fire signals that tend to prevail across a north-west–south-west axis (see Dettinger *et al.* 1998; Kitzberger *et al.* 2001). Swetnam and Betancourt (1990) first described the relatively strong ENSO–climate–fire association in the south-western USA, using both 20th century documentary records and pre-20th century tree-ring based climate and fire records. They found relatively consistent synchrony of regional large (small) fire years and dry (wet) years, and the La Niña (El Niño) phases of ENSO for the south-western USA. This initiated efforts in the western USA to better understand, and potentially forecast, variability in fire occurrence as ENSO teleconnections were better understood and forecasts based on this association became feasible (e.g. Westerling *et al.* 2002).

Subsequent fire–climate research with additional climate drivers (e.g. PDO and AMO) indicated that variability in historic fire occurrence in various regions of western North America and southern South America was associated with variability and phase combinations of ocean–atmosphere oscillations (Heyerdahl *et al.* 2002, 2008; Norman and Taylor 2003; Westerling and Swetnam 2003; Hessl *et al.* 2004; Schoennagel *et al.* 2005; Brown 2006; Sibold and Veblen 2006; Kitzberger *et al.* 2007; Skinner *et al.* 2008; Sherriff and Veblen 2008; but see Kipfmueller *et al.* 2012). As global and regional downscaled climate models improve and are able to simulate the oscillations of ocean and atmospheric variability (e.g. Sutton and Hodson 2005), the potential also increases for applying fire–climate relationships to forecasting the response of fire regimes to changing climate (McKenzie *et al.* 2004). Within the south-western USA, associations between ENSO, PDO, AMO and fire scar records of low severity surface fire have been demonstrated as part of a larger analysis of the western USA (Kitzberger *et al.* 2007), but effects of these ocean–atmosphere teleconnections on upper elevation, high-severity fire regimes of the region are unknown.

Our first objective was to quantify relationships between tree-ring reconstructed regional moisture variability in the south-western USA and individual, and phase combinations, of ocean–atmosphere oscillations potentially affecting regional climate (i.e. ENSO, PDO and AMO). Our second objective was to quantify historical fire–climate (drought, precipitation and temperature) relationships for upper elevation fires (>2700 m), including stand-replacing fires, reconstructed from a network of 16 tree-ring fire history sites in the south-western USA. Our third objective was to identify individual and phase combinations of ocean–atmosphere drivers of climatic conditions associated with historical upper elevation fire occurrence.

Data and methods

Fire history data

We compiled the available tree-ring reconstructed fire dates from upper elevation forest sites (>2700 m) from throughout the south-western USA; 16 sites in eight mountain ranges (Grissino-Mayer *et al.* 1995; Margolis *et al.* 2007; Margolis *et al.* 2011) (Fig. 1; Table S1 of the Supplementary material). Post-fire, seral, quaking aspen (*Populus tremuloides* Michx.) stands that are evidence of historical stand-replacing fire are present throughout the region above ~2700 m in elevation, thus we used this elevation to define the lower limit for the study area. Mean distance between sites was 360 km, ranging from 10 to 950 km. All reconstructed fires were from upper elevation, mesic mixed conifer, quaking aspen and spruce–fir forest stands. This network is qualitatively different from prior tree-ring based fire–climate research in the south-western USA. Previous studies have primarily based local to regional fire event reconstruction on fire scar samples from the pine-dominated, mid-elevation forests of the region (e.g. Grissino-Mayer and Swetnam 2000; Swetnam and Baisan 2003). The fire scar-based network from the south-western USA, therefore, most clearly represents fire occurrence and extent patterns in surface-fire regimes at mid-elevations in pine dominant and dry mixed conifer forests, whereas the network used here is generally representative of mixed severity and stand-replacing fire regimes in mesic mixed conifer–aspen and spruce–fir forests of this region.

Reconstructed fires from Margolis *et al.* (2007, 2011) were grouped into three sets for the analysis: (1) all fires (115 fires, 84 fire years, 1623–1904), (2) synchronous fires (42 fires, 20 fire years, 1685–1904) and (3) stand-replacing fires (17 fires, 10 fire years, 1685–1904). We 'filtered' the fire data into these subsets to minimize the noise related to all fire occurrence (e.g. site-level inter-annual differences in lightning ignitions, fuel and fire weather) and highlight the mesoscale fire–climate signal (Swetnam and Betancourt 1998). Synchronous fires and stand-replacing fires are non-independent subsets of all fires. Synchronous fires were defined as fires recorded at two or more sites in the same year. Stand-replacing fire dates were determined

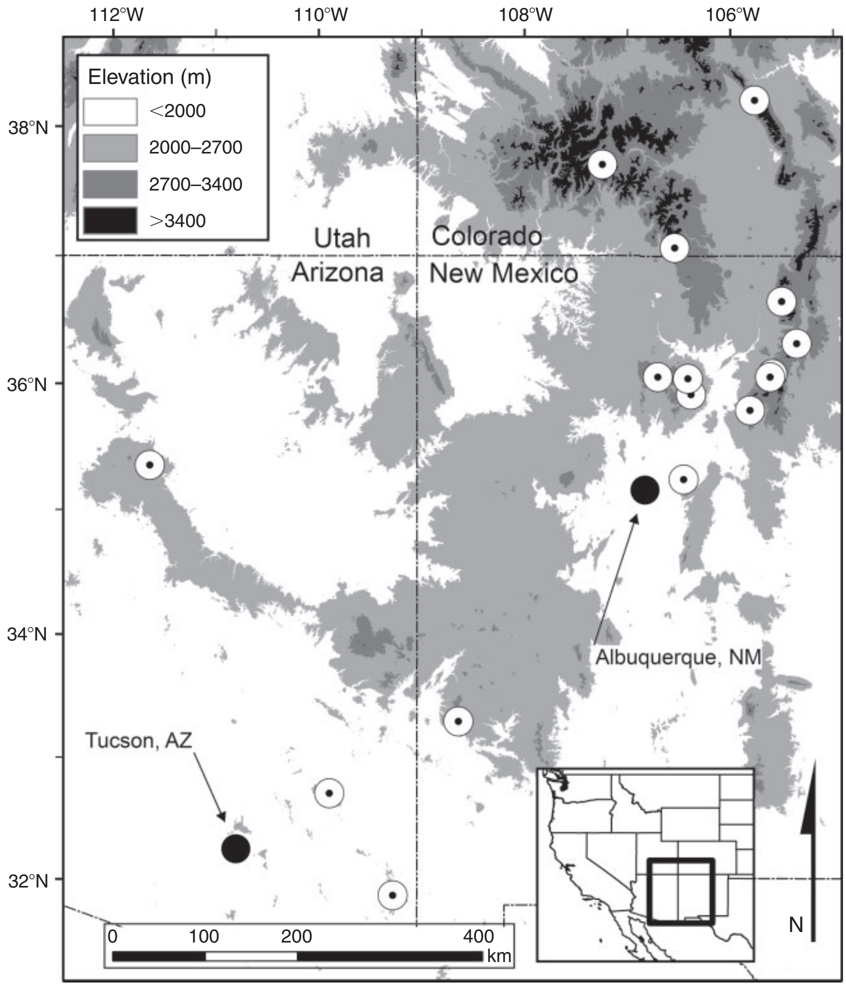

Fig. 1. Map of study area containing 16 upper elevation (>2700 m) fire history sites in the south-western USA.

from multiple lines of tree-ring evidence including: (1) quaking aspen, Engelmann spruce (*Picea engelmannii* Parry) and sub-alpine fir (*Abies lasiocarpa* [Hook] Nutt.) inner-ring dates, (2) conifer fire scars, (3) conifer bark-ring dates and (4) conifer injury or growth change dates. We interpreted the coincidence of direct evidence of fire (e.g. fire scar or fire-killed conifer bark-ring dates), a recruitment pulse (beginning within 5 years post-fire – quaking aspen; beginning within 10 years post-fire – spruce–fir), and no fire survivors within 30 to >1000 ha patches as evidence of stand-replacing fire.

Climate data

Regional drought was represented by averaging tree-ring reconstructed summer (June –August) Palmer Drought Severity Index (PDSI) values from the five grid points (2.5° spacing) within the study area from the Cook and Krusic (2004) network (grid points 104–105, 118–120). Tree-ring reconstructions of precipitation and temperature from the Southern Colorado Plateau were used as sub-regional climate variables (Salzer and Kipfmueller 2005).

As a proxy index of ENSO we used the tree-ring reconstructed Niño3 index (Cook 2000) of winter (December–February) sea surface temperature (SST) from the eastern equatorial Pacific Ocean (5°N–5°S, 90–150°W). Fourteen tree-ring width chronologies from the south-western USA and northern Mexico were used in the Niño3 reconstruction. Positive Niño3 index values (+N) represent warm SSTs – El Niño, and negative values (−N) represent cool SSTs – La Niña. We used the D'Arrigo *et al.* (2001) annual PDO index reconstruction derived from temperature sensitive tree-ring sites from coastal Alaska (5) and Oregon (1), and two tree-ring reconstructed PDSI grid points in northern Mexico (Cook *et al.* 1999). Positive index values (+P) correspond with warm phases and negative values (−P) with cold phases of the primary mode of variability in Pacific Ocean SSTs polewards of 20°N (Mantua *et al.* 1997). Our justification for choosing this PDO reconstruction is presented in the Discussion section. We used the Gray *et al.* (2004) tree-ring-width based reconstruction of the AMO index derived from 12 tree-ring chronologies from south-east North America, Scandinavia, Europe, North Africa and the Middle East. Positive index values (+A) indicate warm values of the 10-year running mean of detrended SST anomalies in the North Atlantic Basin (0–70° N) and negative values (−A) indicated cool SST anomalies. All climate reconstructions used for analysis extended before the earliest reconstructed fire (1623) except the PDO reconstruction, which begins in 1700. The common period for all climate data was 1700–1978.

Ocean–atmosphere associations with regional climate

To test for associations between ocean–atmosphere oscillations and regional climate within the study area we used ANOVA to compare mean tree-ring reconstructed regional PDSI during all eight phase combinations of ENSO, PDO and AMO. To test for dominant effects of individual ocean–atmosphere oscillations on regional PDSI we used a contrast *t*-test (SPSS 14.0). Specifically, we used this test to compare mean regional PDSI during the four phase combinations that included negative versus positive phases for each of the three reconstructed ocean atmosphere indices (e.g. PDSI during all four phase combinations including +AMO *v.* PDSI during all four combinations including −AMO). This analysis was conducted for both the reconstructed fire period (1700–1904) and the fire exclusion period (1905–1978) to examine stability through time of these relationships. The fire exclusion period begins 1 year after the last recorded fire (1905) and ends at the common end date for the reconstructed climate time series (1978). The reconstructed fire period was limited by the common beginning year of the climate time series (1700). The frequency of occurrence (number and percentage of total years) for each AMO/PDO/ENSO phase combination was determined for the reconstructed fire (1700–1904) and fire exclusion (1905–1978) periods. Chi-square analysis was used to compare the observed number of each of the phase combinations in the fire exclusion period with the expected occurrence, which was derived from the 1700–1904 period frequency of occurrence. To test for stability through time in regional teleconnections of phase combinations of ocean–atmosphere oscillations we used a student's *t*-test to compare mean PDSI values for each phase combination between the reconstructed fire and the fire exclusion periods.

Fire–climate relationships

Inter-annual fire climate relationships were examined using a combination of graphical and statistical methods. We assessed spatial patterns of drought during reconstructed stand-replacing fire years by averaging PDSI grid-point maps for western North America (Cook and Krusic 2004). All fire years, synchronous fire years, stand-replacing fire years and the regional PDSI time series were plotted together to illustrate fire–climate relationships through time. All fire years were plotted as a 60-year running sum (plotted on year 30) to examine low-frequency trends. We tested for inter-annual associations between all upper elevation fires, synchronous fires and stand-replacing fires, and reconstructed climate variables (regional PDSI, Niño3 index, and southern Colorado Plateau precipitation and temperature) using superposed epoch analysis (SEA; Swetnam 1993). SEA tests for departures of mean climate values from the period mean during, before and after fire event years using a Monte Carlo simulation with 1000 iterations to derive confidence intervals around the period mean. Confidence intervals are derived from resampling of contiguous *n*-year segments from the original time series, where *n* is defined by the window length. The test was run with an 11-year window and we present a 7-year window around the fire year spanning 4 years before and 2 years after the fire event. The period of analysis varied depending on the overlap in time of the fire and climate data. Some studies (e.g. Heyerdahl *et al.* 2008) have removed autocorrelation from time series before analysis with SEA, but this method has not been explicitly tested and ultimately alters the original climate variable being analysed. Other studies indicate that for time series with low-order autocorrelation the default 11-year analysis window (segment length or block length) sufficiently accounts for autocorrelation in the confidence intervals (e.g. Adams *et al.* 2003). As a sensitivity analysis of the two methods, we ran the SEA with the original time series and pre-whitened time series. Both methods produce the same results. We present the results with the autocorrelation retained. A thorough analysis of the effects of autocorrelation on SEA is needed.

We tested for association between fire occurrence and individual and phase combinations of ocean–atmosphere oscillations using contingency analysis. Chi-square analysis was used to test for independence between observed fire occurrence and the expected fire occurrence during negative and positive phases of individual AMO, PDO and Niño3 indices, and the eight possible phase combinations (e.g. +A−P−N). Expected fire occurrence was derived from the frequency of occurrence of the different climate phase combinations (e.g. because −A+P+N occurred during 19% of the years (1700–1904), then 19% ($n = 13$) of all fire years were expected to occur on −A+P+N years). The expected number of years for stand-replacing fire occurrence was <5; therefore we used the Fisher's exact test instead of Chi-square analysis. All statistical analyses were performed on counts. Percentages are reported in some cases to facilitate comparisons between datasets with different absolute counts. Analyses were limited to the common period of all reconstructed climate indices and fires. The *a priori* level of significance for all statistical tests was set at $\alpha = 0.05$.

Results

Ocean–atmosphere oscillations associated with regional climate

During both the fire exclusion period (1905–1978) and the reconstructed fire period (1700–1904), tree-ring-reconstructed moisture variability was associated with tree-ring-reconstructed phase combinations of ocean–atmosphere oscillations, as would be predicted by instrumental data (i.e. negative PDSI was associated with +AMO, −PDO and −Niño3). Mean regional PDSI was significantly different among the eight AMO, PDO and Niño3 phase combinations ($P < 0.001$; Fig. 2; Table 1). PDSI during all four phase combinations including La Niña years (−N) was significantly lower (drier) than all combinations including El Niño years (+N) ($P < 0.001$) during both analysis periods. PDSI during all four phase combinations including negative PDO was lower (drier) than combinations including positive PDO ($P < 0.01$) during the reconstructed fire period, but not the fire exclusion period. PDSI during all four phase combinations including positive AMO years was lower (drier) than all combinations including negative AMO ($P < 0.05$) during the fire exclusion period, but not during the reconstructed fire period (Fig. 2; Table 1).

The frequency distribution of all eight AMO, PDO and Niño3 index phase combinations was similar between the reconstructed fire period and the fire exclusion period. The one exception was the +A+P+N phase combination (associated with wet conditions). It occurred with greater than twice the frequency during the fire exclusion period (1905–1978; 20%, $n = 15$ years) compared to the reconstructed fire period (1700–1904; 9%, $n = 19$ years) ($P < 0.01$).

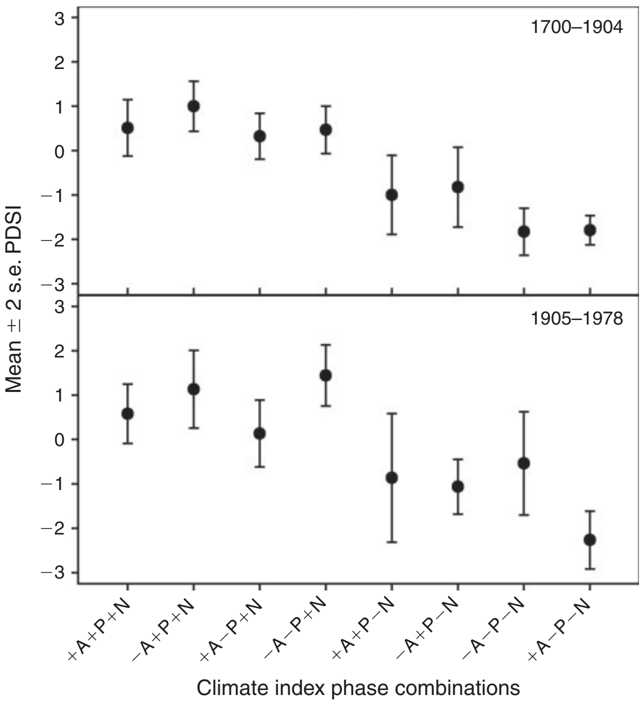

Fig. 2. Mean and two standard errors (s.e.) of tree-ring reconstructed Palmer Drought Severity Index for all eight possible phase combinations of tree-ring reconstructed AMO, PDO and Niño3 (see Table 1 legend) climate indices for the reconstructed fire period (top – 1700–1904) and the fire exclusion period (bottom – 1905–1978).

All eight ocean–atmosphere phase combinations were consistently associated with either dry or wet conditions (negative or positive PDSI) during both the fire exclusion and reconstructed fire periods (Fig. 2; Table 1). In one case, the magnitude of the associated drought changed. Mean regional PDSI for the −A−P−N phase combination during the reconstructed fire period (−1.83, 1700–1904) was significantly drier than during the fire exclusion period (−0.54, 1905–1978) ($P < 0.05$) (Fig. 2; Table 1).

Fire–climate relationships

All stand-replacing fires occurred during regional drought (mean regional PDSI = −2.59; Figs 3, 4). Spatial patterns of PDSI during stand-replacing fire years (1685–1904, $n = 10$ years) clearly indicate regional drought centred in the south-western USA (Fig. 4). This drought pattern was also associated with wet conditions in the north-west USA (i.e. the dipole pattern). Interestingly, coincident wet conditions were also present in east-central Mexico.

In total, 18 of 20 synchronous fire years occurred during regional drought years (mean reconstructed PDSI = −2.35) (Fig. 3). Of the stand-replacing fire years, 7 of 10 occurred during synchronous fire years. In total, 70% (59 of 84) of all upper-elevation fire years were associated with regional drought. Of the 30% of fires that occurred in years with positive regional PDSI, all but one was from the southernmost sites in the 'Sky Island' region of south-eastern Arizona. This possible sub-regional difference in fire–climatology is discussed below. The peak number of upper elevation fires occurred in the mid-1800s, following a local minimum *c.* 1800 (Fig. 4).

All fire years, synchronous fire years and stand-replacing fire years were significantly associated with negative (dry) departures from mean regional summer PDSI, and southern Colorado Plateau precipitation (Fig. 5). All fire years, synchronous fire years and stand-replacing fire years were associated with negative SST departures from the mean Niño3 index (i.e. La Niña

Table 1. Mean PDSI and percentage of expected (E) and observed (O) number of upper elevation (>2700 m) fire years during phase combinations of tree-ring reconstructed AMO, PDO and ENSO indices

AMO, Atlantic Multidecadal Oscillation index (A; Gray *et al.*, 2004); PDO, Pacific Decadal Oscillation index (P; D'Arrigo *et al.* 2001); ENSO, Niño3 sea surface temperature (SST) index (N; Cook 2000). Superscript letters indicate phase combinations including positive (capital) and negative (lower case) phases of Niño3 (N,n), PDO (P,p) and AMO (A,a) with significantly different ($P < 0.05$) mean PDSI between phases (contrast *t*-test with unequal variance). Mean PDSI between 1700–1904 and 1905–1978 periods are significantly different at *, $P < 0.05$ (Student's *t*-test)

	+A+P+N		−A+P+N		+A−P+N		−A−P+N		+A+P−N		−A+P−N		−A−P−N		+A−P−N	
	E	O	E	O	E	O	E	O	E	O	E	O	E	O	E	O
All fire years; $n = 70$ (1700–1904)	9	7	19	13	17	11	16	14	4	4	7	10	14	21	15	19
Synchronous fire years; $n = 20$ (1700–1904)	9	0	19	6	17	17	16	6	4	6	7	17	14	33	15	17
Stand-replacing fire years; $n = 9$ (1842–1904)	14	0	13	0	25	11	8	11	3	11	3	0	10	33	25	33
Mean PDSI (1700–1904)	$0.51^{N,P}$		$1.00^{N,P}$		$0.32^{N,p}$		$0.47^{N,p}$		$-1.00^{n,P}$		$-0.82^{n,P}$		$-1.83^{n,p,*}$		$-1.79^{n,p}$	
Mean PDSI (1905–1978)	$0.58^{N,A}$		$1.13^{N,a}$		$0.13^{N,A}$		$1.44^{N,a}$		$-0.86^{n,A}$		$-1.06^{n,a}$		$-0.54^{n,a,*}$		$-2.27^{n,A}$	

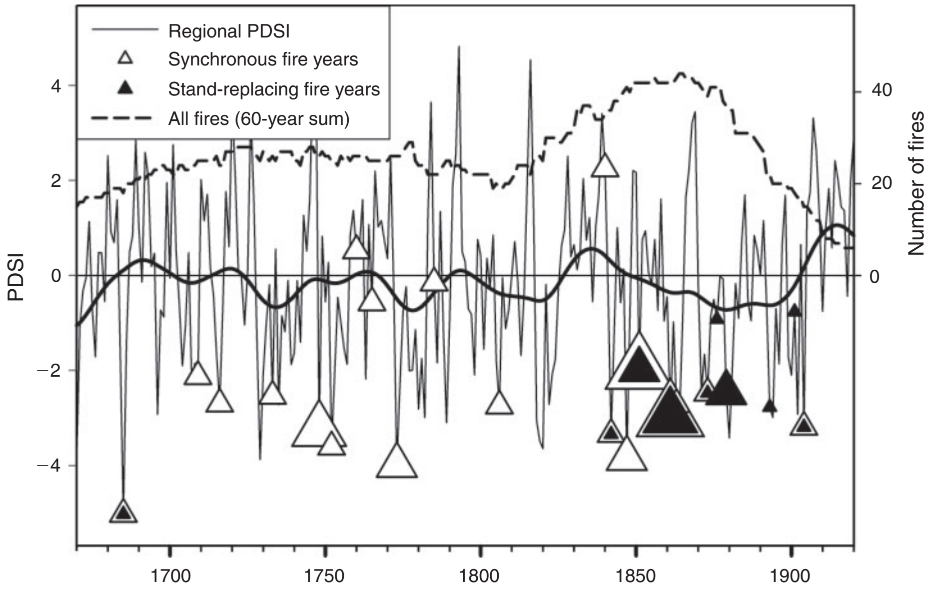

Fig. 3. Upper elevation (>2700 m) stand-replacing and synchronous fire years plotted on the regional tree-ring reconstructed Palmer Drought Severity Index (PDSI) time series (Cook and Krusic 2004). The smooth black line is the 35-year spline of regional PDSI. The size of the symbol indicates the number of sites recording fire that year: synchronous fire years, 2–5 sites; stand-replacing fire years, 1–4 sites. Dashed line is 60-year running sum of all fires (plotted on year 30).

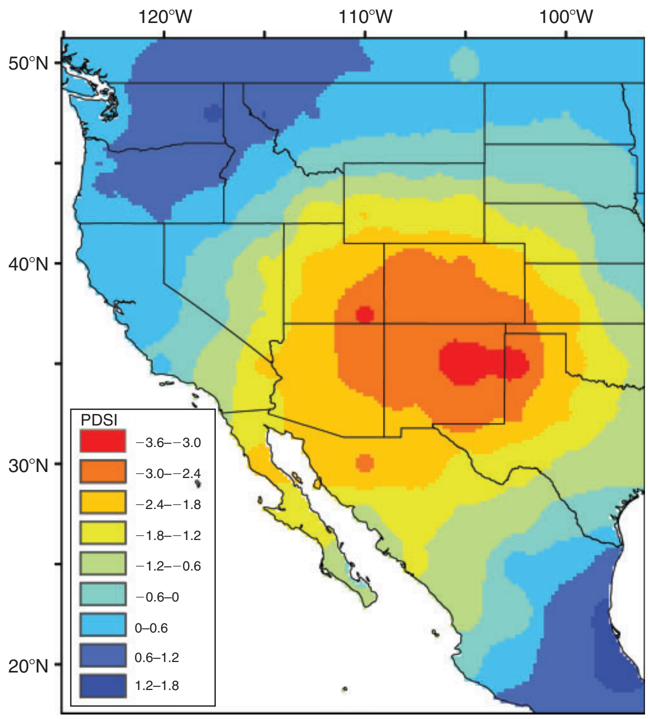

Fig. 4. Mean tree-ring reconstructed summer Palmer Drought Severity Index (Cook and Krusic 2004) during stand-replacing fire years ($n = 10$ years, 1685–1904).

conditions). Upper elevation fire occurrence was not associated with antecedent wet or El Niño conditions. Synchronous and stand-replacing fires were associated with more severe drought and stronger La Niña conditions than were all fires (Fig. 5). Upper elevation fire occurrence was not associated with inter-annual variations in PDO or southern Colorado Plateau temperature (results not shown).

Observed stand-replacing, synchronous and all fire year occurrence was significantly greater than expected during all ocean–atmosphere phase combinations that included La Niña (−N) years, and lower than expected during El Niño (+N) years ($P < 0.05$) (Fig. 6; Table 1). Observed fire occurrence was not significantly greater than expected during phases of the individual PDO or AMO, or combined phases of Niño3, PDO and AMO (Fig. 6; Table 1). However, the maximum percentage of all fire years (21%), synchronous fire years (32%) and stand-replacing fire years (33%) occurred during (La Niña, −N), negative PDO phase combinations (Fig. 6). This phase combination was associated with the most severe drought during the reconstructed fire period (mean PDSI = −1.83, −A−P−N and −1.79, +A−P−N) (Table 1). The minimum percentages of stand-replacing (0%, 0%) and synchronous (0%, 6%) fire years occurred during the two +P+N phase combinations (+A, −A) (Fig. 6), which had the highest (wettest) mean PDSI (0.51, 1.00) (Table 1). No stand-replacing or synchronous fire years, and 7% of all fire years occurred during the +A+P+N phase combination, which occurred during 9% of the reconstructed fire period (1700–1904) and 20% of the fire exclusion period (1905–1978).

Discussion

Ocean–atmosphere oscillation teleconnections

A clear understanding of the interactions and strength of ocean–atmosphere oscillation teleconnections on regional climate are the foundation for interpretations of fire–climate analyses. Our results support the dominance of ENSO teleconnections on south-western USA inter-annual moisture variability during

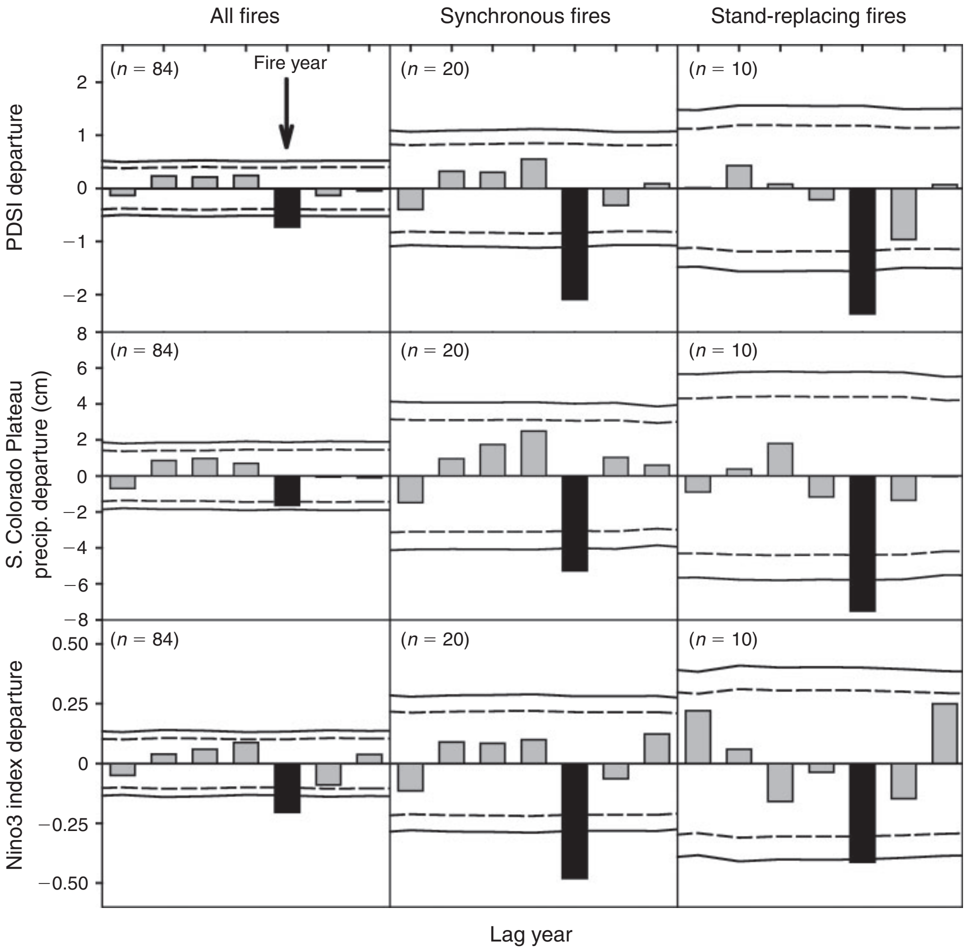

Fig. 5. Superposed epoch analysis illustrating the departure from mean reconstructed climate indices (regional Palmer Drought Severity Index, Southern Colorado Plateau precipitation and Niño3 index) associated with upper elevation fire. Period of analysis: all fires (1619–1906), synchronous and stand-replacing fires (1681–1906). Dashed and solid lines represent 95 and 99% confidence intervals determined from a Monte Carlo simulation with 1000 iterations; *n*, number of fire years.

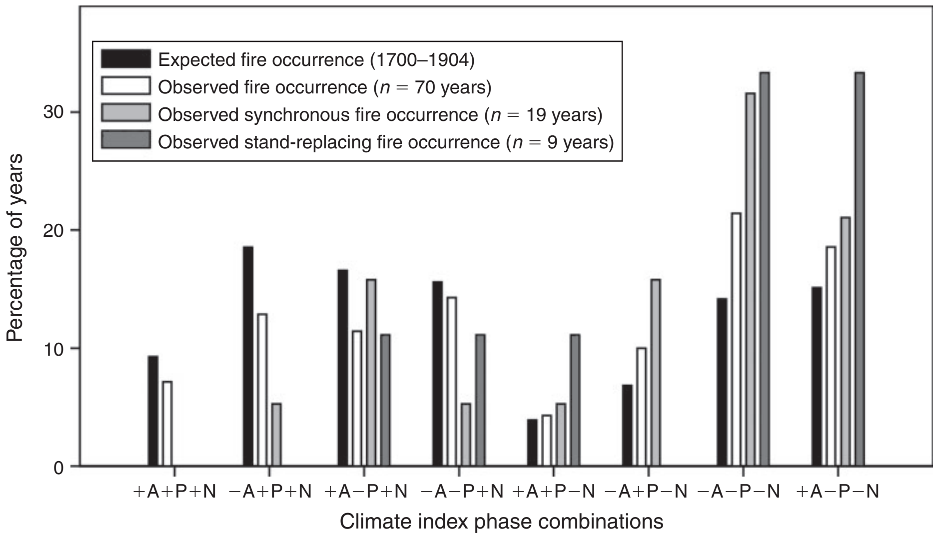

Fig. 6. The percentage of expected and observed number of all fire years, synchronous upper elevation fire years (i.e. fires occurring at multiple sites) and stand-replacing fire years during each of eight possible phase combinations of the Atlantic Multidecadal Oscillation (A; Gray *et al.*, 2004), the Pacific Decadal Oscillation (P; D'Arrigo *et al.* 2001) and Niño3 (N; Cook 2000). Expected fire occurrence was derived from the frequency occurrence of the climate phase combinations for the entire period (1700–1904).

both pre- and post-20th century periods, with La Niña consistently associated with drought (Diaz and Markgraf 2000). Regional drought was also associated with negative PDO and positive AMO, but the relationships were weaker and less consistent (Table 1). The driest conditions were consistently associated with the constructive (i.e. same sign) cool phases of ENSO and PDO (Table 1), which supports the instrumental observations of cool north Pacific SSTs enhancing La Niña-driven drought in the south-western USA (McCabe and Dettinger 1999; Brown and Comrie 2004). Overall, the associations we found between tree-ring reconstructed drought and ENSO, PDO and AMO in the south-western USA are consistent with instrumental observations and modelled 20th century relationships (Brown and Comrie 2004; McCabe *et al.* 2004; Seager *et al.* 2005).

Fire–drought relationships

Drought during the fire year, with no antecedent wet lags, was significantly associated with all three classes of upper elevation (>2700 m) fire occurrence in the south-western USA including: (1) all fire years, (2) synchronous fire years and (3) stand-replacing fire years. A similar fire year–drought relationship exists in other upper elevation and stand-replacing fire regimes in the Rocky Mountains (Schoennagel *et al.* 2005; Sibold and Veblen 2006). This supports the interpretation that relatively productive upper elevation forests generally contain sufficient fuel for burning, and hence do not require antecedent moisture to increase fuel loads or continuity, but do require sufficiently dry conditions for successful ignition and fire spread (Schoennagel *et al.* 2004). This pattern of mesic, more productive forests commonly showing no significant prior-year wet conditions has also been shown for mixed conifer forests in the south-western fire scar network, and a fire scar network from mixed conifer on the west slope of the Sierra Nevada in California (Swetnam and Baisan 2003). Occasionally, historical fires at mixed conifer sites in the south-western USA have been associated with prior-year wet lags, which may be caused by proximity to drier, less-productive forests that act as fire ignition sources and do require wet years for sufficient fuel accumulation (Margolis and Balmat 2009). We found that the mean PDSI departure from normal conditions during synchronous or stand-replacing fire years was 2–4 times as dry as that associated with all fire years, suggesting that the occurrence of synchronous or stand-replacing fire years generally requires exceptionally dry conditions (Figs 3–5). Perhaps prior-year wet conditions even inhibit fire occurrence in very mesic upper elevation forests by creating a moisture buffer that cannot be overcome by even an extremely dry subsequent single year. Further quantification of this fire–drought relationship may reveal a minimum threshold PDSI value that must be exceeded for stand-replacing fire occurrence, or values below which a high probability of stand-replacing fire occurrence exists. Other important variables that likely affect upper elevation fire occurrence probability include time-since-fire, which in turn would affect fuel loads and fuel structure. A probabilistic approach may be most appropriate based on the observation that some extremely dry years occurred without evidence of stand-replacing fire.

Variability in fire–climate relationships between classes of upper elevation fire occurrence and potential sub-regional geographic variability are suggested by our results. The occurrence of 30% ($n = 25$) of all upper elevation fires during positive regional PDSI years was not expected for these generally mesic sites. All but one of the fires co-occurring with regional positive PDSI conditions was from the two southernmost Sky Island sites in south-eastern Arizona (Fig. 1). Due to the large latitudinal range covered by our study area (>6°), sub-regional differences in precipitation patterns (e.g. Comrie and Glenn 1998) are likely to drive sub-regional variability in fire occurrence on some years. The climatology of southern Arizona includes a consistently dry and hot pre-monsoon period (May–June) every year (Sheppard *et al.* 2002). This local climate feature can be sufficient to override a winter moisture surplus, desiccate fine fuels and allow fire occurrence, particularly on south-facing slopes. Additionally, although the south-western USA is generally affected by similar climate, areas on the periphery of the region may experience different climatic conditions that may be more conducive to fire during some years. Potential sub-regional variability in fire severity may also be evident, such that a majority of the stand-replacing fire dates were from the northern portion of the study area and a majority of the synchronous fire dates were from the southern part (due in part to the lack of stand-replacing fire and longer fire scar records). This sub-regional variability was considered in interpreting the fire–climate results, but given that La Niña-driven drought during the fire year was associated with all classes of upper elevation fire, it seems that a common climate signal is associated with fire occurrence across the region. Developing more upper elevation fire history sites would allow for sub-regional fire–climate analyses, which could help strengthen the regional fire–climate relationships we describe and tease out the anomalies.

Ocean–atmosphere oscillation relationships with fire

The maximum percentage of all three classes of upper elevation fire occurrence was coincident with –P–N phase combinations, which had the lowest mean regional PDSI (−1.83, −A and −1.79, +A). Sibold and Veblen (2006) found that the +A−P−N phase combination was associated with 71% of large fires recorded in sub-alpine forests of Rocky Mountain National Park in northern Colorado and produced the driest conditions. Brown (2006) also found greater than expected tree-ring reconstructed fire occurrence during this climate phase combination in Ponderosa pine (*Pinus ponderosa*) forests of the Black Hills, South Dakota–Wyoming. Our results suggest that constructive cool phases of PDO and ENSO are important for drought and upper elevation fire occurrence in the south-western USA, but teleconnections and fire occurrence relationships with AMO are not clear. Schoennagel *et al.* (2005) found that constructive cool phases of ENSO and PDO were more important for sub-alpine fire and drought occurrence in the Southern Rockies than were the individual phases. Kitzberger *et al.* (2007) report that constructive cool phases of ENSO and PDO associated with both positive and negative AMO were important for synchronous fires burning both within and between sub-regions of the south-western USA (i.e. Arizona, southern New Mexico and northern New Mexico). Their results also show that the greatest synchrony of fires over western North America from southern British Columbia to northern Mexico occurred during positive AMO coincident with constructive cool phases of ENSO and PDO. Thus, although the AMO has been associated with the dominant modes of 20th century drought and historical fire synchrony over the western USA (including southern British Columbia, Canada and northern Mexico), AMO phase may not have been as important for regional variability in fire occurrence within the south-western USA.

Multi-decadal change in fire occurrence

Multiple fire history studies in south-western North America (north Mexico, Arizona, New Mexico and Colorado) and southern South America document a period of decreased fire occurrence, or a 'gap,' between *c*. 1780 and 1840 (Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000; Kitzberger *et al.* 2001; Stephens *et al.* 2003; Sibold and Veblen 2006). This change in fire frequency has been associated with a period of decreased ENSO amplitude (Kitzberger *et al.* 2001) and a negative AMO phase (Sibold and Veblen 2006; Kitzberger *et al.* 2007), both of which may lead to fewer droughts and reduced variability in climate. This period is notable in our reconstruction for a reduced occurrence of upper elevation fires and a lack of stand-replacing fires, even though there were multiple drought years in the 1810s and 1820s (Fig. 3). The longest interval between synchronous fire years occurred during this early 19th century period (1806–1840, 37 years). Mean intervals between synchronous fire years before (1685–1785) and after (1840–1904) the gap were respectively 8.0 and 11.6 years. Coincident decreases in all upper elevation fires, synchronous upper elevation fires, and stand-replacing fires makes a strong case for a multi-decadal, climate-driven change in upper elevation fire regimes in the south-western USA during this period.

Uncertainty in PDO reconstructions and historical fire–PDO relationships

Historical fire–PDO relationships have been repeatedly identified throughout the Western USA (e.g. Kitzberger *et al.* 2007), but Kipfmueller *et al.* (2012) has suggested that variability among the different PDO reconstructions may influence these results. In our analyses we selected the D'Arrigo *et al.* (2001) PDO reconstruction because: (1) it explains the most variance during the instrumental calibration period and; (2) it uses tree-ring chronologies from the broadest geographic range (Gulf of Alaska to north-western Mexico) where climate variability is associated with north Pacific SSTs in the instrumental record (Mantua and Hare 2002). Our results using this PDO reconstruction showed that the cool phase of PDO was related to drought in the south-western USA during the reconstructed fire period and that the constructive cool phases of ENSO and PDO were associated with greater than expected historical fire occurrence driven by drought (Table 1; Figs 2, 6). These results from the reconstructed fire period (1700–1904) are consistent with other paleofire–climate analyses (Kitzberger *et al.* 2007), the instrumental climatology (Brown and Comrie 2004) and instrumental fire–climatology (Collins *et al.* 2006) of the south-western USA.

Although we agree with Kipfmueller *et al.* (2012) that reconciling the dissimilarities between PDO reconstructions should be a primary focus of paleo–climatic research and will ultimately benefit paleofire–climate research, we submit that networks of fire history data are useful as independent evidence to corroborate with paleo–climatic reconstructions (Trouet *et al.* 2010; Swetnam and Brown 2011). These should be used in combination with alternative paleo–proxy reconstructions to reconcile the discrepancies among the existing reconstructions, and test new reconstructions of SST variability in the north Pacific Ocean. We interpret our PDO–fire results as support for the D'Arrigo *et al.* (2001) reconstruction (and geographically distributed reconstruction method), at least for teleconnections in the south-western USA. New PDO reconstructions should be used to determine if our results and similar results from other studies in the south-western USA and Southern Rockies (e.g. Brown 2006; Sibold and Veblen 2006; Kitzberger *et al.* 2007) are robust.

It is important to note that our results indicate that ENSO was the primary driver of fire in the upper elevations of the south-western USA, similar to fire–climate patterns in the mid-elevation pine-dominated forests (Swetnam and Betancourt 1990). However, a consistent pattern of modulation by an additional climate driver (possibly the North Pacific Ocean) seemed to enhance or decrease the regional ENSO drought teleconnection and consequently fire occurrence. PDO modulation of the ENSO drought response and fire in the south-western USA has been observed repeatedly in the instrumental record (Brown and Comrie 2004; Collins *et al.* 2006) and thus it is logical that similar relationships may have existed in the past. Combining paleo–climate studies with paleo–fire studies may be the best approach to resolve the uncertainties in historic PDO–fire relationships identified by Kipfmueller *et al.* (2012), and we believe this is an important line of research that will improve our understanding of past, present and future climate drivers of fire both in the region and in greater western North America.

In summary, multiple classes of upper elevation (>2700 m) fire occurrence in mesic mixed conifer, quaking aspen and spruce–fir forests of the south-western USA, including stand-replacing fires, were associated with variability in drought and individual and phase combinations of Pacific and Atlantic Ocean–atmosphere oscillations. The strong and overriding influence of ENSO variability on south-western USA fire regimes, with potential modulation by PDO and AMO, provides a valuable tool for seasonal fire forecasting. Not surprisingly, the 2011 fire season in the south-western USA, which was the largest and most severe in the instrumental record, was preceded by coincident −Niño3 (La Niña), −PDO and +AMO conditions, as would be predicted by modern fire–climatology, our results and prior paleofire–climate studies. In addition to the observed and predicted effects of increasing temperatures on fire regimes (Westerling *et al.* 2006) modelling climate change effects on ENSO frequency, magnitude, teleconnections and modulation by low frequency ocean–atmosphere oscillations will be vital to understanding future fire regimes in the south-western USA

Acknowledgements

This research was supported by Cooperative Agreement Number 99CRAG0024 between the US Geological Survey Biological Resources

Division Global Change Program and the University of Arizona Laboratory of Tree-Ring Research. Two anonymous reviewers provided valuable comments that improved the manuscript.

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