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ENSO Controls Interannual Fire Activity in Southeast Australia

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Key Points:

- ENSO modulates interannual fire activity in southeast Australia
- Fire occurrence in southeast Australia is strongly dependent on seasonal variations of ENSO
- Decadal-scale frequencies in ENSO are linked with fire activity in southeast Australia

Supporting Information:

- Supporting Information S1

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ENSO controls interannual fire activity in southeast Australia

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Abstract El Niño–Southern Oscillation (ENSO) is the main mode controlling the variability in the ocean-atmosphere system in the South Pacific. While the ENSO influence on rainfall regimes in the South Pacific is well documented, its role in driving spatiotemporal trends in fire activity in this region has not been rigorously investigated. This is particularly the case for the highly flammable and densely populated southeast Australian sector, where ENSO is a major control over climatic variability. Here we conduct the first region-wide analysis of how ENSO controls fire activity in southeast Australia. We identify a significant relationship between ENSO and both fire frequency and area burnt. Critically, wavelet analyses reveal that despite substantial temporal variability in the ENSO system, ENSO exerts a persistent and significant influence on southeast Australian fire activity. Our analysis has direct application for developing robust predictive capacity for the increasingly important efforts at fire management.

1. Introduction

Fire is a ubiquitous Earth system process that began soon after the appearance of terrestrial plants 420 million years ago [*Scott and Glasspool*, 2006]. At the global scale, fire affects ecosystem patterns and processes, determines vegetation distribution [*Bond and Keeley*, 2005; *Bond et al.*, 2005], impacts the climate system [*Bowman et al.*, 2009], and contributes to the carbon cycle [*Liu et al.*, 2015; *Santín et al.*, 2016]. Moreover, climate-driven changes in fire activity are a significant threat for human populations living in flammable biomes [e.g., *Parisien*, 2016] and for ecosystem services and function [*Calder et al.*, 2015]. The predicted increase in fire activity in many regions on Earth in response to climate change [*Parisien and Moritz*, 2009; *Moritz et al.*, 2012; *Westerling et al.*, 2006], therefore, represents a significant challenge for attempts of a sustainable management of the Earth system. Despite the clear importance of fire and recognition of climate as a key component controlling this process, the relationship between climate and fire is still poorly understood in many regions on Earth. In southeast Australia, one of the most fire-prone areas on Earth [*Hennessy et al.*, 2005], the main climate mode controlling key determinants of fire weather (moisture and temperature variability) is the El Niño–Southern Oscillation (ENSO) [*Risbey et al.*, 2009]. In general, El Niño events, the warm phase of ENSO, starve southeast Australia of rainfall and promote drought and wildfire [*Kiem and Franks*, 2004; *Verdon et al.*, 2004; *Nicholls and Lucas*, 2007; *Murphy and Timbal*, 2008; *Hill et al.*, 2009]. The current amplification of El Niño activity due to anthropogenic climate change [*Power et al.*, 2013] then heralds a serious threat to southeast Australia's water security, remnant fire-sensitive ecosystems and the ever expanding flammable bush-urban interface [*Guilyardi*, 2006; *Lenton et al.*, 2008; *Sharples et al.*, 2016]. Here we present a novel analysis of climate-fire dynamics in southeast Australia in an attempt to elucidate the dominant climatic drivers of fire in both space and time in this heavily populated region.

An enhanced understanding of the climatic precursors of increased fire activity can lead to improved predictive power [e.g., *Verdon et al.*, 2004; *Nicholls and Lucas*, 2007; *Harris et al.*, 2014]. This is particularly important for areas such as southeast Australia where the quasiperiodic frequency of oscillations in key climate phenomena, such as ENSO, makes fire prediction a difficult task. ENSO is a particularly important control over fire regimes across the entire Pacific region, and the spatiotemporal variability of ENSO is evident from the range of analyses that attempt to elucidate the role of ENSO in governing fire activity. Indeed, significant correlation between ENSO and fire activity has been reported for the Florida everglades between 1948 and 1999 [*Beckage et al.*, 2003], California during the last 150 years [*Herweijer et al.*, 2007], tropical Mexico between 1984 and 1999 [*Román-Cuesta et al.*, 2003], southwest United States between 1700 and 1905 [*Swetnam and Betancourt*, 1990], Indonesia over the last 250 years [*van der Kaars et al.*, 2010], and southern South

America over the most recent centuries [*Veblen et al*., 1999; *Holz and Veblen*, 2012; *Holz et al*., 2012a]. While there is evidence that El Niño events increase the chance of fire weather in southeast Australia [e.g., *Fox-Hughes et al*., 2014; *Grose et al*., 2014; *Williams et al*., 2001], few analyses from this region assess the influence of ENSO over actual fire occurrence (area burnt and/or number of fires). Of these, anecdotal evidence of an ENSO control over fire activity has been reported from the island of Tasmania, where fires over the historical period are significantly related to sea surface temperatures (SSTs) in the Coral Sea, a location influenced by ENSO [*Nicholls and Lucas*, 2007]. More concrete evidence comes from the south coast of the region (state of Victoria), where a significant correlation between ENSO and both area burnt and number of fires has been reported between 1972 and 2012 [*Harris et al*., 2014]. While ENSO is most often considered the dominant control over southeast Australian climate and fire activity, the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM), both important controls over climatic variability in this region, have been shown to influence fire activity within the southeast Australian sector [e.g., *Cai et al*., 2009; *Mariani and Fletcher*, 2016], suggesting that multiple modes of climatic variability must be considered when attempting to determine the drivers of fire activity in this region.

A critical limitation of previous analyses of ENSO-fire relationships in southeast Australia is the lack of a regional synthesis of actual fire activity conducted through a rigorous climatological framework. A case in point is the work on the role of ENSO in governing fire activity in Tasmania [*Nicholls and Lucas*, 2007]. Tasmania is a topographically complex midlatitude island in which the climatic determinants of fire weather and activity are polarized between ENSO in the north and east and the SAM in the south and west [*Mariani and Fletcher*, 2016]. SAM relates to changes in the position and intensity of the circumpolar southern westerlies, a system that, while periodically synergistic with ENSO through time [*Fogt et al*., 2011], primarily acts independently to ENSO. Indeed, recent evidence reveals that fire activity in the south and west of Tasmania is determined by SAM, with ENSO having little explanatory power over fire activity through the recent and deeper past [*Mariani and Fletcher*, 2016]. Further, analyses of the climatic determinants of fire activity in southeast Australia have seldom employed actual fire data [*Harris et al*., 2014; *Nicholls and Lucas*, 2007; *Mariani and Fletcher*, 2016], rather, most employ indices of fire weather to ascertain the link between climate and the potential for fire occurrence [*Fox-Hughes et al*., 2014; *Grose et al*., 2014; *Williams et al*., 2001]. Moreover, of those that do employ actual fire occurrence data, only those focused on the island of Tasmania exclude planned burns from their analysis [*Nicholls and Lucas*, 2007; *Mariani and Fletcher*, 2016], an important source of noise that reduces the efficacy of the fire occurrence data set for correlation with climate variability.

Here we present a multiscale analysis of the role of ENSO in governing actual fire activity in southeast Australia. Our specific aims are to (1) explore the relationship between ENSO and fire occurrence in the densely populated and highly flammable southeast of Australia; (2) synthesize the seasonal importance of ENSO in determining interannual fire activity in this region; and (3) test whether or not ENSO and fire occurrences have coherent time-frequency domains. We conducted our climate-fire analysis using the Southern Oscillation Index (SOI), an index of ENSO variability that strongly affects precipitation in southeast Australia [*Risbey et al*., 2009]. We employed observed fire history data filtered to include unplanned fires only and conducted correlation function and wavelet analyses to determine long-term seasonal-scale associations and time frequencies coherence between SOI and fire activity through time.

2. Methods

To visualize the spatial pattern of the influence of ENSO on southeast Australian precipitation, we created a correlation map between annual and seasonal precipitation totals and the Southern Oscillation Index (SOI). SOI is calculated as the normalized difference between mean sea level pressure at Tahiti and Darwin, and it is negative during El Niño events and positive during La Niña events [*Trenberth*, 1984]. Although there are several indices for ENSO (e.g., Niño 4, Niño 3.4, ENSO-Modoki Index, EMI), we used the SOI because it has shown to have the highest correlation values with rainfall in Australia compared to the other indices [*Risbey et al*., 2009]. This is probably because the SOI is more closely related to the rainfall process in southeast Australia through its relationship with large-scale surface pressure, compared to ocean-based indices which rely on sea surface temperature (SST) [*Risbey et al*., 2009]. We calculated Pearson correlation coefficients (r) between seasonal/annual rainfall during the period 1961–1990 for 1208 meteorological stations across the southeast Australia and the seasonal/annual SOI. Precipitation data were obtained from the Australian

Bureau of Meteorology (BOM). The *r* values from the stations were spatially interpolated using the Universal Kriging method in ArcMap 10.2 [*ESRI-Environmental Systems Resource Institute*, 2011, Redlands, California].

To account for fuel limitations, an essential parameter in determining fire activity [*Krawchuk et al*., 2009; *Cochrane*, 2003; *Pausas and Ribeiro*, 2013; *Bradstock*, 2010; *McWethy et al*., 2013; *Boer et al*., 2016], we constrain our analysis to the cool temperate forest biome of southeast Australia (latitude between 28°S and 44°S; longitude between 140°E and 155°E), where biomass is considered to be always abundant and in which climate is the principal determinant of temporal changes in fire activity [*Bradstock et al*., 2014]. This screening removed fires from the Australian Alps, as much of this landscape approaches biomass limitation with respect to fire [*Bradstock et al*., 2014]. Observed fire occurrence data were obtained through local administrative databases and span the period between the fire seasons of 1951/1952 and 2013/2014 (hereon, we define a fire season year by the year in which the fire season ends—e.g., fire season 1951/1952 = 1952). We determine the "fire season" as the period between December and March, during which the majority of fire events occur [*Williamson et al*., 2016]. For Tasmania, only the eastern and northern side of the state was considered, as fire activity and precipitation in the west of this island have been linked to variability in the SAM, with no identified relationship between fire activity and ENSO [*Mariani and Fletcher*, 2016].

Fire activity is represented in this study as two metrics: number of occurrences and area burnt, representing different components of a fire regime. Area burned represents the outcome of a fire season and includes ignitions as well as fire weather and fuels that determine fire spread. Fire occurrence is mainly linked to ignitions and is more sensitive to artifacts linked to detection. The fire activity data (number of fires and area burnt) were first filtered to include all fires except deliberate management fires and then normalized by the standard deviations (*z* scores). *Z* scores values higher (lower) than 0.5 (-0.5) were used to identify significant "fire years" ("nonfire years") [*Mariani and Fletcher*, 2016]. The list of years used in the analysis is shown in Table S1 in the supporting information. A persistent increase in the number of fires toward the present likely reflects improving detection and recording through time; thus, we applied linear detrending to the time series to extract the interannual variability. Figure 1 presents the location of all fires recorded in southeast Australia from 1951 to 2014.

To identify a relationship between the annual and seasonal SOI and fire activity in the southeast Australia, we performed Superposed Epoch Analysis (SEA) analysis in R package (dplR package [*Bunn et al*., 2016]). This analysis allows for assessing the significance of the departure from the mean for a given set of key event years (e.g., fire years) and lagged years using bootstrapped confidence intervals [*Lough and Fritts*, 1987]. To analyze the relationship between fire activity and the SOI, we used significant "fire years" and "nonfire years" during the 1951–2014 period and annual and seasonal SOI values. The seasonal indices of SOI were defined as Winter (June–July–August of the fire season end year), Spring (September–October–November of the fire season end year), Summer (December of the previous year and January and February of the fire season end year), and Autumn (March–April–May of the fire season end year). Given the importance of the SAM and IOD in the climate-fire dynamics of the Southern Hemisphere [e.g., *Cai et al*., 2009; *Risbey et al*., 2009; *Hill et al*., 2009; *Garreaud et al*., 2009; *Mariani and Fletcher*, 2016], the same analysis using SEA has been also conducted with these climate modes to test whether they have a significant relationship with fire activity in the study region.

To test whether the fire frequency and area burnt and the SOI show a similar periodicity, wavelet coherence analysis was undertaken using the wt() and wtc() functions respectively in the R package "Biwavelet" [*Gouhier et al.*, 2016]. For this analysis, the spring-summer period was chosen as it represents the season with the highest significant correlation (p value < 0.05) between the SOI and the two fire activity metrics (Table S2 in the supporting information). Wavelet analyses have often been applied to climate data [e.g., *Meyers et al*., 1993; *Lau and Weng*, 1995; *Wang and Wang*, 1996] and provides a useful tool to reveal frequency localization in climate signals in time. The Morlet continuous wavelet transform was applied and the data were padded with zeros at each end to reduce wraparound effects [*Torrence and Webster*, 1999].

3. Results

A total of 25,390 unplanned fires with a total area of 37,291,374 ha were recorded in the temperate biome region of southeast Australia during the period 1951–2014 (Figure 1a). A total of eight significant fire years were determined for fire occurrence, whereas 22 significant fire years were found using the area burnt metric

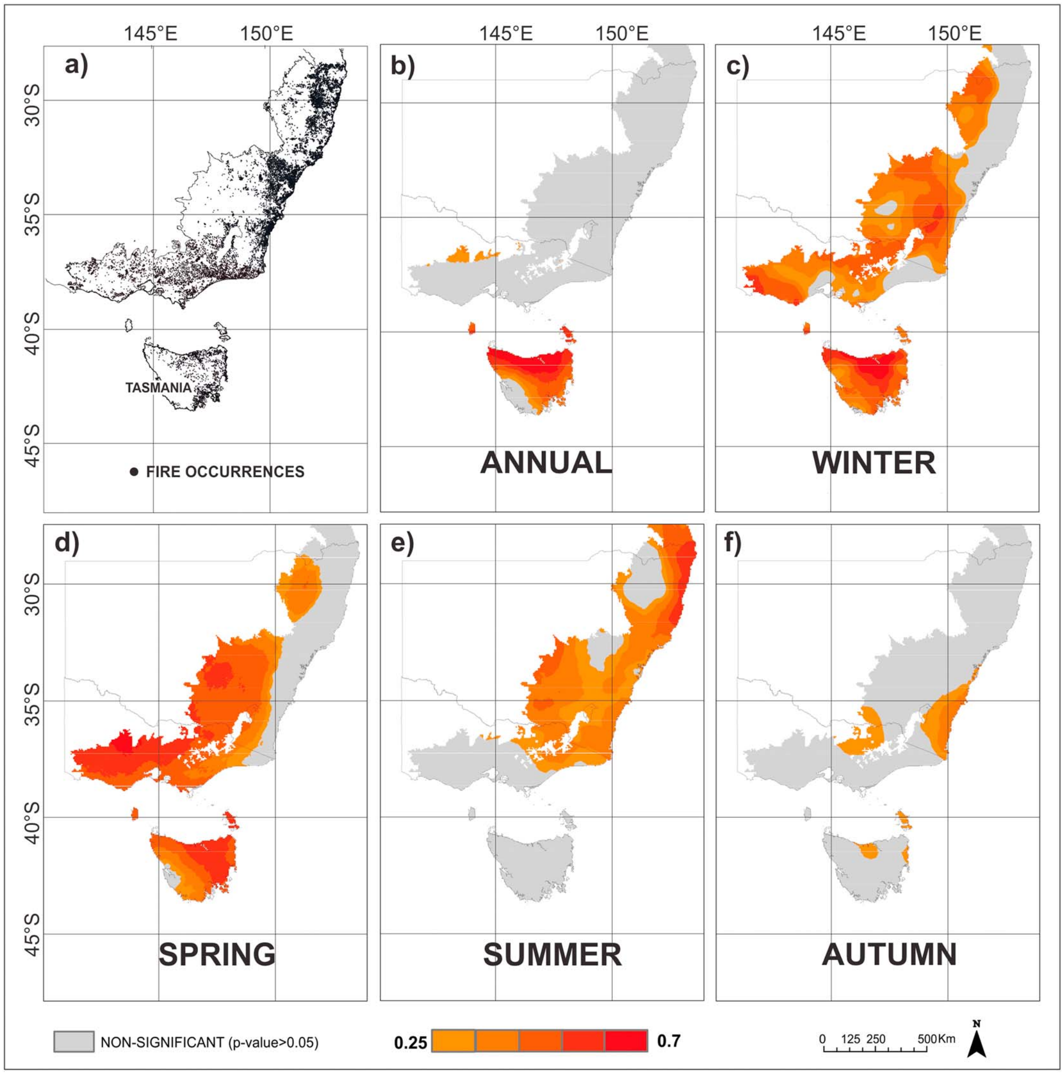

Figure 1. (a) Location of the 25,390 fire occurrences recorded in southeast Australia and correlation map between (b) annual and (c–f) seasonal rainfall and the SOI during the reference period 1961–1990. Grid resolution is 0.05° × 0.05°. Significance has been tested across the 1208 stations used for the interpolation across southeast Australia and only areas with a p value < 0.05 are shown.

(Figures 2c and 2d). The total of significant nonfire years was 10 and 19 for the number of fires and area burnt, respectively (Figures 2c and 2d). The list of years used in the SEA is presented in Table S1. The spatial climate correlation analysis shows a complex pattern of correlation between SOI and rainfall anomalies across southeast Australia using annual and seasonal values (Figures 1b–1f). The strongest positive correlations between SOI and rainfall across most of the study region occur in winter and spring, while weak negative correlations occur in summer and autumn. An exception to this is the northeast of the study region, in which the strongest positive correlations occur during summer and a neutral/negative correlation is present during winter and spring (Figures 1c and 1d). Together, this variable seasonal pattern renders the annual SOI-rainfall correlations signature near neutral in most of the region, except northeastern Tasmania (Figure 1a). Importantly, negative correlations shown in the maps are always weak (i.e., r value < -0.3; p value > 0.05), indicating a probable nonsignificance of these correlations during the reference period (1961–1990).

Testing both number of fires and area burnt metrics, the SEA revealed a statistically significant (p value < 0.05) negative SOI departure (El Niño conditions) occurring in winter and spring of the preceding year and during summer and autumn of the same year (Figures 3a and 3b); i.e., fire activity is significantly related to SOI in the full seasonal cycle leading up to and including a fire season. To support this result, we show that

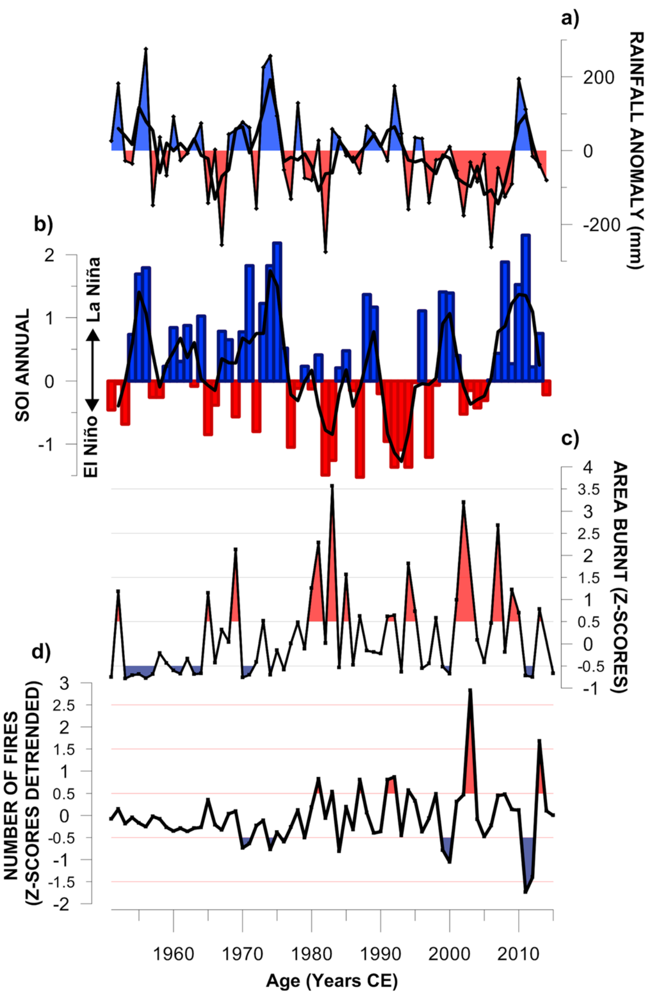

Figure 2. Summary figure for the period 1951–2014 showing (a) rainfall anomaly for the southeastern Australian region (data from BOM); (b) annual SOI, red (blue) bars represent El Niño (La Niña) anomalies; (c) *z* scores of the area burnt values; and (d) detrended *z* scores of the number of fire occurrences.

nonfire years (fire seasons with an anomalously low fire occurrence) correspond to a significant (p value < 0.05) positive departure in SOI (La Niña conditions) during the same seasons (Figures 3a and 3b). At an interannual scale, significant negative annual SOI departures (El Niño) were found during the fire years using the number of fires, whereas area burnt shows negative but not significant departures for annual SOI (Figure 3b). During the nonfire years for area burnt and number of fires, a significant positive SOI departure (La Niña) was found at lag zero. The analyses of both SAM and IOD seasonal and annual indices with the two fire activity metrics did not produce significant results (see Figure S1 and S2 in the supporting information), while analyses using both Nino 3.4 and the EMI are consistent with the SOI results, thus reinforcing the robustness of our results (Figure S3 and S4).

Wavelet coherence indicates that negative SOI (El Niño) occurred in concert with positive anomalies in fire occurrence and area burnt at the respective time frequency during the time periods (Figure 4). The number of fire metrics shows a strong anticorrelated coherence pattern (i.e., a leftward arrow indicated that *x* and *y* are anticorrelated) with the spring-summer SOI with a short-period frequency (1–4 years) between 1963 and 1978, while area burnt shows a strong antiphase frequency between 2 and 5 years over the same 1963–1978 period. During the 1998–2010 period a strong antiphase coherence pattern with the spring-summer SOI with a periodicity between 1 and 5 years is observed in the area burnt coherence plot. A persistent strong antiphase coherence pattern with periodicity between 10 and 18 years was found both in the area burnt and fire occurrence metrics throughout the entire analysis period. Areas outside the "cone of influence," where edge effects are present, have not been considered for the interpretation of the results.

4. Discussion

Our analysis constitutes the first synthesis of the fire-climate teleconnections over the last 60 years across temperate southeast Australia, a highly flammable and densely populated region that is subject to frequent catastrophic wildfires that have major societal, cultural, and economic impacts [*Sharples et al.*, 2016]. The SEA clearly indicates a multiseasonal control of ENSO on fire activity in this region, most likely due to ENSO-related precipitation anomalies. The significant negative departure of SOI during winter and spring of the year preceding the fire season (Figure 3), and the strong relationship between precipitation and ENSO (Figures 1 and 2), indicates that a reduction in water availability in this period is crucial for successful ignition during the following fire season. Likewise, another important factor emerging from this analysis is the ENSO state occurring during

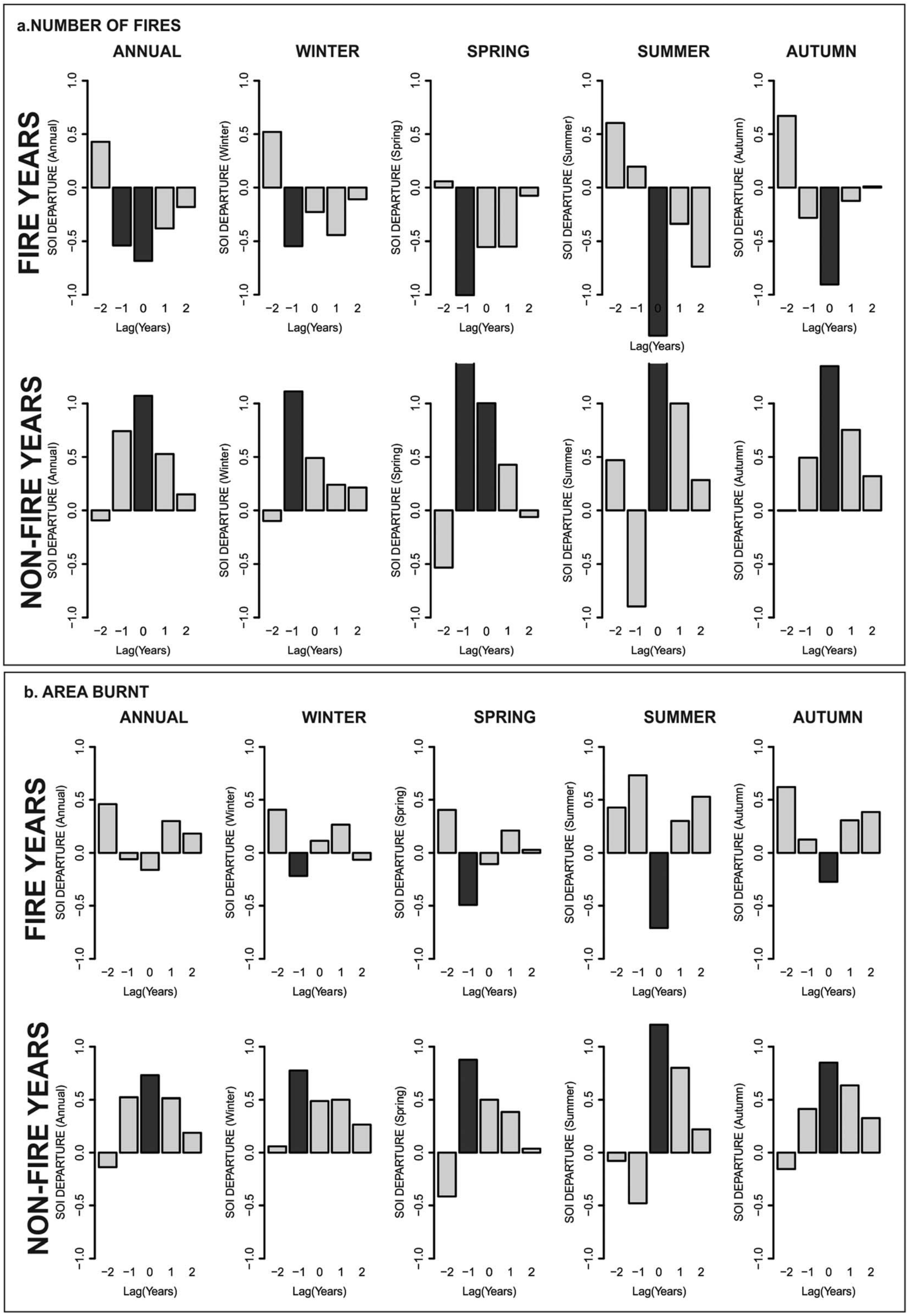

Figure 3. Results from the superposed epoch analysis (SEA) (a) between annual and seasonal SOI and number of fires; and (b) between annual and seasonal SOI and area burnt during fire years and nonfire years. Dark bars indicate lags with a significant SOI departure (p value < 0.05).

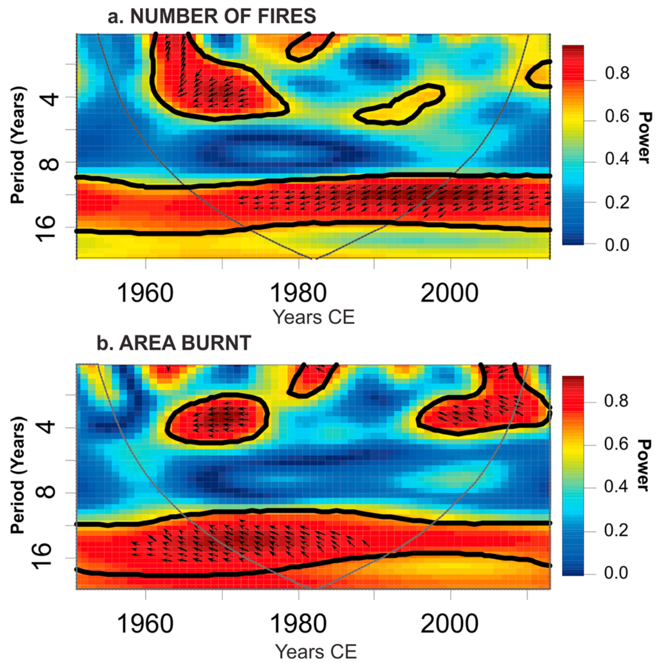

Figure 4. Results from the wavelet coherence analysis for the period 1951–2013 showing (a) coherence between spring-summer SOI and number of fires; (b) coherence between spring-summer SOI and area burnt. Black solid lines indicate areas exceeding the 90% confidence intervals. Leftward arrows indicate that *x* and *y* are anticorrelated; i.e., negative SOI (El Niño) occur in concert with high number of events and with positive anomalies in area burnt at the respective time frequency during the time periods shown in the figures. Dark grey solid line represents the "cone of influence," where edge effects become important.

the fire season: an El Niño condition present during summer and autumn is more likely to result in an increase in both number of fires and area burnt. Moreover, significant nonfire years are correlated with La Niña (high moisture) conditions during the preceding winter and spring and current summer and autumn (Figures 3a and 3b). Interestingly, the results for nonfire years using the number of fires show a significant SOI positive departure at lag −1 and 0. This may relate to the general persistence of a La Niña conditions during consecutive years (Figure 2b). Additionally, we find no evidence for a dominant role of the IOD in governing fire activity across the temperate forest biome of southeast Australia through our analysis period, in direct contrast to the study of *Cai et al.* [2009]. The lack of consistency between our results and that of *Cai et al.* [2009] likely results from the low number of fire seasons ($n = 21$), narrow analysis period (1950–2008) and use of spring-summer Niño 3.4 ENSO index, an index shown to have lower correlation values with Australian rainfall relative to the SOI [*Risbey et al.*, 2009], in the latter analysis.

The strong coherency we have identified in our wavelet analysis at a 12 year periodicity between spring-summer El Niño events and fire activity (area burnt and fire number) throughout most of the analysis period (1963–2000) (Figure 4) indicates, for the first time, a clear and persistent decadal-scale modulation of fire activity in southeast Australia by ENSO. Given the irregular frequency found in the ENSO time series [*An and Wang*, 2000; *Wang*, 2001], it is remarkable that the observed decadal-scale modulation of fire activity by ENSO is fixed throughout the analysis period, highlighting the persistently dominant influence of ENSO over the climate of this highly flammable region, also given the predicted increase in extreme El Niños by the end of this century [*Cai et al.*, 2014]. Further, the wavelet analysis also reveals a clear correlation between temporal shifts in ENSO variability and actual fire activity in southeast Australia. The higher frequency coherence (1–5 years) between 1963 and 1978 also corresponds to a period of maximum ENSO frequency [*An and Wang*, 2000]. Thus, our results reveal that southeast Australia is highly sensitive to shifts in the frequency of variability in the ENSO system and underscores the potential threat of increased fire activity in this region in response to the recent intensification of the ENSO system [*Power et al.*, 2013]. Interestingly, there is an apparent decoupling between the coherence of area burnt and number of fires and the SOI (Figure 4)—i.e., ENSO seems to be having a control on the spread of fires between 1995 and 2003, but another factor is controlling the ignition during this period. It is possible that cultural factors, such as increased awareness, predictive capacity, and subsequent fire suppression efforts (e.g., construction of fire breaks, increased hazard reduction burning, and increased public awareness) actively suppressed ignition events in the latter part of the record. Importantly, the impact of ENSO on preconditioning the landscape for fire spread once a fire starts appears to have been less affected by these cultural adaptations.

Models of future fire activity predict an increase in fire activity under projections of climate change scenarios in temperate forest biomes, such as southeast Australia [*Moritz et al.*, 2012]. Moreover, global temperature increase has the potential to alter the thermal balance in the equatorial Pacific Ocean, driving an increase in the strength and frequency of El Niño events [*Timmermann et al.*, 1999; *Guilyardi*, 2006], a process that is, indeed, already underway [*Power et al*., 2013]. Our identification of both a persistent and nonstationary influence of ENSO over fire activity in southeast Australia has direct and significant implications for managing ecosystem processes and human populations within the ENSO climate domain. Moreover, extreme variability in the Australian climate complicates attempts to understand the impacts of anthropogenic climate change [*Jolly et al*., 2015], and our analysis provides information on the magnitude and temporal variability of climate-driven fire activity that will significantly enhance the detection of persistent changes in a highly variable system. Our identification of a multiseasonal link between supraannual ENSO dynamics and fire activity in southeast Australia reveals that the relationship between ENSO and fire must be considered at multiple scales and for all seasons when planning for future fire activity in this densely populated region.

Our results provide additional evidence for the long-term influence of ENSO over the Earth system. Over the past millennia, ENSO has been implicated in a variety of processes that include terrestrial ecosystem dynamics in eastern Australia [*Donders et al*., 2007] and southwest Tasmania [*Fletcher et al*., 2014, 2015]; storm patterns in New Zealand [*Gomez et al*., 2011]; coral reef systems in the eastern Pacific [*Toth et al*., 2012]; and human cultural change [*Sandweiss et al*., 2001; *Magilligan and Goldstein*, 2001; *Turney et al*., 2006] and fire activity in temperate southern South America [*Whitlock et al*., 2007; *Holz et al*., 2012b] and Tasmania [*Fletcher et al*., 2015; *Rees et al*., 2015]. Importantly, modern ENSO variability is muted, relative to the last few millennia [e.g., *Moy et al*., 2002; *Conroy et al*., 2008; *Yan et al*., 2011], and it is critical that we gain an understanding of how ENSO variability drives changes locally, regionally, and globally if we are to sustainably manage the Earth systems.

5. Conclusion

Under a warming world scenario and a predicted future increase in fire activity across temperate biomes [*Moritz et al*., 2012], ENSO activity is projected to intensify [*Timmermann et al*., 1999; *Guilyardi*, 2006; *Lenton et al*., 2008; *Power et al*., 2013; *Kim et al*., 2014]. This research constitutes the first attempt in disentangling the role of SOI in driving fire activity across the entire southeastern Australian region during the past 60 years using observed wildfire activity data sets. We reveal that El Niño phases (negative SOI) are significantly linked with fire occurrence (number of fires) and area burnt in this region at the interannual scale throughout all seasons (i.e., winter and spring of the year preceding the fire season and during summer and autumn of the fire season year) and a coherent pattern of decadal-scale frequencies over the spring-summer period. The results obtained in this study reveal the seasonal ENSO states as important parameters to consider in fire forecasting and in ecological and palaeoecological interpretations.

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