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Multi-decadal variability of forest fire risk—eastern Australia

Danielle C. Verdon[A,B], *Anthony S. Kiem*[A] *and Stewart W. Franks*[A]

[A]School of Engineering, University of Newcastle, NSW 2308, Australia.
[B]Corresponding author. Telephone: +61 2 4921 6058; fax: +61 2 4921 6991;
email: danielle.verdon@studentmail.newcastle.edu.au

Abstract. This study investigates the influence that the El Niño/Southern Oscillation (ENSO) and the Inter-decadal Pacific Oscillation (IPO) have on long term daily weather conditions pertinent to high forest fire danger in New South Wales, Australia. Using historical meteorological data for 22 weather stations to compute the daily value of McArthur's Forest Fire Danger Index (FFDI), it is shown that a strong relationship exists between climate variability, on a range of time scales, and forest fire risk. An investigation into the influence of ENSO on fire risk demonstrates that the proportion of days with a high, or greater than high, fire danger rating is markedly increased during El Niño episodes. More importantly, this study also shows that the already significantly enhanced fire danger associated with El Niño events was even further increased during El Niño events that occurred when the IPO was negative. The potential to use simple indices of climate variability to predict forest fire risk is therefore demonstrated to be significant.

Additional keywords: El Niño/Southern Oscillation (ENSO); Inter-decadal Pacific Oscillation (IPO); Pacific Decadal Oscillation (PDO); bushfire; climate variability.

Introduction

The incidence of forest fires in Australia poses a significant threat to lives and property. Devastating forest fires have been found to occur during specific meteorological conditions. 'Fire weather' is a convenient term to use when reference is made to the effect of climate and weather conditions on the chances of a fire starting, its behaviour and the difficulty of suppression. The weather variables that generally increase the risk of forest fires are low precipitation and relative humidity combined with high temperature and wind speed (Luke and McArthur 1986). The high variability of rainfall and temperature in northern and eastern Australia has been strongly associated with the regional influence of the El Niño/Southern Oscillation or ENSO (e.g. Ropelewski and Halpert 1987; Allan 1988; Stone and Auliciems 1992; Kiem and Franks 2001). These studies indicate that large-scale climate variability on an annual/interannual time-scale influences at least two of the four weather variables that contribute to forest fire risk in Australia.

In addition to the annual/interannual effects of ENSO, a number of studies have also examined decadal and longer scale climate variability. Observational records suggest that the Inter-decadal Pacific Oscillation (IPO) modulates the strength and nature of the ENSO cycle (Power *et al*. 1998, 1999; Folland *et al*. 1999; Allan 2000). The IPO is the coherent pattern of sea surface temperature variability occurring on inter-decadal time scales over the Pacific Ocean and is similar to the Pacific Decadal Oscillation or PDO (Mantua *et al*. 1997; Franks 2002*a*). Importantly, Power *et al*. (1999) showed that individual ENSO events (i.e. El Niño and La Niña) had stronger impact across Australia during the negative phase of the IPO. Furthermore it has recently been shown that, in addition to influencing the magnitude of ENSO impacts, the IPO also appeared to modulate the frequency of extreme ENSO events, leading to multi-decadal periods of elevated flood or drought risk depending on the phase of the IPO (Franks 2002*b*; Franks and Kuczera 2002; Kiem and Franks 2004; Kiem *et al*. 2003). However, whilst the relationship between ENSO and fire risk has been studied briefly (Love and Downey 1986; Williams and Karoly 1999), the influence that decadal/multi-decadal climate variability has on forest fire risk has not been investigated prior to this study.

In this study the Forest Fire Danger Index (FFDI), developed by McArthur (1967), is used to assess the daily risk of forest fire in New South Wales (NSW), Australia. The influence of ENSO on NSW forest fire risk is then evaluated by comparing the proportion of days with a high (or greater) fire danger rating based on the FFDI, during El Niño and non-El Niño years. In addition, multi-decadal IPO enhancement

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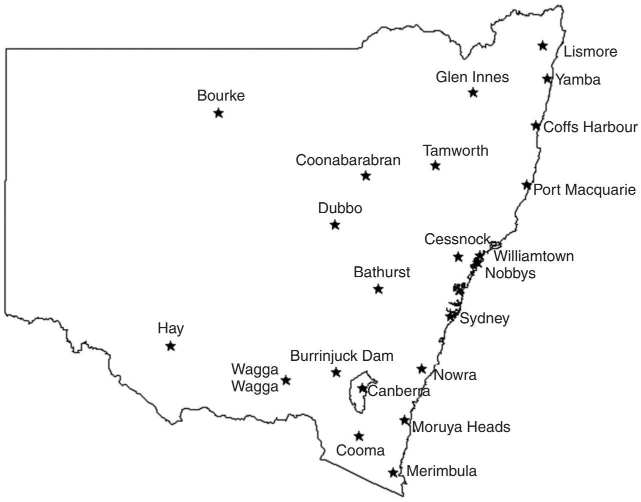

Fig. 1. Location of the 22 study sites within New South Wales, Australia.

of El Niño events, and hence elevated forest fire risk, is also assessed. This is achieved by comparing the fraction of days with a high (or greater) fire danger rating during IPO negative El Niño years with the fraction of high (or greater) fire risk days in all other El Niño years.

Data

Daily data records for precipitation, maximum temperature, dewpoint temperature and average wind speed were obtained from the Australian Bureau of Meteorology for 22 weather stations located across NSW (Fig. 1). Daily relative humidity is then calculated from the daily maximum temperature and the corresponding dew-point temperature. The selection of the study sites is primarily based on the length of meteorological data available. It is also desirable to obtain a number of stations that are positioned so as to observe spatial trends across NSW. As can be seen from Fig. 1, very few stations are available in the middle and western thirds of NSW.

Definition of fire danger

The fire danger rating employed in this study is based on the FFDI, which is designed for general fire danger forecasting purposes and is in common use throughout eastern Australia. The FFDI provides an assessment of the chances of a fire starting, its rate of spread, fire intensity and difficulty of suppression (Noble *et al.* 1980). It is important to note that the FFDI does not provide a measure of actual forest fire events, but rather the climatological conditions associated with severe fire danger. The fire danger rating for any given day is determined based on the daily value of the FFDI, as shown in Table 1. Throughout the remainder of this paper the term 'high' fire danger will be taken to mean high, very high or extreme fire danger (i.e. FFDI > 12).

Table 1. Fire danger ratings based on the Forest Fire Danger Index (FFDI)

Forest fire danger index	Fire danger rating
0–5	Low
5–12	Moderate
12–24	High
24–50	Very high
50–100	Extreme

The daily FFDI value is calculated using the equations provided by Noble *et al.* (1980) and shown below:

$$FFDI = 2.0 \times \exp(-0.450 + 0.987 \times \ln(D) - 0.0345 \times H + 0.0338 \times T + 0.0234 \times V), \quad (1)$$

where H is the minimum relative humidity in percent, T is the maximum air temperature in 24 h in °C, V is the average wind velocity (km h^{-1}) in the open at a height of 10 m, and D is the drought factor for that day. The drought factor (D) is a discontinuous variable obtained using the Keetch-Byram Drought Index (KBDI, Keetch and Byram 1968). The equation used to derive the drought factor is shown below:

$$D = \frac{0.191 \times (I + 104) \times (N + 1)^{1.5}}{(3.52 \times (N + 1)^{1.5} + P - 1)}, \quad (2)$$

where I is the daily KBDI, P is the daily precipitation (in mm), and N is the number of days since rain.

Methods

To determine the probability of daily 'high' fire risk in any year, regardless of ENSO or IPO, the proportion of days between September and February, inclusive, with a fire danger rating of 'high' (FFDI > 12) is calculated for each station over the period that data are available. Only the spring and summer months (September to February) are investigated, as this is generally the period of peak forest fire activity for NSW (Luke and McArthur 1986).

The impact of ENSO on forest fire risk is assessed by classifying all years, and the corresponding proportions of days with a 'high' fire danger rating, as either El Niño, La Niña or Neutral based on the 6-month October to March average Multivariate ENSO Index (MEI) value. The MEI, developed by Wolter and Timlin (1993, 1998) is derived from multiple climate parameters and has been shown to reflect the nature of the coupled ocean–atmosphere system better than either the Southern Oscillation Index or sea surface temperature based indices (Kiem and Franks 2001). The probability of daily 'high' fire risk during El Niño years is then determined by calculating the proportion of days with FFDI > 12 for all El Niño years during the September to February forest fire season at each study site. A similar process is performed to determine the probability of daily 'high' fire risk during non-El Niño years and the results are compared.

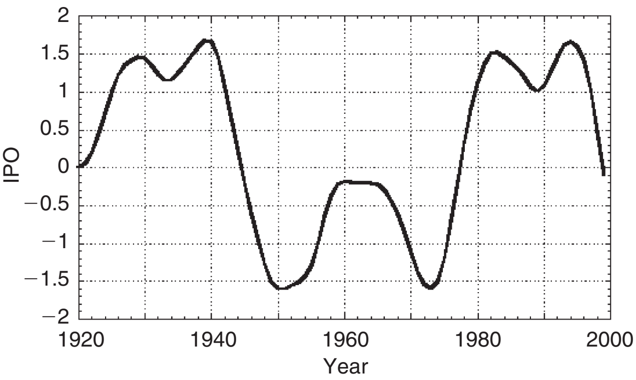

Fig. 2. The Inter-decadal Pacific Oscillation (IPO) from 1920 to 1999.

The probability of daily 'high' fire danger (FFDI > 12) in El Niño years occurring in the negative IPO periods, when ENSO impacts are enhanced, is then compared with the probability of 'high' fire danger in all other El Niño years to determine whether there is a significant difference. To achieve this the El Niño years, and the corresponding proportions of days with a 'high' fire danger rating, are further stratified based on the IPO and the method used by Power *et al.* (1999). In classifying the different IPO phases, Power *et al.* (1999) used the thresholds of ±0.5 to distinguish positive, neutral and negative IPO phases. Figure 2 shows the time series of the IPO from 1920 to 1999. During this period there have been three major phases of the IPO: Two positive phases (IPO > 0.5) between 1924–1943 and 1979–1997 and a negative phase (IPO < –0.5) from 1946 to 1976. These phases exclude the 10 years from 1958 to 1967 when the absolute value of the IPO index was less than 0.5. Only 14 of the 22 study sites had sufficiently long records of 'fire weather' variables for the IPO analysis to be performed.

To further investigate the magnitude of fire risk associated with IPO-negative El Niño years, due to the IPO induced amplification of El Niño impacts (Power *et al.* 1999), the probability of daily 'high' fire danger in IPO negative El Niño years and all non-El Niño years is also compared.

Results

Figure 3 shows the probability of having a day associated with a 'high' fire danger rating (FFDI > 12) during the September to February forest fire season at each of the 22 study sites. Figure 3 demonstrates that some degree of 'high' fire risk exists at all stations; however, the magnitude of risk varies considerably. The results show that the occurrence of days with a 'high' fire risk rating is generally lower along the coast than it is at the inland stations. This is because rainfall totals and relative humidity tend to be higher at coastal locations while temperatures are generally lower than they are inland. The low probability of 'high' fire risk observed at Glen Innes (altitude ~1062 m) also suggests that increased elevation reduces the risk of forest fire, for non-coastal stations.

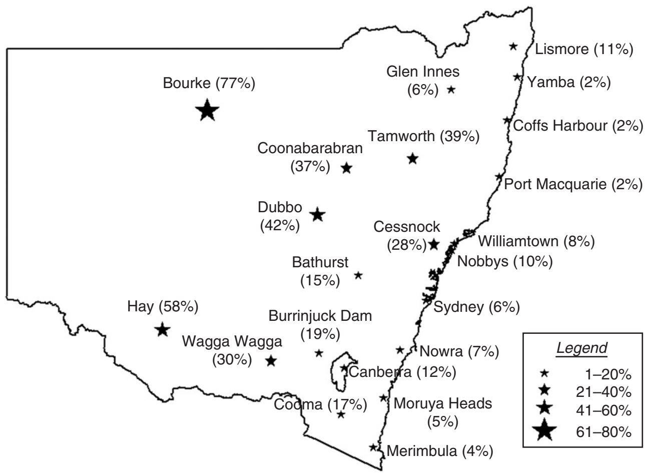

Fig. 3. Percentage of days with 'high' fire risk (FFDI > 12) at each of the 22 study sites.

This is due to rainfall and humidity levels being increased at higher altitudes, whilst temperatures tend to be lower (Tapper and Hurry 1993).

The probability of daily 'high' fire risk during El Niño and non-El Niño years is examined to determine the impact that ENSO has on fire risk at each study sites. The average proportion of days with 'high' fire risk during El Niño and non-El Niño years (i.e. La Nina or Neutral) are compared to determine whether there is any significant difference between El Niño and non-El Niño phases. To test this hypothesis a simple test of proportions is applied (Hogg and Tanis 1988). It is assumed that the sampling distribution of the proportion of El Niño days with 'high' fire danger can be approximated by a normal distribution with a mean of p and a variance of $p(1 - p)/n$, where p is the proportion of El Niño days with FFDI greater than 12, calculated using $p = y/n$, where y is the number of El Niño days with FFDI greater than 12 and n is the total number of El Niño days for the period being investigated. The same calculations were performed for non-El Niño events.

In order to determine whether the probability (P_1) of having a day in an El Niño with FFDI greater than 12 is significantly different from the probability (P_2) of having a day in a non-El Niño year with FFDI greater than 12, the following statistical test is used (Hogg and Tanis 1988). Let y_1 represent the number of El Niño days with FFDI greater than 12 that occurred in the n_1 El Niño days from the period being investigated. Let y_2 be the number of non-El Niño days with FFDI greater than 12 that occurred in the n_2 non-El Niño days during the same period. The test statistic used to test the hypothesis that P_1 equals P_2 is:

$$z = \frac{|p_1 - p_2|}{\sqrt{p(1-p)(1/n_1 + 1/n_2)}}, \qquad (3)$$

where $p_1 = y_1/n_1$, $p_2 = y_2/n_2$, $p = (y_1 + y_2)/(n_1 + n_2)$ and $z \sim N(0,1)$.

Table 2. Results obtained when the daily probability of 'high' fire risk during El Niño years (p_1) is compared to non-El Niño years (p_2)

The P-value indicates the probability that p_1 is equal to p_2 with significance at the <5% and <1% level represented by * and ** respectively

Station	Probability of 'high' fire danger in El Niño years (p_1)	Probability of 'high' fire danger in non-El Niño years (p_2)	p_1/p_2	P-value
Bathurst	0.186	0.134	1.387	0.000**
Bourke	0.846	0.748	1.131	0.000**
Burrinjuck Dam	0.236	0.169	1.402	0.000**
Canberra	0.206	0.093	2.212	0.000**
Cessnock	0.374	0.247	1.510	0.000**
Coffs Harbour	0.028	0.020	1.349	0.026*
Cooma	0.228	0.143	1.591	0.000**
Coonabarabran	0.449	0.331	1.356	0.000**
Dubbo	0.524	0.384	1.367	0.000**
Glen Innes	0.069	0.059	1.175	0.057
Hay	0.633	0.562	1.126	0.000**
Lismore	0.134	0.094	1.422	0.000**
Merimbula	0.080	0.030	2.699	0.005**
Moruya Heads	0.069	0.037	1.856	0.000**
Nobbys	0.125	0.094	1.328	0.001**
Nowra	0.100	0.056	1.790	0.000**
Port Macquarie	0.026	0.020	1.292	0.059
Sydney	0.091	0.054	1.698	0.000**
Tamworth	0.487	0.350	1.392	0.000**
Wagga Wagga	0.391	0.274	1.426	0.000**
Williamtown	0.112	0.074	1.519	0.000**
Yamba	0.024	0.022	1.114	0.256

Table 2 shows, for each of the 22 study sites, the proportion of days with 'high' fire risk during El Niño (p_1) and non-El Niño (p_2) years, with the probability that these proportions are equal indicated by the p-value. To further illustrate the effect of ENSO on fire risk, the ratio of the probability of 'high' fire risk during El Niño years to non-El Niño years is also calculated. This represents the increase in probability of a 'high' fire danger day occurring during an El Niño year when compared to a non-El Niño year. For example a p_1/p_2 value of 1.5 demonstrates that the chance of a 'high' fire risk day occurring in an El Niño year is 50% greater than it is in a non-El Niño year. The ratio of p_1/p_2 for each study site is also shown in Table 2 and the percentage increase in the probability of daily 'high' fire risk during an El Niño is displayed in Fig. 4.

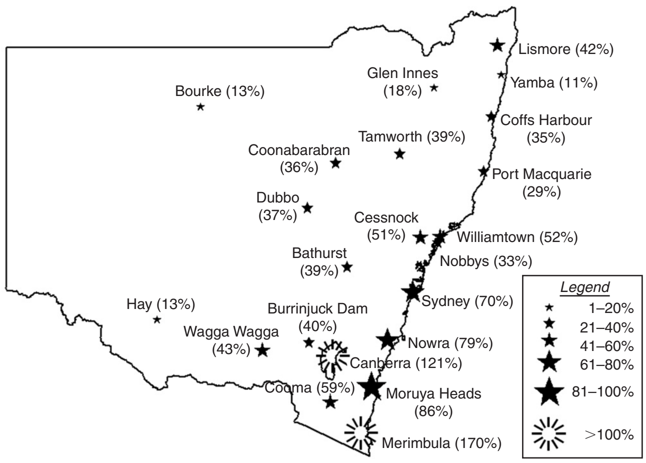

Fig. 4. Percentage increase in the probability of daily 'high' fire risk during El Niño years when compared to non-El Niño years.

It can be seen from Table 2 that the probability of daily 'high' fire danger during El Niño years is significantly different from non-El Niño years at the <1% level for all stations except Coffs Harbour, Glen Innes, Port Macquarie and Yamba (with the difference at Coffs Harbour significant at the <5% level). Figure 4 demonstrates that the probability of daily 'high' fire danger is markedly increased during El Niño years at all stations investigated. The increase in the probability of 'high' fire danger, when El Niño years are compared to all other years, averaged across the 22 study sites is 51%. The influence of El Niño appears to be strongest in the south-eastern corner of NSW and weaker in the west, with Canberra and Merimbula displaying an increase in forest fire risk of 121% and 170% respectively, during El Niño years compared to 13% at Bourke and Hay.

Table 3 shows, for the 14 study sites whose 'fire weather' data records spanned both negative and non-negative IPO phases, the proportion of days with 'high' fire risk during El Niño years occurring when the IPO is negative (p_1) and during all other El Niño years (p_2), with the probability that

Table 3. Results obtained when the daily probability of 'high' fire risk during El Niño years occurring in the negative IPO phase (p_1) is compared to all other El Niño years (p_2)

The P-value indicates the probability that p_1 is equal to p_2 with significance at the <5% and <1% level represented by * and ** respectively

Station	Probability of 'high' fire danger in negative IPO El Niño years (p_1)	Probability of 'high' fire danger in all other-El Niño years (p_2)	p_1/p_2	P-value
Bourke	0.991	0.779	1.271	0.000**
Canberra	0.232	0.198	1.172	0.044*
Coffs Harbour	0.052	0.020	2.630	0.000**
Coonabarabran	0.527	0.423	1.246	0.000**
Dubbo	0.547	0.517	1.059	0.109
Hay	0.676	0.619	1.093	0.008**
Lismore	0.173	0.119	1.456	0.001**
Moruya Heads	0.098	0.059	1.659	0.001**
Nobbys	0.182	0.105	1.730	0.000**
Nowra	0.155	0.080	1.938	0.000**
Port Macquarie	0.042	0.020	2.095	0.002**
Sydney	0.142	0.075	1.897	0.000**
Tamworth	0.514	0.479	1.074	0.077
Yamba	0.044	0.018	2.487	0.000**

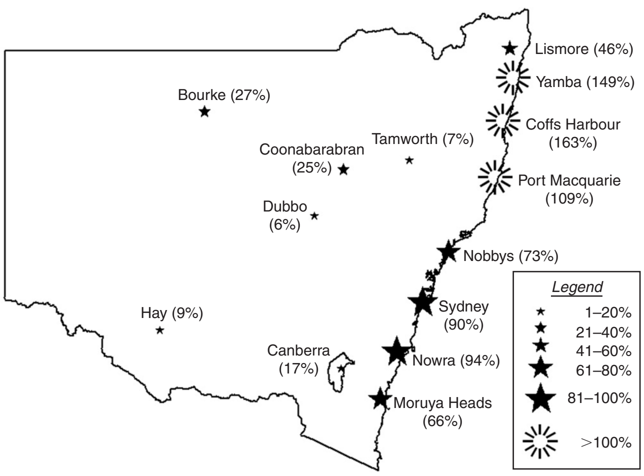

Fig. 5. Percentage increase in the occurrence of daily 'high' fire risk associated with El Niño and IPO negative years compared to all other El Niño years.

these proportions are equal indicated by the p-value. The ratio p_1/p_2 is again calculated to show the increase in fire risk associated with El Niño events that occur when the IPO is negative. Figure 5 displays the percentage increase in the probability of daily 'high' fire risk during IPO negative El Niño years when compared with all other El Niño years.

Table 3 demonstrates that the proportion of days with 'high' fire risk during El Niño years that occur when the IPO is negative is significantly different (at the <1% level) from the proportion during all other El Niño years at 11 of the 14 stations studied (with the difference at Canberra significant at the <5% level). Figure 5 shows that the probability of 'high' fire risk increases during IPO negative El Niño years at all stations studied.

Table 4 shows, for the 14 study sites, the proportion of days with 'high' fire risk during IPO negative El Niño years (p_1) and during all non-El Niño years (p_2), with the probability that these proportions are equal indicated by the p-value. The ratio p_1/p_2 is again calculated to show the increase in fire risk associated with El Niño events that occur when the IPO is negative. Figure 6 displays the percentage increase in the probability of daily 'high' fire risk during IPO negative El Niño years when compared with non-El Niño events.

Table 4 demonstrates that the proportion of days with 'high' fire risk during IPO negative El Niño years is significantly different (at the <1% level) from the proportion during non-El Niño years at all stations studied.

Figure 6 demonstrates that, for all stations studied, the increase in the probability of a 'high' fire danger day occurring when IPO negative El Niño events and non-El Niño events are compared is even greater than the increase observed when all El Niño events are compared to non-El Niño events. The average increase in the risk of 'high' fire danger across the 14 study sites during IPO negative El Niño events is 95% (which is much greater than the average increase of 51% that was obtained when all El Niño and non-El Niño events were compared). The influence of the IPO on El Niño events appears to be strongest along the east coast of NSW and in the south-eastern corner, and weaker in the west. Yamba, Port Macquarie, Sydney, Canberra, Nowra and Moruya Heads all display an increase in forest fire risk of greater than 100% during IPO-negative El Niño years. The average increase in coastal areas is 122% compared with an average of 58% for the six inland stations.

Table 4. Results obtained when the daily probability of 'high' fire risk during El Niño years occurring in the negative IPO phase (p_1) is compared to non-El Niño years (p_2)

The P-value indicates the probability that p_1 is equal to p_2 with significance at the <5% and <1% level represented by * and ** respectively

Station	Probability of 'high' fire danger in negative IPO El Niño years (p_1)	Probability of 'high' fire danger in non-El Niño years (p_2)	p_1/p_2	P-value
Bourke	0.991	0.748	1.325	0.000**
Canberra	0.232	0.093	2.487	0.000**
Coffs Harbour	0.115	0.065	1.777	0.000**
Coonabarabran	0.527	0.331	1.592	0.000**
Dubbo	0.547	0.384	1.426	0.000**
Hay	0.676	0.562	1.202	0.000**
Lismore	0.173	0.094	1.839	0.000**
Moruya Heads	0.098	0.037	2.644	0.000**
Nobbys	0.182	0.094	1.944	0.000**
Nowra	0.155	0.056	2.781	0.000**
Port Macquarie	0.042	0.020	2.126	0.000**
Sydney	0.142	0.054	2.632	0.000**
Tamworth	0.514	0.350	1.468	0.000**
Yamba	0.044	0.022	2.020	0.000**

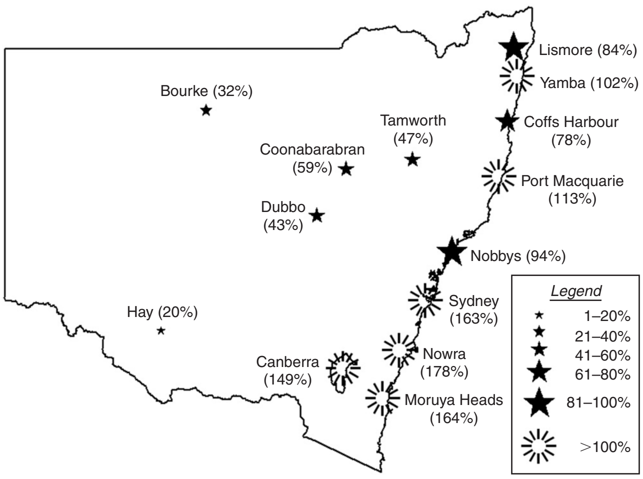

Fig. 6. Percentage increase in the occurrence of daily 'high' fire risk associated with El Niño and IPO negative years compared to non-El Niño years.

Conclusions

This paper has sought to determine how observed multi-temporal scale climate variability influences the risk of forest fire in NSW, Australia. This was achieved by first analysing the overall risk (regardless of ENSO or IPO phase) of forest fire for 22 study sites located within NSW. The impact that ENSO has on forest fire risk, and how this risk is modulated by the IPO, was then assessed.

The results showed that the probability of a 'high' fire risk day (FFDI > 12) occurring is much lower on the coast than it is inland. The results also showed that the risk of forest fire is significantly increased during El Niño events at all sites investigated, with on average a 51% increase in the proportion of days with a 'high' fire danger rating when El Niño years are compared to non-El Niño years. The strongest influence of El Niño appears to be in the south-eastern corner of NSW, with Canberra and Merimbula displaying increases in the probability of a 'high' risk fire day of 121% and 170% respectively.

Further investigation into how the forest fire risk during El Niño years is modulated by the IPO revealed that El Niño years occurring when the IPO is negative are associated with an increased risk of forest fire when compared to all other El Niño years for all 14 stations studied. The average increase in the probability of daily 'high' fire risk, across the 14 stations investigated, when IPO negative El Niño years are compared with all other El Niño years is 63%. This increase in risk is statistically significant at 12 of the 14 stations investigated. This is an important result because, as demonstrated, the risk of forest fire during El Niño years is already significantly increased when compared to non-El Niño years. This implies an extremely high risk of forest fire during IPO negative El Niño years, especially along the east coast and in the south-eastern corner of NSW.

To further illustrate the IPO induced enhancement of El Niño impacts when the IPO is negative, the risk of 'high' fire danger in IPO negative El Niño years was compared to the risk in non-El Niño years. The increase in the probability of daily 'high' fire danger when IPO negative El Niño are compared with non-El Niño years was found to be statistically significant (at the <1% level) at all stations investigated with an average increase across all stations of 95%, which is almost twice the average increase when all El Niño years and non-El Niño years were compared.

A likely example of the enhancement of El Niño impacts in the negative IPO phase might be found in the severe forest fires experienced in much of NSW during the spring and summer of 2002–2003. The 2002–2003 event was the first El Niño in the current negative IPO phase. Despite this event being of only 'moderate' strength, with respect to sea surface temperature and atmospheric pressure anomalies, the impacts associated with it were far worse than other 'stronger' El Niño events that occurred when the IPO was not negative.

This study reveals the potential to use long-term climate variability insight to predict forest fire risk in NSW. It is now possible to predict ENSO events up to 9 months in advance (Kiem and Franks 2001). The implications of this are particularly relevant to the Australian climate. NSW has been plagued with devastating forest fires since colonisation and, whilst it is impossible to eradicate fires of this nature, it is possible to be prepared. This preparation is made possible with the advantage of a 9-month lead-time on an upcoming serious fire season, and the possibility that the IPO may be a feature of the climate system with decadal to multi-decadal persistence.

Acknowledgements

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