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Extreme fire weather in Australia and the impact of the El Niño-Southern Oscillation

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This study investigates the influence of the El Niño-Southern Oscillation on fire weather in Australia, including its impact on the severity of seasonal fire danger and on extreme daily fire danger. The meteorological parameters of McArthur's forest Fire Danger Index (FDI) are analysed for composites of years of extreme high and low Southern Oscillation Index (SOI) during the period 1960 to 1992 using eight stations in different climatic zones. Results show that in southeast Australia and in central Australia, seasonal fire danger is higher in years of strong negative SOI and that the daily FDI has a significantly different distribution (with many more days with extreme fire danger). The Southern Oscillation has an opposite but small impact on the daily FDI distribution in the southwest of Australia. Daily minimum relative humidity (RH) is the fire weather parameter that is most strongly influenced by the Southern Oscillation. In southeastern Australia, RH is significantly lower in years of negative SOI.

Introduction

Fire occurrence and climate are inextricably linked (as shown in Swetnam 1993; McCutchen and Main 1989; Griffin et al. 1983). The aspirations of fire managers to increase the accuracy of predictions of fire occurrence have encouraged investigation of statistical relationships between indicators of fire occurrence (such as area burned and fire frequency) and weather variables and climatic indices (such as the Southern Oscillation Index and drought indices) for various fire prone regions in Australia (Krusel et al. 1993; Tapper et al. 1993; Stern and Williams 1989; Love and Downey 1986; Griffin et al. 1983; Foley 1947). However, the connections between the El Niño-Southern Oscillation (ENSO) phenomenon, which is a prime determinant of climatic variability in Australia, and fire danger in Australia have only briefly been addressed (for example, Stern and Williams 1989; Gill 1983). The focus of this study is the question: how does fire weather in a fire season respond to extreme warm and cold phases of ENSO?

The El Niño-Southern Oscillation is a well documented phenomenon involving interaction between the atmosphere and the ocean in the Pacific region (Trenberth 1991; Bjerknes 1969). El Niño may be considered to be the oceanic component and the Southern Oscillation the atmospheric component of the one global ocean-atmosphere oscillation (as portrayed by

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Bjerknes (1969)). It is an oscillation between a 'warm phase' (El Niño) and a 'cold phase' (La Niña) (Philander 1990) of sea-surface temperatures (SSTs) in the tropical eastern Pacific. A 'warm phase' is indicative of positive SST anomalies off the South American Pacific coast and a 'cold phase' is indicative of negative SST anomalies. An indicator of the phase of ENSO is the Southern Oscillation Index (SOI), which is the normalised pressure difference between Tahiti and Darwin (Troup 1965). A high positive value of the SOI (i.e. higher pressure in the east) indicates a 'cold' ENSO episode while a negative SOI (lower pressure in the east) indicates a 'warm' ENSO episode.

ENSO influences regional and global climate (e.g. Nicholls 1988; Rasmusson and Carpenter 1982) and also ecosystems in the Indo-Pacific region (e.g. Nicholls 1991). The influence on Australia's rainfall is particularly strong on the inland eastern side of the continent, in the south during winter and in the north during the monsoon period (Ropelewski and Halpert 1996; Nicholls and Kariko 1993; McBride and Nicholls 1983). Expanding on the SOI / rainfall correlations, Stern and Williams (1989) found a strong relationship between ENSO and a specific meteorologically determined fire risk in Victoria. Contrasting with this, however, Gill (1983) found no correlation in southeastern Australia between SOI and the soil dryness index (a component of fire danger indices), area burned, or the number of fires in a given time period.

In order to clarify the influence of ENSO on fire weather and fire danger in Australia, we have computed the McArthur forest Fire Danger Index (FDI) from daily meteorological observations at eight representative sites in different fire and climatic regions in Australia. The definition of the FDI and the reasons for the choice of the eight sites are given in the next section. Composites of years with extreme high and low fire danger are used to identify the influence of different weather parameters on the FDI. Also, composites of years with extreme high and low SOI are used to show the influence of ENSO on seasonal fire danger and on the distribution of daily fire danger. The final section summarises and concludes the main findings of the research.

Methods

Definition of fire danger

The tool used here to indicate fire danger on a national scale is the McArthur Forest Fire Danger Index Mark 5 (McArthur 1967).

$$\mathrm{FDI} = 1.275D^{0.987}\exp(0.0338T+0.0234V-0.0345H)$$

where T is maximum air temperature (°C), V is maximum wind speed (km/h), H is minimum relative humidity (%), D is a drought factor

$$D = 0.191\,(I+104)\,(N+1)^{1.5} / (3.52\,(N+1)^{1.5} + R-1)$$

where I is the Keetch-Byram Drought Index (Keetch and Byram 1968), R is precipitation (mm), and N is the number of days since rain. (Equations from Noble et al. (1980).)

This meter was originally designed for general forecasting purposes in southeastern Australia and was intended to be interpreted as indicative of the chances of a fire starting, its rate of spread, fire intensity and difficulty of suppression. However, it is also a valid indicator of fire danger over the entire continent which can be used for comparison of intraseasonal and interannual fire danger variability. It must be emphasised that this is not an assessment of actual fire occurrence but rather the climatological conditions conducive to severe fire danger.

Site selection

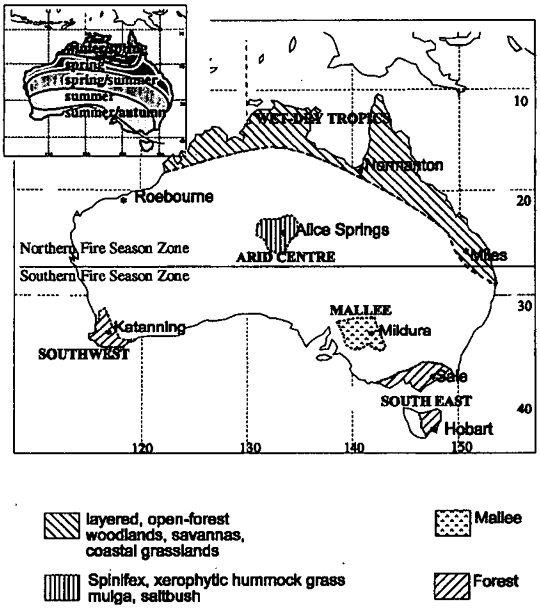
The distribution and number of meteorological observing stations used in this study was determined by using selection criteria based primarily on the location of fire zones from Luke and McArthur (1978), the length of station records available (at least from 1960 to 1992), and the location of vegetation zones. Eight sites were selected, with their locations shown in Fig. 1 and other details shown in Table 1. Each of the five zones based on fire seasons as defined by Luke and McArthur (1978) are represented (although slightly different fire seasons are used here). Five biogeographical regions are represented (Pyne 1995; Gill et al. 1981). Each station is assumed to be representative of a large area, which is reasonable given that climatic variations usually involve large spatial scales.

Data

Archived data from each observing station were obtained from the National Climate Centre (NCC), Australian Bureau of Meteorology. The meteorological data obtained were daily rainfall, three-hourly temperature, three-hourly wind speed, and three-hourly dewpoint temperatures from 1960 to 1992. Daily minimum relative humidity is calculated from the temperature and dew-point temperature at the time when the maximum temperature was recorded.

Monthly mean values of the SOI (the Troup SOI) were also obtained from the NCC. The Troup SOI is the standardised anomaly of the surface pressure between Tahiti and Darwin. Annual mean SOI was calculated by averaging the monthly SOI values for the 12 months from April to the following March. The 12 months from April to March rather than the usual January-December year is more appropriate because it captures the ENSO warm and cold episodes starting early in the calendar

Fig. 1 **The location of the eight sample sites, the schematic boundaries of the four biogeographical zones (shaded), and the two fire season zones. The inset indicates the boundaries of fire seasons as defined by Luke and McArthur (1978). Severe fires in lower latitudes occur predominantly in winter/spring, and in summer/autumn in higher latitudes.**



year and finishing early in the following year (e.g. Ropelewski and Halpert 1987; Rasmusson and Carpenter 1982).

Fire seasons

Fire occurrence and fire danger in Australia is highly seasonal. Luke and McArthur (1978) illustrate the seasonal progression southward of fire season zones. In this paper, two fire seasons are used for the entire continent in order to provide a common reference: a northern fire season (July to November inclusive at the sites Miles, Alice Springs, Normanton and Roebourne) and a southern fire season (November to March inclusive at Mildura, Sale, Hobart and Katanning). The sum of the daily FDI for the entire season is called the seasonal cumulative FDI (seasonal ΣFDI). Severe fire weather outside the fire seasons is considered to be inconsequential in terms of influencing patterns of interannual fire danger.

Extreme high and low fire danger

The impact of the different weather parameters on the variation of seasonal ΣFDI at each of the eight sites between 1960 and 1992 was determined by comparing the composite of the six years of highest seasonal ΣFDI with the composite of the six years of lowest seasonal ΣFDI. The differences between the seasonal means of each composite for each weather parameter and the annual SOI are summarised in Table 2. The pattern that each parameter forms is striking in its consistency over the eight sites. The difference in mean values of variables is not always statistically significant, but there is a consistent direction of change. At all sites in the years with extreme high seasonal ΣFDI, rainfall is lower than in the low FDI composite; maximum temperature is higher; minimum relative humidity is lower; wind speed is higher; and, except for Katanning, the SOI is negative.

The amount by which the variables differ between the two composites of extreme years varies between each station. Comparing the composites of extreme low and high seasonal ΣFDI, Alice Springs has the greatest difference in seasonal ΣFDI (closely followed by Mildura and Roebourne). Alice Springs also has the greatest difference in SOI. Hobart has the greatest difference in rainfall, Miles has the greatest difference of minimum relative humidity, and Roebourne has the greatest difference in temperature. Normanton has the greatest difference in wind speed, closely followed by Roebourne.

Table 1. Stations used in the analysis. Daily data from 1960 to 1992 is used.

Station name	*Station number*	*Symbol*	*Latitude*	*Longitude*	*Fire season*
Hobart	94029	H	42°49'S	147°6'E	Nov-March
Sale	85072	S	38°7'S	147°0'E	Nov-March
Mildura	76031	MD	34°13'S	142°5'E	Nov-March
Katanning	10579	K	33°40'S	117°32'E	Nov-March
Miles	42023	M	26°35'S	150°18'E	July-Nov
Alice Springs	15590	A	23°42'S	133°58'E	July-Nov
Roebourne	4035	R	20°43'S	117°10'E	July-Nov
Normanton	29041	N	17°52'S	140°58'E	July-Nov

Table 2. Changes of weather parameters between composites of years of extreme high and low fire danger. If a parameter in the high FDI composite has a higher mean than in the low FDI composite, then the site is listed under 'High values', and vice-versa for lower means. Differences between the composite mean values which are significant at the 90% level using Student's two-tailed t test are indicated. Each site is represented by the first letter in its name, apart from Mildura shown by MD.

Variable	*Low values*			*High values*		
	Significant	*Not significant*	*Total*	*Significant*	*Not significant*	*Total*
rainfall	K,H,A,M,S,N,MD	R	8			0
temp			0	R,A,M,S,N,MD	K,H	8
RH	K,R,H,A,M,S,N,MD		8			0
wind			0	R,H,A,S,N,MD	K,M	8
SOI	H,A,S,N	R,MD,M	7		K	1

Relationships between seasonal ΣFDI and fire weather and SOI

Correlations of the interannual variations of the different variables shown in Table 3 indicate the relationships between seasonal ΣFDI and fire weather and annual SOI. At most stations seasonal minimum relative humidity has the greatest correlation with ΣFDI. At the stations in the eastern and southeastern regions of Australia and at Alice Springs, an average of approximately 85 per cent of the variance in the seasonal ΣFDI is accounted for by minimum relative humidity. However, this relationship is weaker at the two northernmost stations, Normanton and Roebourne. The interannual variability of seasonal ΣFDI at these two stations is more strongly influenced by wind speed.

There are clear climatological similarities between Hobart, Sale and Mildura. As shown in Table 3, rainfall, temperature, and the SOI are similarly related to the seasonal ΣFDI at each of these three sites. The correlations between seasonal ΣFDI and these three variables at Alice Springs are similar to those at Hobart, Sale and Mildura. The similar interannual variability between different stations indicates large-scale influences, and these are expanded upon later.

Extreme SOI and fire danger

In order to analyse extreme SOI events, composites of the six years with most negative annual SOI and with the most positive annual SOI were compiled. The years used in these SOI composites are listed in Table 4. The typical biennial cycle of ENSO variability is seen in the selection of years in the composites. Warm ENSO episodes are often preceded or followed by cold ENSO episodes, and vice-versa.

Although the differences in the seasonal ΣFDI and fire weather parameters between the positive and negative SOI composites are not always statistically significant, there are important consistencies in the direction of change (see Table 5 and Fig. 2). In agreement with the previously mentioned studies on the influence of SOI on rainfall in Australia, in the composite of extreme negative SOI years, rainfall is lower than in years of positive SOI. Also, the temperature is higher in the negative SOI composite, minimum relative humidity is lower, wind speed is higher, and seasonal ΣFDI is higher. SOI fluctuations have the strongest influence on the fire season relative humidity (as shown in Fig. 2(c)). Rainfall is also strongly affected but, unlike relative humidity values,

Table 3. Correlations between interannual variations of seasonal ΣFDI and fire weather parameters

Station	*Rainfall*	*Temp*	*Relative humidity*	*Wind speed*	*SOI*
Hobart	-0.74	0.47	-0.90	0.62	-0.50
Sale	-0.75	0.57	-0.94	0.51	-0.51
Mildura	-0.70	0.65	-0.92	0.53	-0.58
Katanning	-0.41	0.54	-0.73	0.42	-0.06
Miles	-0.52	0.61	-0.93	0.34	0.01
Alice Springs	-0.86	0.70	-0.92	0.36	-0.38
Roebourne	-0.32	0.50	-0.42	0.64	-0.26
Normanton	-0.55	0.47	-0.57	0.63	-0.34

Table 4. **Years used for the high SOI and low SOI composites during 1960-92.**

High SOI years	1970, 1971, 1973, 1974, 1975, 1988
Low SOI years	1965, 1972, 1977, 1982, 1987, 1991

the differences in seasonal rainfall totals of the high and low SOI composites are not statistically significant (shown in Fig. 2(d)). However, the SOI does affect the seasonal rainfall at more stations (7 stations) than it does the relative humidity (5 stations).

In the previous section it was demonstrated that the interannual variation of relative humidity has a strong influence on seasonal ΣFDI. Figure 3 shows the relationship between seasonal ΣFDI and relative humidity at a sample of the eight stations (this is a sample of stations with the widest range of relationships), and highlights significant variations due to extreme SO phases. The relationship between relative humidity and seasonal ΣFDI is strongest (r = -0.9) at the three southeast stations, Alice Springs and Miles. Except for Miles, the SOI has a significant effect on the relative humidity at these stations.

Fig. 2 **Differences of fire weather parameters between six-year composites of extreme negative SOI years and positive SOI years in 1960-92. The asterisk indicates that the difference between the two groups of years is significant at the 90% level (using Student's two-tailed t-test). (a) Mean seasonal ΣFDI. (b) Seasonal mean of daily maximum temperature. (c) Seasonal mean of daily minimum relative humidity. (d) Mean seasonal rainfall.**

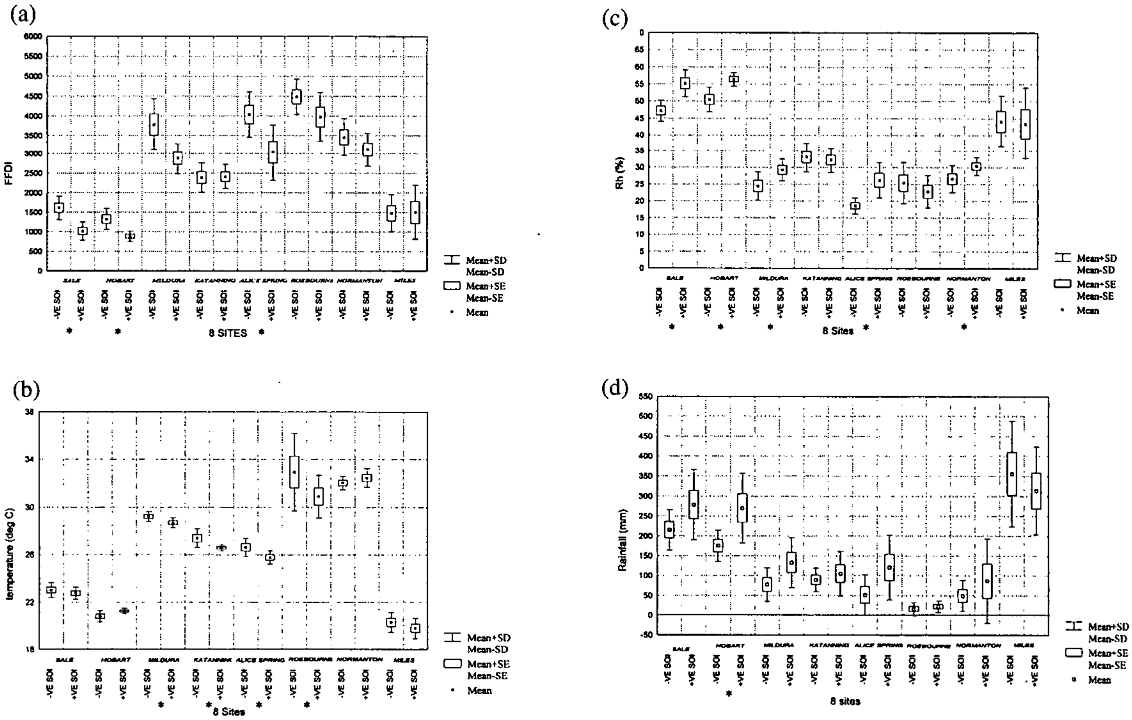


Table 5. **Changes of weather parameters and FDI for composites of years of extreme high SOI values relative to years with low SOI. Otherwise, as for Table 2.**

Variable	*Low values*			*High values*		
	Significant	*Not significant*	*Total*	*Significant*	*Not significant*	*Total*
rainfall		M	1	H	S,MD,K,A,R,N	7
temp	MD,K,A,R	S,M	6		H,N	2
RH		K,R,M	3	S,H,MD,A,N		5
wind	H	S,MD,A,R	5		K,N,M	3
ΣFDI	S,H,A	MD,R,N	6		K,M	2

Fig. 3 **The relationship between seasonal ΣFDI and relative humidity at Alice Springs and Miles in the northern fire season zone and Mildura and Sale in the southern fire season zone during the period 1960-92. The cross (X) highlighted by the arrow indicates the average seasonal ΣFDI and relative humidity for a composite of extreme SOI events.**

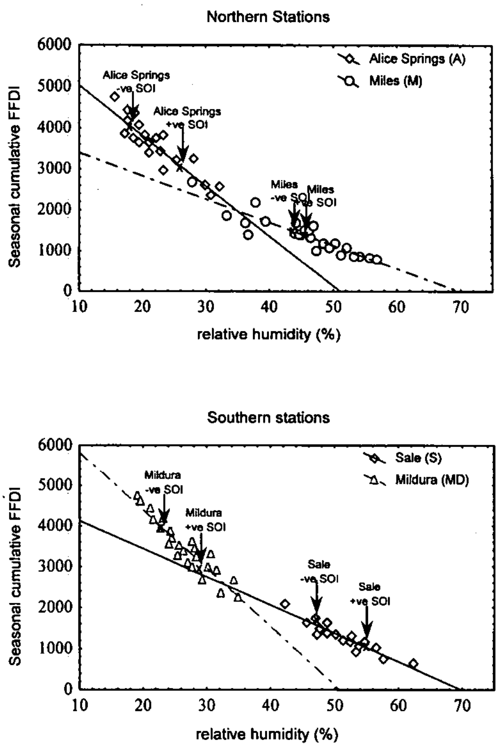
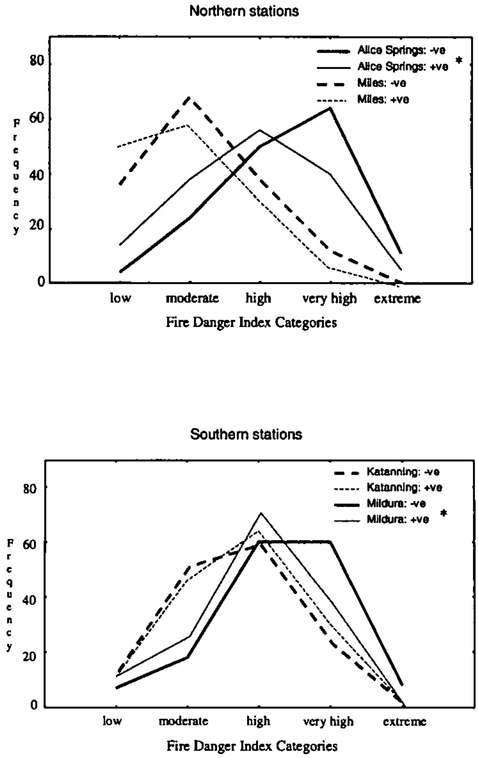


Fig. 4 **The distribution of daily FDI in extreme negative SOI years (SOI -ve) and extreme positive SOI years (SOI +ve) in the period 1960-92 at Alice Springs and Miles in the northern fire season zone, and Katanning and Mildura in the southern fire season zone. The asterisk indicates that the difference between the frequency distributions of the two SOI composites is significant at the 90% level (using the chi-squared test). The other four sites not shown have distributions that are similar to those displayed.**



Seasonal ΣFDI is a useful tool for comparing seasonal fire danger severity. It is of more use if it is combined with the impact of ENSO on the change in the frequency distribution of daily FDI events, especially the number of extremely high FDI days. The frequency distributions of daily FDI for a sample of the eight sites for the two ENSO composites are shown in Fig. 4.

Three clear conclusions can be drawn from the analysis of frequency distributions. First, the strongest differences (that is, the statistically significant differences) between years of positive SOI and years of negative SOI consistently occur at Sale, Hobart, Mildura, and Alice Springs where there are a greater number of extreme FDI days in the negative SOI composite. Second, at Normanton, Roebourne and Miles the trend is not as well defined but indicates that more days with higher FDI occur in the negative SOI composite. Third, the opposite is observed at Katanning where there are more extreme FDI days in the positive SOI composite, but the change is not significant.

Comparing the frequency distributions of daily values of the four meteorological parameters, ENSO had the greatest impact on minimum relative humidity. As with daily FDI, the most significant effect is seen at Sale, Mildura, Hobart, and Alice Springs. The changes at these four stations are all in the same direction: in years of extreme negative SOI there are more days of low minimum relative humidity and more days of high FDI.

From the above discussions it is clear that some stations have similar features in terms of the relationships between seasonal ΣFDI and fire weather parameters (inter-station correlations are not shown here). In the southern fire season zone, the three southeastern stations Hobart, Sale and Mildura have significantly correlated seasonal ΣFDI. In the northern zone, Alice Springs, Miles, and Normanton have significantly correlated seasonal ΣFDI. The strongest correlations are between Sale and Hobart, and Sale and Mildura. Neither of the west coast stations (Katanning and Roebourne) correlate with any other of the eight stations. Fire weather parameters do not correlate between stations as well as seasonal ΣFDI does. There are however significant correlations between some stations. Hobart and Sale have the most similar influences on fire weather. Rainfall, temperature, and humidity are all significantly correlated between these two stations.

Conclusions

There is a direct association between ENSO and fire danger at most of the selected sites in Australia. At six of the eight study sites there is a more severe season of fire danger in the years of extreme negative SOI compared to that of positive SOI. The strongest relationship is in southeast Australia and at Alice Springs. At these sites, there are at least twice as many days with very high fire danger in years of negative SOI than in years of positive SOI. The interannual variability of the FDI meteorological parameters is also clearly influenced by ENSO. Minimum relative humidity is the fire weather parameter most strongly influenced by ENSO and Hobart is the site with the most parameters influenced by ENSO. The effect of ENSO on minimum relative humidity is greatest at Alice Springs and the three southeast stations. The number of days of low minimum relative humidity increases in warm ENSO events.

Generally, the fire weather parameters at all the sites displayed similar responses to ENSO. However Katanning, in the southwest of Western Australia, is the exception as the fire weather parameters there showed little response to ENSO.

Given the common evolution of ENSO warm episodes, usually starting in the first half of one calendar year and persisting through the following summer, the results from this study can be used to provide guidance on increased fire danger in southeastern Australia and central Australia. However, the correlations in Table 5 indicate that a large fraction of the interannual variability of fire danger at these sites is not associated with ENSO. In addition, actual fire occurrence depends on many factors apart from fire danger, including vegetation type and fuel load (for example, in Victoria the severe 1938-39 season was not associated with an ENSO event). Hence fire activity will depend on these factors as well as the influence of ENSO and other natural climate variations on fire danger.

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