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RESEARCH LETTER

Inter-hemispheric synchrony of forest fires and the El Niño-Southern Oscillation

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ABSTRACT

Fire histories were compared between the south-western United States and northern Patagonia, Argentina using both documentary records (1914–87 and 1938–96, respectively) and tree-ring reconstructions over the past several centuries. The two regions share similar fire–climate relationships and similar relationships of climatic anomalies to the El Niño–Southern Oscillation (ENSO). In both regions, El Niño events coincide with above-average cool season precipitation and increased moisture availability to plants during the growing season. Conversely, La Niña events correspond with drought conditions. Monthly patterns of ENSO indicators (southern oscillation indices and tropical Pacific sea surface temperatures) preceding years of exceptionally widespread fires are highly similar in both regions during the 20th century. Major fire years tend to follow the switching from El Niño to La Niña conditions. El Niño conditions enhance the production of fine fuels, which when desiccated by La Niña conditions create conditions for widespread wildfires. Decadal-scale patterns of fire occurrence since the mid-17th century are highly similar in both regions. A period of decreased fire occurrence in both regions from *c.* 1780–1830 coincides with decreased amplitude and/or frequency of ENSO events. The interhemispheric synchrony of fire regimes in these two distant regions is tentatively interpreted to be a response to decadal-scale changes in ENSO activity. The ENSO–fire relationships of the south-western USA and northern Patagonia document the importance of high-frequency climatic variation to fire hazard. Thus, in addition to long-term trends in mean climatic conditions, multi-decadal scale changes in year-to-year variability need to be considered in assessments of the potential influence of climatic change on fire regimes.

Key words Climate-induced disturbance, El Niño–Southern Oscillation, fire synchrony, Northern Patagonia, south-western United States, tree-ring reconstructions.

INTRODUCTION

Weather anomalies lasting one to several years that are associated with El Niño–Southern Oscillation (ENSO) events affect ecological processes in many regions of the world. Ecological processes demonstrated to be influenced by ENSO events range from flowering and fruiting behaviour of plants, population responses of seed predators and radial growth of trees, to landscape-scale patterns of disturbance by fire (Simard *et al.*, 1985; Nicholls, 1992; Ashton *et al.*, 1988; Swetnam & Betancourt, 1998; Curran *et al.*, 1999; Lima *et al.*, 1999). For example, extensive wildfires occurred in Indonesia, Australia and Amazonia during the El Niño events of 1982–83 and 1997–98 (Leighton & Wirawan, 1986; Brown, 1998; Laurance, 1998). Enormous forest fires set by humans for forest clearance in Indonesia and Amazonia during the unusual drought conditions associated with these

El Niño events triggered widespread political controversy and also intensified scientific interest in understanding the long-term role of ENSO-related climatic variability in influencing fire regimes (Brown, 1998; Laurance, 1998). A critical issue regarding regional to global scales and decadal to centennial time-scales is the importance of widespread climatic variation associated with ENSO events (e.g. see Kiladis & Diaz, 1989) in synchronizing variations in fire regimes in disjunct regions.

Although the well-publicized association of large fires in tropical areas with ENSO events in the 1980s and 1990s suggests a global scale linkage of fire and ENSO, the stability of this relationship over longer time periods is largely unknown. This question could be answered through the development of multi-century and annually resolved records of fire and climatic variation derived from tree rings, but tree-ring studies of fire history in the tropics are still at an early stage of development (e.g. Grau & Veblen, unpublished). However, for northern hemisphere temperate regions, in particular for western North America, there are abundant tree-ring records of fire and climatic variation (e.g. Swetnam & Betancourt, 1990, 1998; Veblen *et al.*, 2000). The recent development of robust fire records derived from tree rings in temperate South America (Kitzberger *et al.*, 1997; Kitzberger & Veblen, 1998; Veblen *et al.*, 1999) provides the first opportunity to examine potential interhemispheric synchrony of wildfires and ENSO events. In this paper, we compare fire histories in the south-western United States and northern Patagonia, Argentina, two ENSO-sensitive regions of similar fire–climate relationships, to evaluate the hypothesis that ENSO events can synchronize fire occurrence at an interhemispheric scale.

Tree-ring reconstructions show that, before European settlement in the late 19th century, wildfires burned frequently in the semi-arid forests and woodlands of ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws) in the south-western United States and in similar woodlands of ciprés (*Austrocedrus chilensis* (Don) Flor. et Boutl.) in northern Patagonia (Veblen *et al.*, 1992; Swetnam & Baisan, 1996; Kitzberger *et al.*, 1997). Seasonal and interannual fluctuations in rainfall in the south-western United States and in northern Patagonia, Argentina are linked to ENSO events (Douglas & Engelhart, 1984; Aceituno, 1988; Andrade & Sellers, 1988; Kiladis & Diaz, 1989). The hydrological cycle in both regions is dominated by cool season (winter and early spring) precipitation, and variations in this seasonal moisture are correlated with southern-oscillation indices (SOI), sea surface temperatures (SST) and tree-ring width indices (Lough & Fritts, 1985; D'Arrigo & Jacoby, 1991; Stahle & Cleaveland, 1993; Villalba, 1994; Stahle *et al.*, 1998). The importance of regional scale climatic effects (e.g. droughts) on past fire activity in both regions is indicated by the repeated occurrence of highly synchronous fire events, among trees and stands, within both regions over the past several hundred years (Swetnam & Baisan, 1996; Kitzberger *et al.*, 1997; Swetnam & Betancourt, 1998; Veblen *et al.*, 1999). Previous research has shown that, in both regions, records of regional fires over the past three centuries typically have a strong climatic signal during the fire year as well as during the previous ≈1–4 years. Regional fire occurrence is often linked to large-scale anomalies of climatic features such as the strength and latitudinal position of subtropical Pacific (Kitzberger *et al.*, 1997) and high-latitude (Veblen *et al.*, 1999) high pressure cells, which affect the westerly flow of moist air over western mid-latitudes of the Americas. ENSO in particular, due to its intrinsic high-frequency oscillatory behaviour in the region of ≈2–6 years, and its strong influence over large-scale climatic features, has been invoked as a main force that predisposes the occurrence of widespread fire. Relatively robust ENSO influences on winter–spring rainfall at mid-latitudes of the western Americas determine that fire is promoted in these regions when previous cool season moisture is lower during cold phases of the SO (i.e. La Niña conditions). Conversely, fire activity is usually reduced when previous cool season moisture is increased during extreme warm phases of the SO (i.e. El Niño conditions; Swetnam & Betancourt, 1990, 1998; Kitzberger & Veblen, 1998; Veblen *et al.*, 1999).

DATA SOURCES AND METHODS

Documentary records of fire occurrence were used for analysing the temporal association of fire with instrumental indicators of ENSO activity during the 20th century. From fire records of the US

Forest Service (1914–87) and the Argentinean National Park Service (1938–96) we identified years of widespread burning. For the south-western United States, these event years were the 14 years of greatest surface area burned between 1914 and 1987. For Patagonia, these years of widespread fire were the 9 years of most abundant lightning-caused fires between 1938 and 1987. Only lightning-caused fires were considered in Patagonia, because humans account for the majority of ignitions in the post-1938 fire record for this region.

Variations in indicators of ENSO activity were examined for the months preceding, during and following these event years of widespread fire. Standard deviations of monthly sea surface temperature (SST) from Niño 1 + 2 Region in the eastern tropical Pacific were plotted over a 6-year window approximately centred on the fire season of each region. Standard deviations of the monthly Southern Oscillation Index (SOI; the sea level pressure difference between Darwin and Tahiti) were similarly plotted. El Niño conditions are indicated by high SST and low SOI, and La Niña conditions are indicated by the reverse.

To establish long-term records of fire history, tree rings were used to date past fires. Tree-ring reconstructions of fire histories in both regions were based on sampling and analyses of hundreds of widely distributed fire-scarred trees. The south-western United States fire history network is composed of 933 crossdated *Pinus ponderosa* fire scars from 63 (≈1–10 ha) woodland stands distributed over the states of Arizona and New Mexico (Swetnam & Baisan, 1996; Swetnam & Betancourt, 1998). The Argentinean dataset is composed of 214 cross-dated *Austrocedrus chilensis* fire scars from five disjunct woodlands (each ≈2 km^2 in area) located between ≈39°30′ and ≈41°S along the northern Patagonian forest–steppe ecotone (Kitzberger & Veblen, 1998).

To identify years of widespread fire that probably reflect weather influences on fire occurrence rather than local impacts of humans on ignition, three indices of successively more widespread fire were computed on the basis of synchronous fire occurrence at disjunct sampling sites. In the south-west, the three indices used for identifying regional fire years were years when fire was recorded at more than 10, 15 and 20 sites out of 63. In Patagonia, where fewer but larger sampling areas were utilized, regional fire years were years when fire was recorded at more than 10, 15 and 30% of all 214 trees in five sites. To describe multi-decadal scale patterns of fire occurrence, the numbers of these three levels of regional-scale fire years were plotted over a moving 49-year window in the south-west United States and Patagonia.

In order to identify time/frequency domains in which the two series oscillated similarly, two different spectral analyses were performed on the south-western United States and Patagonia fire-scar series (1700–1900): singular spectrum analysis (SSA) (Vautard & Ghil, 1989) and evolutive spectral coherence analysis (SCA) (Bloomfield, 1976). To remove the low frequency component (secular trends), each time-series of fire events was first detrended by fitting it to a 50-year cubic spline function. SSA was used to identify and compare dominant waveforms (i.e. period ranges in both series that absorb the highest amount of variance) in both fire-scar series. SSA is an extension of empirical orthogonal function analysis that samples lagged copies of a time series at equal time intervals and calculates eigenvalues and eigenvectors of the autocovariance matrix. Subsets of eigen elements and associated principal components provide the identification of oscillatory components (Vautard & Ghil, 1989). The complete sum of eigen elements returns the original input series. SSA (Fortran code SSA Version 1.06p) was run on 50-year cubic spline detrended fire-scar series with 31 lags (components). Oscillatory behaviour of dominant waveforms was identified from the sums of the reconstructed components from the nine most important eigenvectors, clustered into three waveforms with periods varying from ≈2.14 to 5.66 years.

Squared coherence, a measure of the similarity in the periodicities of two time series, was computed within the statistical package STATISTICA over a 70-year moving window as a function of the period (i.e. the inverse of the frequency) for periods in the 2–10 years bandwidth. Squared coherency is the squared cross-amplitude divided by the product of the spectrum density estimates for each series and represents the squared correlation of the cyclical components in the two series at the respective period. The squared coherence values range from 0 to 1, giving a measure of the stochastic coupling of the two signals within a certain frequency band. Uncorrelated signals will yield coherence values of 0, whereas the more two signals are correlated, the more the squared coherence will increase towards 1. Evolutive (time-period) spectral coherence was analysed by plotting squared coherency as a function of period (0.1-year period intervals) and the mid-point of a sequentially moving 70-year window (1-year time intervals). Evolutive SCA was performed over mid-points between 1735 and 1875 within the 2–10-year period band.

For comparison of the two regional fire history records with long-term variations in ENSO activity we used several independently derived reconstructions of ENSO extending over the past several centuries. These include records of El Niño/La Niña events from Spanish archival documents (Quinn & Neal, 1992), tree-ring calibrated reconstructions of Southern Oscillation indices from several regional tree-ring networks (Lough & Fritts, 1985; D'Arrigo & Jacoby, 1991; Stahle & Cleaveland, 1993; Villalba, 1994; Stahle *et al.*, 1998), $\delta^{18}O$ time-series from tropical coral (Dunbar *et al.*, 1994) and ice core records (Michaelsen & Thompson, 1992). For each of these proxy records, indices of ENSO activity are plotted over 49-year moving periods for comparison with the two fire records.

RESULTS

Documentary records of fire indicate that years of widespread fires in the south-western United States (1914–87, 14 events) and in northern Patagonia (1938–96, nine events) show similar relationships to indicators of ENSO variation (Fig. 1). Years of widespread fire are preceded by a sequence of approximately 1–2 years of below-average monthly SOI and above-average monthly SSTs (i.e. El Niño conditions), which gives way to one to one-and-a-half years of above-average monthly SOI and below-average SSTs (i.e. La Niña conditions). Thus, the monthly SOI and SST data indicate that major fire years immediately follow a complete cycle from El Niño to La Niña conditions in both regions.

Decadal-scale fluctuations in the frequency of regional fire years derived from tree-ring dating of fire scars are broadly similar between the two regions over the past several hundred years (Fig. 2). The number of regional fire years in a moving 49-year period from 1650 to the present

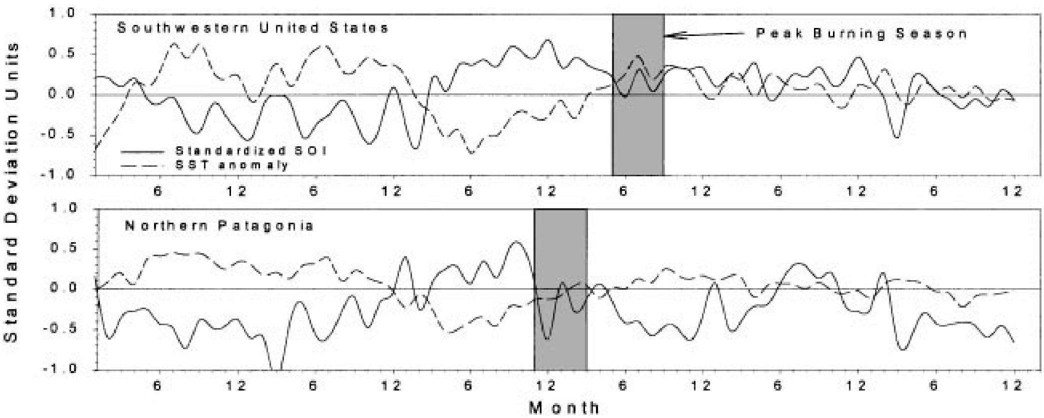

Fig. 1 Standard deviations of mean monthly standardized southern-oscillation indices (SOI, Darwin-Tahiti, solid lines) and of sea surface temperature (SST, from Niño 1 + 2 Region, dashed lines) preceding, during, and following the years in which largest areas burned in the south-western USA (1914–87, 14 events), and the years with largest number of lightning-caused fires in Patagonia (1938–96, nine events). The peak burning season during the years tested is indicated by the shaded period. Note that La Niña conditions (i.e. high SOI values and low SSTs) immediately preceded the peak burning seasons during the major fire years, while El Niño-type conditions (i.e. low SOI values and high SSTs) generally occurred in earlier seasons and years.

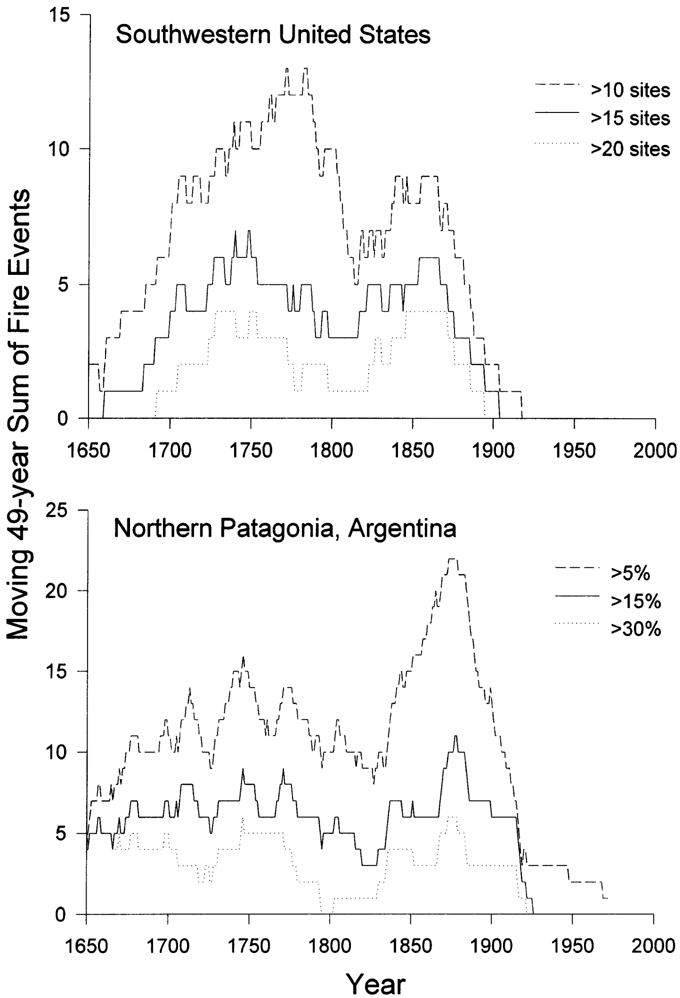

Fig. 2 Numbers of years of widespread fire over a moving 49-year window in the south-west United States and Patagonia. Regional fire years in the south-west were years with fire recorded in more than 10, 15 and 20 sites out of 63, while in Patagonia they were years with fires recorded by more than 10, 15 and 30% of all 214 trees in five sample sites: raw regional fire chronologies from which can be found in Swetnam & Baisan (1996) and Kitzberger & Veblen (1997).

follows a similar pattern in both regions. Relatively low fire frequency periods occurred in both regions before *c.* 1675 and from *c.* 1780 to 1830. High fire frequency periods occurred in both regions from *c.* 1700 to 1750, and from *c.* 1840 to 1890.

SSA performed on these widely separated fire-scar series indicate synchronous decadal–secular changes in the dominant waveforms. Both series show a high amplitude of the ≈2–5-year bandwidth oscillations during *c.* 1720–1780 and 1830–1860 and a reduced amplitude time period centred in the early 1800s (Fig. 3a,b). Evolutive SCA of these fire-scars confirm 1780–1830 as a period of low common signal in the 2–4-year bandwidth. The two fire-scar series were most coherent in the 2–4-year band before *c.* 1780 and after *c.* 1830, whereas during the 1780–1830 period

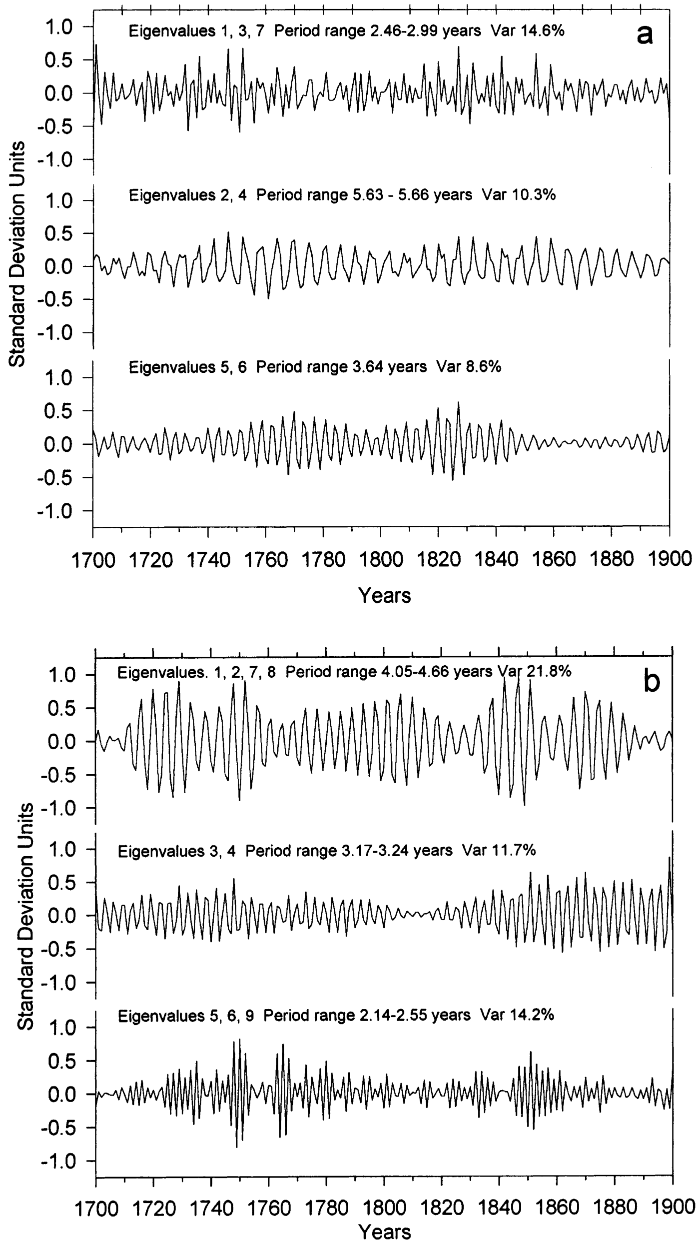

Fig. 3 Dominant waveforms of the northern Patagonia (a), and the south-western United States (b) 50 years cubic spline-detrended fire-scar time series (1700–1900) derived from singular spectrum analysis (SSA; Vautard & Ghil, 1989). Sums of the reconstructed components from the 7–9 most important eigenvectors have been clustered into three waveforms with similar period ranges from ≈2.14–5.66 years. Eigenvector numbers, period ranges and variance explained from the original time series are shown for each cluster.

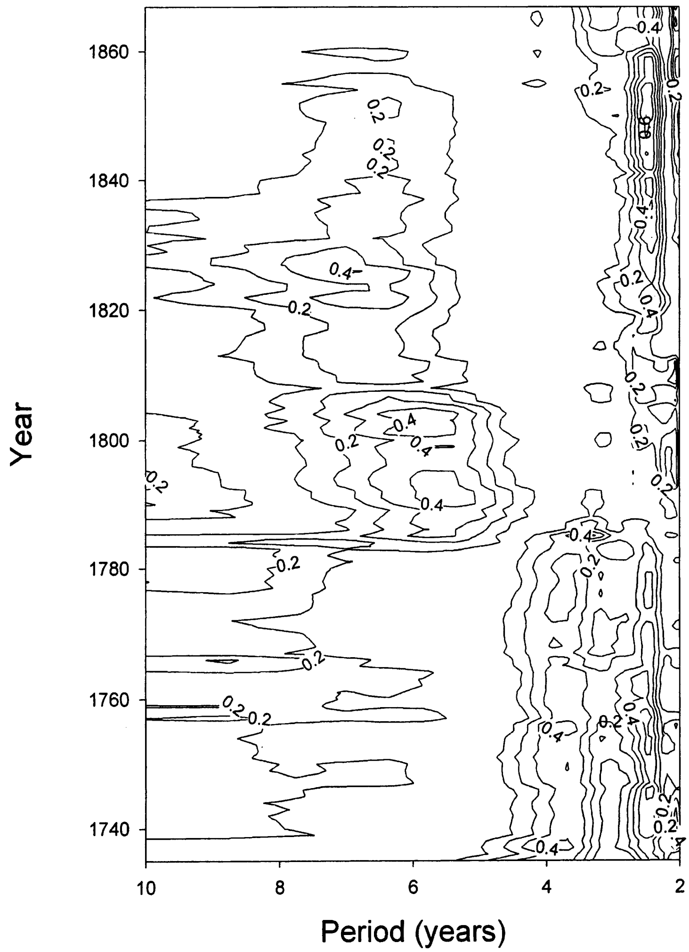

Fig. 4 Evolutive (time-period) spectral coherence between the south-western United States and northern Patagonia fire-scar series (1700–1900). Each series was first detrended with a 50-year cubic spline, then coherence spectra were calculated over a 70-year moving window. Squared coherence (contours) is plotted as a function of period over a 2–10-year bandwidth range and the mid-points of a sequentially moving 70-year window (1735–1875).

coherence was weak in the 2–4-year band but was stronger in the 5–7-year band (Fig. 4). Thus, both the simple time-series comparison of changes in the series periodicity and their spectral coherence through time suggests synchronous decadal–secular shifts in their oscillatory modes.

Several independently derived reconstructions of ENSO show that the decadal-scale pattern of years of widespread fire broadly parallels temporal variations in ENSO events over the past several centuries (Fig. 5). These include records of El Niño/La Niña events from Spanish archival documents (Quinn & Neal, 1992), tree-ring calibrated reconstructions of Southern Oscillation indices from several regional tree-ring networks (Lough & Fritts, 1985; D'Arrigo & Jacoby, 1991; Stahle & Cleaveland, 1993; Villalba, 1994; Stahle *et al.*, 1998), $\delta^{18}O$ time series from tropical coral (Dunbar *et al.*, 1994) and ice core records (Michaelsen & Thompson, 1992). Reduced amplitude and/or frequency of the ENSO during 1780–1830 is indicated by all these records (Fig. 5).

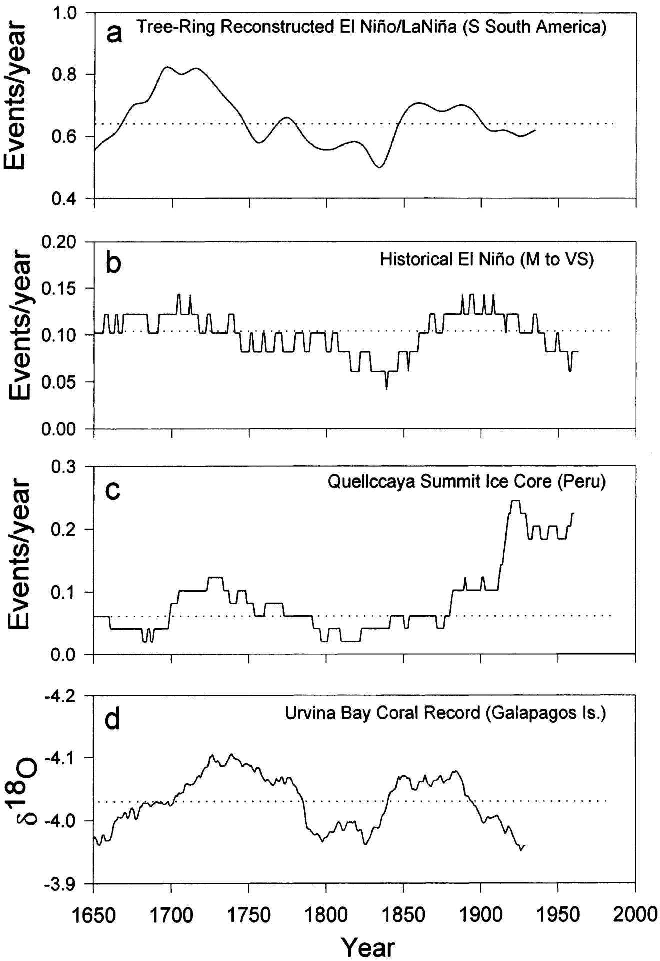

Fig. 5 Multi-proxy reconstructions of low frequency changes in ENSO activity between 1650 and 1990. (a) La Niña and El Niño events reconstructed from tree-ring chronologies in Patagonia and central Chile (Villalba, 1994). (b) Recurrence of moderate to very strong El Niño events reconstructed from archival documents (Quinn & Neal, 1992). (c) El Niño recurrence based on years when $\delta^{18}O$ was >−16‰ (i.e. warm events) in the Quelccaya summit ice core record (Michaelsen & Thompson, 1992). Plots are mean number of events per year based on moving 49-year sums of all indices. (d) Record of ENSO-related central Pacific upwelling based on $\delta^{18}O$ (‰) coral from Urvina Bay, Galapagos Islands (Dunbar *et al.*, 1994; 49-year running mean). In all cases the horizontal solid line represents long-term mean values.

DISCUSSION

The similar patterns of monthly SOI and SSTs over the two to three years preceding major fire years in both the south-western United States and northern Patagonia strongly imply that the switching from El Niño to La Niña conditions is conducive to widespread fire. We believe that this switching of extreme phases of the SO favours widespread fires in both regions through a combination of weather influences on fuel quantities and on fuel desiccation over periods of 2–3 years. For example, the increased winter and spring precipitation typically associated with extreme El Niño events in these regions (Andrade & Sellers, 1988; Kiladis & Diaz, 1989) result in deep and long-persisting snow pack in the mountains. Greater spring and early summer moisture availability, in turn, results in enhanced growth of fine fuels, especially grasses. When followed by La Niña-induced conditions of increased temperatures and reduced precipitation during the winter and growing season, fuel desiccation creates conditions for widespread fire in both regions (Kitzberger & Veblen, 1998; Swetnam & Betancourt, 1998; Veblen *et al.*, 1999). Conversely, during the fire seasons immediately preceded by El Niño conditions, the extended melt and runoff of snow, coupled with enhanced understorey plant growth in the spring, often leads to greener conditions and higher live and dead fuel moistures during the ordinarily dry late spring and early summer. Fire ignitions and spread are therefore greatly reduced under El Niño conditions.

Despite the similar patterns of fire and ENSO variation for the two regions during the documentary period and also recorded in longer-term tree-ring-based studies (Kitzberger & Veblen, 1998; Swetnam & Betancourt, 1998; Veblen *et al.*, 1999), we also recognize substantial variation in the effects of individual ENSO events on climate and fire. Regional fire regime responses to ENSO events can be variable, in particular in Patagonia, depending upon the seasonal timing and magnitude of the event relative to seasonality of precipitation distribution. In Patagonia, for example, major fire years can also coincide with late developing El Niño events. When the event develops relatively late in the calendar year, precipitation is not typically above average during the winter–spring (June–November) immediately preceding the fire season, but summers are warmer than normal. Among the 10 years of most widespread fire since 1740, six occurred during summers that immediately followed El Niño years and that were significantly warmer than the long-term average (Veblen *et al.*, 1999). Thus, there are at least two kinds of ENSO events that promote regional fire events in Patagonia: La Niña, and late-occurring El Niño events.

Although the coincidence of years of widespread fire with one of the two phases of the SO has been demonstrated previously for other regions (e.g. Simard *et al.*, 1985; Nicholls, 1992), the fire history records of the south-western United States and northern Patagonia imply that switching from extreme El Niño to La Niña events is important in favouring years of exceptional fire occurrence. Increased fine fuel production in previous seasons and years appears to be important for regional fire activity, as indicated by the relatively short documentary record of fires in both regions. A pattern of one to several years of El Niño conditions leads to fuel build-up through both increased plant productivity and decreased fire activity. Subsequent La Niña conditions result in drying of the accumulated fine fuels and pre-existing coarser fuels, leading to more successful fire ignitions and widespread burning (Swetnam & Baisan, 1996; Kitzberger *et al.*, 1997; Swetnam & Betancourt, 1998; Veblen *et al.*, 1999). Given this mechanism of increased fire occurrence due to the switching of SO phases, the parallelism of centennial scale variations in fire regimes in the south-western United States and northern Patagonia may reflect a causal relationship with ENSO variability. Frequent interannual switching (i.e. high climate variability) from wet to dry, corresponding to the high-frequency end of the ENSO spectrum (2–4 years), appears to be critical to frequent regional fire years. Conversely, reduced amplitude and/or frequency of this switching (i.e. weaker or fewer El Niño and/or La Niña events) results in reduced regional fire frequencies.

We suggest that the reduced fire frequency and change in spectral coherence from *c.* 1780 to the 1830s is an indication of interhemispheric fire regime responses to a decadal-scale change in the ENSO system. However, we offer this interpretation cautiously because of the relatively small number of samples for the pre-1800 period of the Patagonian record and because of the potential influence of humans on decadal-scale patterns of fire regimes. For example, human influence on fire regimes is demonstrated in both regions by a reduced fire frequency after *c.* 1900 due to fire control by government agencies, in combination with varying degrees of decreased intentional burning (by aboriginal hunters and/or early European settlers), and due to the reduction of fuels by introduced livestock. Changes in aboriginal and/or European burning practices could potentially have affected fire frequencies during the 18th and 19th centuries in both regions. However, by limiting our analysis to years of very widespread fire (e.g. evidence of synchronous fire in areas separated by many kilometres) we believe our results reflect a pattern controlled more by climatically controlled fuel conditions than by frequency of human ignitions.

In addition to the relationship of years of widespread fire to changes in ENSO events, we also note that the most extensive and well-calibrated multi-proxy temperature reconstruction for the northern hemisphere exhibits very cold decades during the early 1800s coinciding approximately with several major volcanic eruptions and a period of low solar irradiance (Mann *et al.*, 1998). These decadal cold periods followed a relatively warm period during the mid-1700s and are also recorded in tree-ring records from Patagonia (Villalba *et al.*, 1996). It is not clear, however, what forcing mechanisms may have been most important in causing the cold decades after the warm mid-1700s, nor are the relations with the ENSO system understood. Whatever global-scale causes and linkages were involved, the combined evidence from multiple proxy records, now including interhemispheric forest fire records, indicate that the 1780s–1830s was a period of striking climatic change.

The strong influence of high frequency climatic variability on fire regimes in the south-western United States and northern Patagonia supports a similar conclusion about climatic variability and fire frequency in a review of Holocene-length pollen and charcoal sediment studies in Patagonia (Markgraf & Anderson, 1994). These findings emphasize the importance of climatic variability at the interannual to decadal scales in controlling regional fire activity, rather than directional change in climatic means or trends (e.g. warming), which have more commonly been assessed in palaeo-fire/climate and modelling studies (Clark, 1988; Overpeck *et al.*, 1990; Swetnam, 1993; Price & Rind, 1994).

Testing and developing greater confidence in these fire patterns and interpretations will require additional fire history and climate reconstructions in these and other regions. Expanding fire history networks into regions with opposite responses to ENSO (relative to the south-western United States and Patagonia) may be especially fruitful, as anomalies may be even more clearly defined in such regional contrasts and comparisons. Studies of other synoptic climate–fire patterns are also needed, since ENSO obviously does not explain all of the variance in either climate (Villalba *et al.*, 1996, 1997, 1998) or fire regimes in these regions (Veblen *et al.*, 1999). With more extensive and strategic sampling in both regions it may be possible to expand spatial scales, extend the temporal length of fire histories and evaluate both human and climatic influences on past fire regimes.

Expanded studies of fire history that allow regional comparisons are of potential use to resource managers and planners. For example, increased fuel accumulation during recent decades of fire suppression in ecosystems of western North America and northern Patagonia coincides with unusually frequent El Niño events during the past several decades. This may be creating an explosive fire situation unprecedented during the documentary record. The combination of an extreme El Niño event followed closely by La Niña conditions such as the 1997–98 El Niño and the 1998–99 La Niña events is the precise formula for a regional fire year in the south-western United States and northern Patagonia (Kitzberger *et al.*, 1997; Swetnam & Betancourt, 1998; Veblen *et al.*, 1999). It is encouraging, however, that the onset and development of ENSO events precede the affected fire season by months to years, because this offers a window of opportunity for alerting resource managers and the public to changes in the potential for extensive wildfires.

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REFERENCES

Aceituno, P. (1988) On the functioning of the Southern Oscillation in the South American sector. Part 1. Surface climate. *Monthly Weather Review*, **116**, 505–524.

Andrade, E.R. Jr & Sellers, W.D. (1988) El Niño and its effect on precipitation in Arizona and western New Mexico. *Journal of Climate*, **8**, 403–410.

Ashton, P.S., Givnish, T.J. & Appanah, S. (1988) Staggered flowering in the Dipterocarpaceae: new insights into floral induction and the evolution of mast fruiting in the aseasonal tropics. *American Naturalist*, **132**, 44–66.

Bloomfield, P. (1976) *Fourier analysis of time series. An Introduction*. Wiley, New York.

Brown, N. (1998) Out of control: fires and forestry in Indonesia. *Trends in Ecology and Evolution*, **13**, 41–44.

Clark, J.S. (1988) Effect of climate change on fire regimes in northwestern Minnesota. *Nature*, **334**, 233–235.

Curran, L.M., Caniago, I., Paoli, G.D., Astianti, D., Kusneti, M., Leighton, M., Nirarita, C.E. & Haeruman, H. (1999) Impact of El Niño and logging on canopy tree recruitment in Borneo. *Science* **286**, 2184–2188.

D'Arrigo, R.D. & Jacoby, G.C. (1991) A 1000-year record of winter precipitation from northwestern New Mexico, USA: a reconstruction from tree-rings and its relation to El Niño and the southern oscillation. *The Holocene*, **1**, 95–10.

Douglas, A.V. & Engelhart, P. (1984) Factors leading to the heavy precipitation regimes of 1982–83 in the United States. *Proceedings of the 8th Annual Climate Diagnostics Workshop*, US Government Printing Office, NTis PB 84–192418. Washington, DC. pp. 42–54.

Dunbar, R., Wellington, G.M., Colgan, M.W. & Glynn, P.W. (1994) Eastern Pacific sea surface temperature since 1600 AD. The $d^{18}O$ record of climate variability in Galapagos corals. *Paleoceanography*, **9**, 291–316.

Kiladis, G.N. & Diaz, H.F. (1989) Global climatic anomalies associated with extremes in the Southern Oscillation. *Journal of Climate*, **2**, 1069–1090.

Kitzberger, T. & Veblen, T.T. (1998) Influences of humans and ENSO on fire history of *Austrocedrus chilensis* woodlands in northern Patagonia, Argentina. *Ecoscience*, **4**, 508–520.

Kitzberger, T., Veblen, T.T. & Villalba, R. (1997) Climatic influences on fire regimes along a rainforest-to-xeric woodland gradient in northern Patagonia, Argentina. *Journal of Biogeography*, **23**, 35–47.

Laurance, W.F. (1998) A crisis in the making: responses of Amazonian forests to land use and climate change. *Trends in Ecology and Evolution*, **13**, 411–415.

Leighton, M. & Wirawan, N. (1986) Catastrophic drought and fire in Borneo tropical rain forest associated with the 1982–83 El Niño Southern Oscillation event. *Tropical rain forest and the world atmosphere* (ed. by G.T. Prance), pp. 75–102. Westview Press, Boulder.

Lima, M., Marquet, P.A. & Jaksic, F.M. (1999) El Niño events, precipitation patterns, and rodent outbreaks are statistically associated in semiarid Chile. *Ecography*, **22**, 213–218.

Lough, J.M. & Fritts, H.C. (1985) The southern oscillation and tree rings: 1600–1961. *Journal of Climate and Applied Meteorology*, **24**, 952–966.

Mann, M.E., Bradley, R.S. & Hughes, M.K. (1998) Global-scale temperature patterns and climate forcing over the past six centuries. *Nature*, **392**, 779–787.

Markgraf, V. & Anderson, L. (1994) Fire history in Patagonia: climate versus human cause. *Revista Do Instituto Geografico Do Sao Paulo*, **15**, 35–47.

Michaelsen, J. & Thompson, L.G. (1992) A comparison of proxy records of El Niño/Southern Oscillation. *El Niño: historical and paleoclimatic aspects of the Southern Oscillation* (ed. by H.F. Diaz and V. Markgraf), pp. 323–348. Cambridge University Press, Cambridge.

Nicholls, N. (1992) Historical El Niño/Southern Oscillation variability in the Australasian region. *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation* (ed. by H.F. Diaz and V. Markgraf), pp. 151–173. Cambridge University Press, Cambridge.

Overpeck, J.T., Rind, D. & Goldberg, R. (1990) Climate induced changes in forest disturbance and vegetation. *Nature*, **343**, 51–53.

Price, C. & Rind, D. (1994) The impact of a $2 \times CO_2$ climate on lightning-caused fires. *Journal of Climate*, **7**, 1484–1494.

Quinn, W.H. & Neal, V.T. (1992) The historical record of El Niño events. *Climate since AD 1500* (ed. by R.S. Bradley and P.D. Jones), pp. 623–646. Routledge, London.

Simard, A.J., Haines, D.A. & Main, W.A. (1985) Relations between El Niño/Southern Oscillation anomalies and wildland fire activity in the United States. *Agricultural and Forestry Meteorology*, **36**, 93–104.

Stahle, D.W. & Cleaveland, M.K. (1993) Southern oscillation extremes reconstructed from tree rings of the Sierra Madre Occidental and Southern Great Plains. *Journal of Climate*, **6**, 129–140.

Stahle, D.W., D'Arrigo, R.D., Krusic, P.J., Cleaveland, M.K., Cook, E.R., Allan, R.J., Cole, J.E., Dunbar, R.B., Therrell, M.D., Gay, D.A., Moore, M.D., Stokes, M.A., Burns, B.T., Villanueva-Diaz, J. & Thompson, L.G. (1998) Experimental dendroclimatic reconstruction of the Southern Oscillation. *Bulletin of the American Meteorological Society*, **79**, 2137–2152.

Swetnam, T.W. & Baisan, C.H. (1996) Historical fire regime patterns in the Southwestern United States since AD 1700. *USDA Forest Service General Technical Report RM-GTR*, **286**, 11–32.

Swetnam, T.W. & Betancourt, J.L. (1990) Fire–Southern Oscillation relations in the Southwestern United States. *Science*, **24**, 1017–1020.

Swetnam, T.W. & Betancourt, J.L. (1998) Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate*, **11**, 3128–3147.

Swetnam, T.W. (1993) Fire history and climate change in giant sequoia groves. *Science*, **262**, 885–889.

Vautard, R. & Ghil, M. (1989) Singular spectrum analysis in non-linear dynamics, with application to paleoclimatic time series. *Physica*, **35D**, 395–424.

Veblen, T.T., Kitzberger, T. & Lara, A. (1992) Disturbance and forest dynamics along a transect from Andean rain forest to Patagonian shrubland. *Journal of Vegetation Science*, **3**, 507–520.

Veblen, T.T., Kitzberger, T. & Donnegan, J. (2000) Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. *Ecological Applications*, **10**, 1178–1195.

Veblen, T.T., Kitzberger, T., Villalba, R. & Donnegan, J. (1999) Fire history in northern Patagonia: The roles of humans and climatic variation. *Ecological Monographs*, **69**, 7–67.

Villalba, R. (1994) Tree-ring and glacial evidence for the Medieval Warm Epoch and the Little Ice Age in southern South America. *Climatic Change*, **26**, 183–197.

Villalba, R., Boninsegna, J.A., Lara, A., Veblen, T.T., Roig, F.A., Aravena, J.C. & Ripalta, A. (1996) Interdecadal climatic variations in millenial temperature reconstructions from southern South America. *Climatic forcings of the last 2000 years* (ed. by P.D. Jones and R. Bradley), pp. 161–189. NATO Advanced Sciences Institutes Series, vol. 41. Springer-Verlag, Berlin.

Villalba, R., Cook, E.R., D'Arrigo, R.D., Jacoby, G.C., Jones, P.D., Salinger, M.J. & Palmer, J. (1997) Sea-level pressure variability around Antarctica since AD 1750 inferred from subantarctic tree-ring records. *Climate Dynamics*, **13**, 375–390.

Villalba, R., Cook, E.R., Jacoby, G.C., D'Arrigo, R.D., Veblen, T.T. & Jones, P.D. (1998) Tree-ring based reconstructions of precipitation in Patagonia since AD 1600. *The Holocene*, **8**, 659–674.