Senate Standing Committee on Environment and Communications
Legislation Committee
Answers to questions on notice
Environment portfolio

Question No: 117

Hearing: Supplementary Budget Estimates

Outcome: Agency

Programme: Bureau of Meteorology

Topic: Forest Fire Index Places

Hansard Page: 43

Question Date: 18 November 2013

Question Type: Spoken

Senator Pratt asked:

Senator PRATT: Can I ask, on notice, for the locations of those forest fire index places that have had an increased risk?
Mr Vertessy: I would have to take that on notice.

Answer:

A paper developed in consultation with the Bureau of Meteorology titled *Changes in Australian fire weather between 1973 and 2010* which analysed trends in data of observed fire weather in Australia using the McArthur Forest Fire Danger Index was published in the International Journal of Climatology in April 2012, and is provided at **Attachment A.**

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Changes in Australian fire weather between 1973 and 2010

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ABSTRACT: A data set of observed fire weather in Australia from 1973–2010 is analysed for trends using the McArthur Forest Fire Danger Index (FFDI). Annual cumulative FFDI, which integrates daily fire weather across the year, increased significantly at 16 of 38 stations. Annual 90th percentile FFDI increased significantly at 24 stations over the same period. None of the stations examined recorded a significant decrease in FFDI. There is an overall bias in the number of significant increases towards the southeast of the continent, while the largest trends occur in the interior of the continent and the smallest occur near the coast. The largest increases in seasonal FFDI occurred during spring and autumn, although with different spatial patterns, while summer recorded the fewest significant trends. These trends suggest increased fire weather conditions at many locations across Australia, due to both increased magnitude of FFDI and a lengthened fire season. Although these trends are consistent with projected impacts of climate change on FFDI, this study cannot separate the influence of climate change, if any, with that of natural variability. Copyright © 2012 Royal Meteorological Society

KEY WORDS wildland fire; bush fire; wildfire; Forest Fire Danger Index; observations; trends

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1. Introduction

The probability of wildland fire is driven by the amount and dryness of fuel, ambient weather and ignitions (Archibald *et al*., 2009). Fire regimes can be characterized in part by differences in these drivers – for instance those ecosystems where wildland fire occurrence is limited by the amount of fuel and those where it is limited by a combination of fuel availability and ambient weather (Bradstock, 2010). Humans have a substantial and diverse impact on fuel and ignitions across the globe, for instance through land clearing, active fire suppression and burning off of agricultural debris. In contrast, there is no clear human imprint on fire weather – yet. Each of the drivers of wildland fire is highly sensitive to changes in climatic conditions, but fire weather is one of the first phenomena that could be expected to show a response to existing trends in climate change. The effects of climate change on biomass growth and fuel availability are complex and because of the nature of climate variability and human influence it may take decades for this to be clearly discernible.

Fire weather is typically expressed through some combination of surface air temperature, precipitation, relative humidity and wind speed. There are a number of different indices that integrate these meteorological variables into a single fire danger measure, for example the McArthur Forest Fire Danger Index (FFDI; Luke and McArthur, 1978), the Canadian Forest Fire Weather Index System (FWI; Van Wagner, 1987) and the United States National Fire Danger Ratings System (NFDRS; Deeming *et al*., 1978). Other metrics focus on the water and energy balance above the surface. The Haines Index (Haines, 1988) and a variant adapted to Australia (Mills and McCaw, 2010) link vertical atmospheric stability and humidity with erratic fire behaviour. The 850 hPa temperature gradient has been linked to extreme fire weather events over southeastern Australia (Mills, 2005).

Some trends have been observed in the variables underlying fire weather indices. Since 1960, the mean temperature in Australia has increased by about 0.7 °C. The entire country has experienced warming, in some areas by 1.5–2 °C (CSIRO and Bureau of Meteorology, 2010). Warming has occurred in all seasons; however, the strongest warming has occurred in spring (about 0.9 °C) and the weakest in summer (about 0.4 °C). There has been an increase in the number of record hot days and a decrease in the number of record cold days each decade since 1960 (Alexander and Arblaster, 2009; CSIRO and Bureau of Meteorology, 2010). The increase in temperature has been formally attributed to anthropogenic increases in greenhouse gases (Stott, 2003; Nicholls, 2006). Australian rainfall patterns are highly variable, with no consistent sign of change across the country and trends that depend more on start points. In southwestern Australia, a significant decline in rainfall since the 1970s has been attributed to a combination of natural variability and anthropogenic greenhouse gases (Timbal *et al*., 2006; Bates *et al*., 2008). Decreases in rainfall since 1960

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have also occurred in southeast Australia, while there was an increasing trend over northwestern Australia over the same period. Between 1957 and 2003, dew point temperature either remained the same or increased over much of Australia, with a national averaged trend of 0.1 °C per decade (Lucas, 2010a). These results are broadly similar to those from a global humidity data set with 5° resolution (Willett *et al*., 2007), although its starting point (1973) coincides with an exceptionally wet period over Australia, leading to more negative trends. From 1975 to 2006, there has been a small stilling trend in wind speed of -0.009 m s^{-1} year^{-1} across Australia (McVicar *et al*., 2008). This trend is widespread, with almost 90% of the 0.1° resolution grid cells showing a decline, and 58% of them a significant decline. These trends have occurred in the presence of considerable interannual fluctuations in the Australian climate, due to the El Niño-Southern Oscillation (ENSO) and other drivers of climate variability (Risbey *et al*., 2009).

Furthermore, the meteorological variables described above do not match exactly with those used in the calculation of the FFDI, which is used operationally by weather forecasters and fire agencies in Australia to declare fire weather warnings and total fire bans and to determine fire danger (the difficulty of putting out fires which may occur). The Australian humidity data set (Lucas, 2010a) is for dew point temperature, has monthly resolution and has been homogenized for measurements at 0900 local time (LT). FFDI uses relative humidity typically calculated at 1500 LT, when relative humidity is close to a minimum. The wind trends reported by McVicar *et al*. (2008) are based on total daily wind run, whereas FFDI uses wind speed at 1500 LT, averaged over the previous 10 min. Moreover, in the calculation of FFDI each variable is weighted differently (see Section 2), such that a one unit increase in one variable does not equate to a one unit increase in another, for example. Therefore, it is only in cases where just a single variable has changed, or where the direction of trend in all variables effectively coincides (i.e. temperature and wind speed increasing, relative humidity and precipitation decreasing) that we may state with confidence that a change in fire weather is likely. The impact of a given change in fire weather – for example in extreme values of the FFDI at a certain time of year – will be moderated by regional differences in fire seasonality as well as the relative importance of fire weather among fire limiting processes (Bradstock, 2010).

The creation of Australia's first high-quality observational FFDI data set (Lucas, 2010b) presents an opportunity to pose the question: Given the observed and regionally varied changes in the Australian climate, do we observe any significant trends in average and extreme fire weather and if so, what are their spatial patterns? Some trends from this data set have previously been reported in the context of a study on climate change projections for southeastern Australia (Lucas *et al*., 2007). We expand upon this earlier work on by including more recent data, additional stations from the entire continent and correcting for inhomogeneities in the wind record (see Section 2). Finally, an examination of historical trends should add value to the interpretation of existing and future projections of fire weather in Australia under climate change.

2. Data and methods

2.1. Study area

Australian fire regimes are highly seasonal in nature. In the forested southeast and southwest, summer and spring are the dominant fire seasons, while in the savanna landscapes of monsoonal northern Australia fire danger peaks late in the winter dry season (Luke and McArthur, 1978). The roughly latitudinal gradient in continental scale fire patterning is explained to a large extent by rainfall seasonality (Russell-Smith *et al*., 2007).

2.2. Fire weather and climate variables

For this study, FFDI is chosen to quantify fire weather conditions. This index was empirically derived in the late 1960s to relate weather conditions to expected fire behaviour and rate of spread. A series of threshold values are used to determine fire danger ratings: 0–11 (low/moderate), 12–24 (high), 25–49 (very high), 50–74 (severe), 75–99 (extreme) and 100+ (catastrophic). The FFDI – or its similarly derived counterpart the Grassland Fire Danger Index (GFDI) – is widely used across Australia as the basis for fire weather warnings issued by fire agencies. The methods of calculation used in this study are described by Lucas (2010b).

FFDI utilizes standard weather observations of temperature, relative humidity, 10 min averaged wind speed and rainfall to estimate the fire weather conditions. The basic equation for FFDI is given by Noble *et al*. (1980):

$$\mathrm{FFDI} = 2 \times \exp(0.987 \times \ln(\mathrm{DF}) - 0.0345 \times H + 0.0338 \times T + 0.0234 \times V - 0.45) \quad (1)$$

where DF is the drought factor, T is the temperature (°C), V the wind speed (km h^{-1}) and RH the relative humidity (%). In the formulation used here, fully described in Lucas (2010b), a fire weather data set with daily time resolution is created using observations of maximum temperature and V and RH as measured at 1500 LT. The drought factor, an empirical estimate of the state of the fuel, is calculated following the methodology described in Griffiths (1999) and uses the Keetch–Byram Drought Index (Keetch and Byram, 1968) as its input for soil moisture deficit, based on rainfall measurements collected at 0900 LT.

The methodology described in Lucas (2010b) provides a consistently calculated fire weather data set. The methodology ignores local variations in fuel amounts and

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types, as well as the slope of the terrain. These factors have a significant impact on the fire behaviour. While this presents problems for understanding the exact details of fire behaviour, our goal is to understand the weather and climate aspects of the issue. Uncertainties in the amounts of historical grassland curing make the use of GFDI problematic. In any case, future climate projections show a great deal of overlap in the behaviour of the GFDI and FFDI (Hennessy *et al.*, 2005). Furthermore, a comparison of FFDI with the widely used Canadian FWI shows considerable similarities between the two (Dowdy *et al.*, 2010).

To analyse the long-term trends of fire weather in Australia, these daily data are further summarized on both annual and seasonal time scales. Across much of Australia, the peak fire season occurs during the summer half of the year, roughly from September to March (Luke and McArthur, 1978). To accommodate this, a 'fire year' is chosen to run from 1 July to 30 June of the following year for the annual calculations. The variables chosen to summarize the fire weather climate are:

1. *Annual cumulative FFDI (ΣFFDI)*: This variable is calculated as the sum of all daily FFDI values over the entire fire year (Beer and Williams, 1995). It provides a useful metric to compare relative levels of fire weather danger over long time periods and/or different spatial areas. Cumulative FFDI is computed from the 1973–1974 through the 2009–2010 fire years, a total span of 37 years.
2. *Annual 90th percentile FFDI*: The daily values during a fire year are sorted, and the 36th highest value is chosen. This variable is indicative of the extreme end of the fire weather spectrum, times when the largest, most intense wildfires are more likely to occur and be more active. This variable is computed over the same period as ΣFFDI.
3. *Seasonal median and 90th percentile FFDI*: The median and 90th percentile FFDI over the standard southern hemisphere meteorological seasons are chosen (i.e. December–January–February (DJF), March–April–May (MAM), etc.). Each season is approximately 90 d long. This variable provides information on any potential changes in the annual timing of the fire season. It is available from MAM 1973 through DJF 2011.

2.3. Data homogenization and station selection

When investigating the long-term behaviour of any climate variable, the homogeneity of the data set is important. Homogeneous data are those which are free from artificial trends or discontinuities, such as those caused by station relocations, instrument changes and/or changes in observational practices. Lucas (2010b) examined the homogeneity of the FFDI data set and its components. While all the individual data sets show some degree of inhomogeneity, those in the wind speed data have the largest impact on the FFDI. These inhomogeneities in the wind speed arise from the changing local environment of the wind measurement as well as the changing instrumentation used to record wind speeds (see also Jakob, 2010), particularly those associated with the modernization of the observing network and the introduction of Automatic Weather Stations (AWS). Further, before the introduction of the AWS, wind reports at many of the rural stations in the data set were made through visual estimates of the effects of wind on vegetation. The quality of these measurements is greatly dependent on the skill of the observer, and they often show many inhomogeneities. They are also often inconsistent with later records made with the modern AWS instrumentation, with very different means, variance and skewness characteristics. As a general rule, the mean of past wind speed measurements is lower than those measured with contemporary AWS anemometers. However, there are exceptions.

Lucas (2010b) described a correction methodology for the wind inhomogeneities, applicable to statistics of the FFDI distribution rather than individual observations. Breakpoints in the wind speed time series are identified using two-phase regression similar to that described by Easterling and Peterson (1995). The bulk change in FFDI (ΔFFDI) at a given percentile level (e.g. median or 90th percentile) for a given change in wind speed (ΔV) is given by:

$$\Delta\mathrm{FFDI} = 0.0234 \times \mathrm{FFDI} \times \Delta V \qquad (2)$$

Past FFDI values are adjusted so that they are in relative homogeneity with contemporary measurements. The sensitivity of this homogenization methodology was discussed in Lucas (2010b). It was found to adequately account for changes in the FFDI distribution at most percentile levels. However, this was not true at the extreme upper ends of the FFDI distribution, where the changes to the variance and the skewness of the winds had a significant effect. This generally occurred at percentile levels above 90%; the homogenization correction at higher levels is subject to more uncertainty.

A scheme based on similar principles is determined for ΣFFDI. For this variable, an amount of adjustment is estimated by integrating Equation (2) multiplied by the observed relative frequency of occurrence of each value of FFDI over the observed FFDI distribution. This is done individually for each station resulting in a unique correction factor at each location.

The data set described in Lucas (2010b) was comprised of 77 individual stations. However, many of these stations were not suitable for use in this analysis. Two criteria are used in this study:

1. Stations that contain wind speed measurements based on visual estimates are excluded. In many cases, the wind speed time series at these stations show frequent changes in the mean and considerable differences compared to later instrumental observations, suggesting that they are unreliable. Furthermore, differences in the statistical distributions make the homogenization more subject to uncertainty.

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2. Stations with more than 1 year (365 d) of cumulative missing observations between 1973 and 2010 are excluded. This is equivalent to a record that is 98% complete.

Applying these criteria results in 38 stations selected for this analysis (Table I). There is considerable overlap between the two sets of stations that fail to meet the criteria. Stations with visually estimated winds are mostly rural, where in general there are more missing data. The stations chosen tend to be located in the more populated areas, often at airports or meteorological offices. The locations of the chosen stations are shown in Figure 1. While the number of stations is approximately halved, the national coverage of the complete data set is maintained, albeit with some gaps in northern Queensland (QLD) and in the desert regions along the eastern border of Western Australia (WA).

Table I. List of stations used in this study.

Station (Abbreviation)	State	Latitude (°)	Longitude (°)
Adelaide (AD)	SA	−34.92	138.62
Albany Airport (AL)	WA	−34.94	117.80
Alice Springs (AS)	NT	−23.80	133.89
Amberley (AM)	QLD	−27.63	152.71
Brisbane Airport (BA)	QLD	−27.39	153.13
Broome (BR)	WA	−17.95	122.23
Cairns (CA)	QLD	−16.87	145.75
Canberra (CB)	ACT	−35.30	149.20
Carnarvon (CN)	WA	−24.89	113.67
Ceduna (CE)	SA	−32.13	133.70
Charleville (CH)	QLD	−26.42	146.25
Cobar (CO)	NSW	−31.49	145.83
Coffs Harbour (CF)	NSW	−30.31	153.12
Darwin (DA)	NT	−12.42	130.89
Esperance (ES)	WA	−33.83	121.89
Geraldton (GE)	WA	−28.80	114.70
Hobart (HO)	TAS	−42.89	147.33
Kalgoorlie (KA)	WA	−30.78	121.45
Launceston Airport (LA)	TAS	−41.54	147.20
Laverton (LV)	VIC	−37.86	144.76
Mackay (MA)	QLD	−21.12	149.22
Meekatharra (MK)	WA	−26.61	118.54
Melbourne Airport (ME)	VIC	−37.68	144.84
Mildura (MI)	VIC	−34.23	142.08
Moree (MO)	NSW	−29.49	149.85
Mt Gambier (MG)	SA	−37.75	140.77
Mt Isa (MT)	QLD	−20.68	139.49
Nowra (NO)	NSW	−34.95	150.54
Perth Airport (PE)	WA	−31.93	115.98
Port Hedland (PO)	WA	−20.37	118.63
Rockhampton (RO)	QLD	−23.38	150.48
Sale (SA)	VIC	−38.12	147.13
Sydney Airport (SY)	NSW	−33.94	151.17
Tennant Creek (TE)	NT	−19.64	134.18
Townsville (TO)	QLD	−19.25	146.77
Wagga (WA)	NSW	−35.16	147.46
Williamtown (WI)	NSW	−32.79	151.84
Woomera (WO)	SA	−31.16	136.81

2.4. Trend analysis

The trends in this study are estimated by using ordinary least squares linear regression with time taken as the independent variable. There is no physical reason why trends in fire weather should be strictly linear. Rather, this method is chosen as it is simple, widely used and easily understood. The possibility of more complex trend shapes cannot be excluded. The 95th percentile confidence interval for linear trends was also calculated for each time series. The F-statistic ($p < 0.05$), a comparison of the variance explained by the linear fit and the total variance of the system, was examined as an indicator of the significance of the trend.

The calculation of climate trends is sensitive to the choice of start and end dates of the calculation. The robustness of trends calculated here is examined with some simple sensitivity tests. These are:

1. changing the start and end dates by 1, 5 and 10 years and
2. randomly removing increasing numbers of stations and in each case re-calculating trends.

3. Results

3.1. Annual statistics

The time series of wind-corrected ΣFFDI anomaly for each station in this study is shown in Figure 2. Although there is considerable interannual variability throughout the record, a clear upward trend is apparent at many of the stations and in the nationally averaged anomaly. Many of the lowest values at individual stations are observed in the early 1970s. There is evidence of a 'jump' in ΣFFDI at many stations after 2000, as noted in Lucas *et al*. (2007) for southeastern Australia. Some degree of coherence is seen in the signal, with peaks and troughs in the individual time series tending to occur simultaneously. This coherent interannual variability is broadly consistent with the known modulation of the fire-weather climate by ENSO (Williams and Karoly, 1999). El Niño years (e.g. 1982–1983, 1997–1998, 2002–2003, 2006–2007) are often higher than normal; La Niña periods (e.g. 1973–1975, 1998–2000) show negative anomalies.

Table II lists the trend values of ΣFFDI at individual stations. Mean values for ΣFFDI and all other metrics used here are shown in Table III to aid interpretation of these trends. Sixteen of 38 stations show a significant positive trend; none show a negative trend, significant or otherwise. The multi-station mean shows that on average across Australia, there has been an increase in annual cumulative FFDI since 1973 of 212 points per decade. This increase is not an artefact of the correction procedure. At 36 of 38 stations, the trend in ΣFFDI is reduced by the correction process, many times by over 50% of its original value. The two stations where the correction procedure results in an increased trend occur at Albany Airport and Mackay although the magnitude

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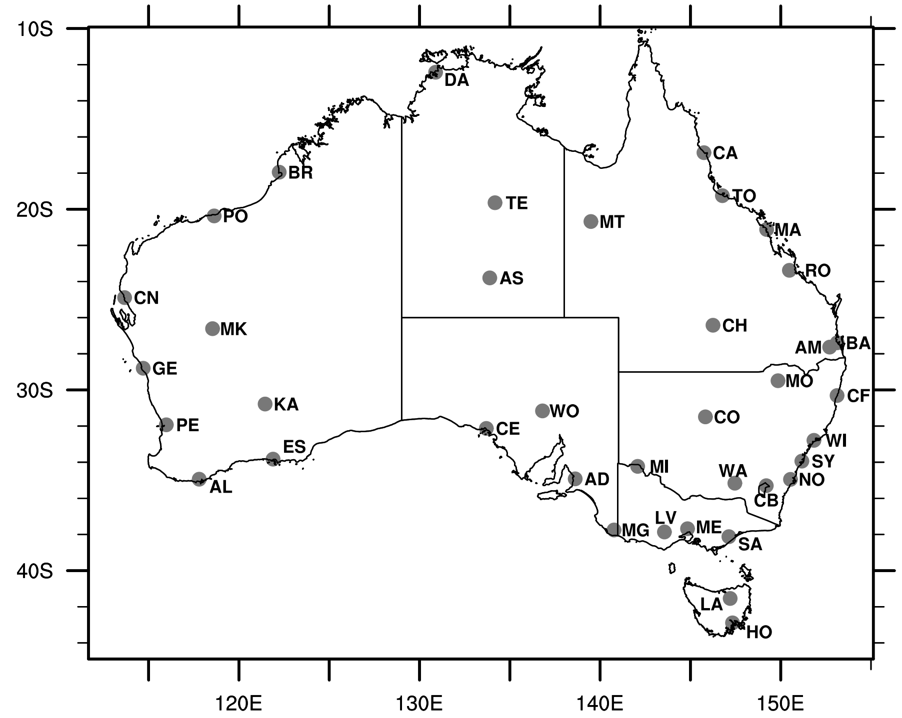

Figure 1. Map of station locations. See Table I for key. The marker for Laverton (LA) has been moved west to avoid overlap with Melbourne Airport.

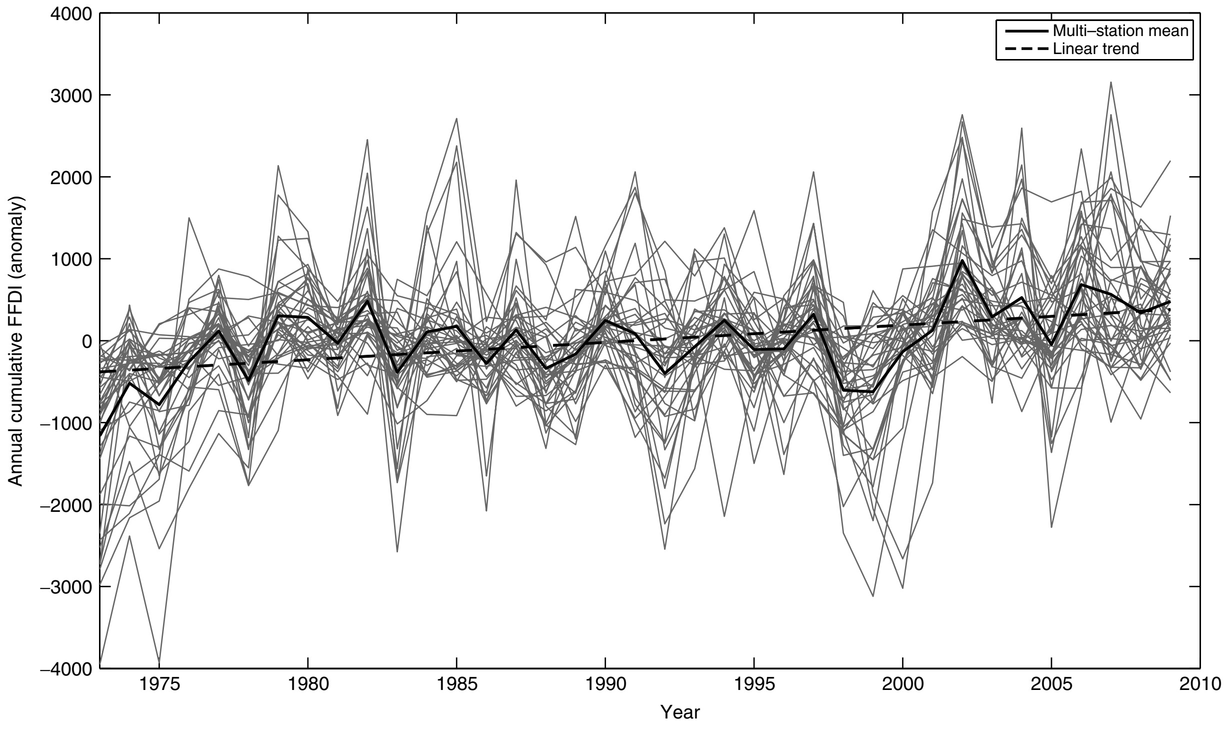

Figure 2. Time series of annual cumulative FFDI anomaly at each station. The thick line indicates the multi-station mean. The thick dotted line indicates the linear trend.

is small and the trend is near-zero before and after correction. As previously noted (see Section 2), this is consistent with the known historical shortcomings and tendencies in the observed wind speed data.

The spatial pattern of the trends in ΣFFDI is shown in Figure 3. An area of large, significant positive trend is seen in the southeast of the country, extending from Alice Springs southeastwards through South Australia (SA), western New South Wales (NSW), Victoria (VIC) and into northern Tasmania (TAS). With the exception of the Tasmanian station, trends in this region are well above 100 points per decade and at their strongest

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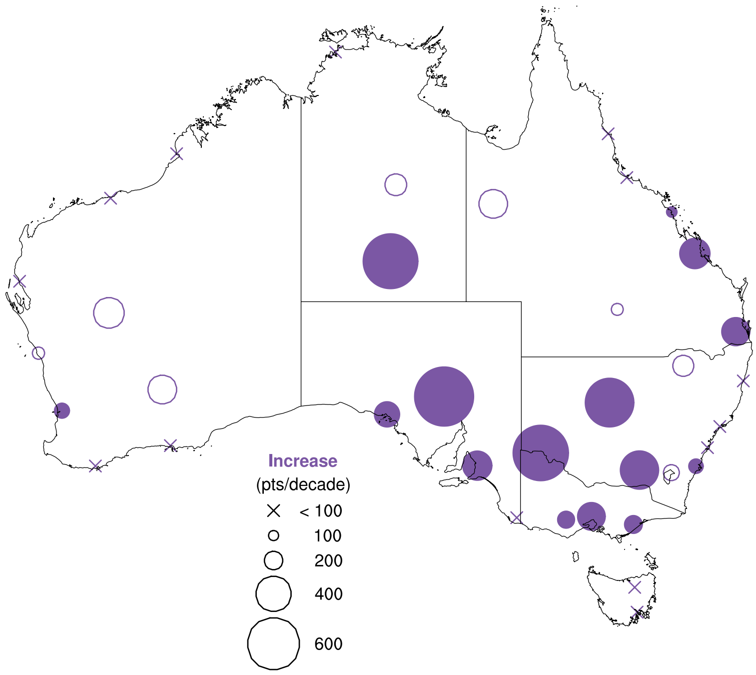

Figure 3. Map of trend magnitude in annual cumulative FFDI. Marker size is proportional to the magnitude of trend. Reference sizes are shown in the legend. Filled markers represent trends that are statistically significant. The marker for Laverton has been moved west to avoid overlap with Melbourne Airport. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

exceed 600 points per decade. Furthermore, trends at Mt Isa in western QLD and Moree in northern NSW are significant if the 90% ($p < 0.10$) level is considered. Outside of this region, an area of significant trends is noted in southeast QLD at Mackay, Rockhampton and Amberley. However, the coastal Brisbane Airport does not show a significant trend. Perth Airport in Western Australia has a significant positive trend in ΣFFDI; Kalgoorlie and Esperance have trends that are significant at the 90% level. Across much of tropical north Australia small and insignificant trends are observed. Coastal regions of New South Wales, including Sydney, Williamtown and Coffs Harbour also have small insignificant trends.

Figure 4 shows the time series of the annual 90th percentile FFDI anomaly at each station. The shape of the time series shares many traits with the time series of ΣFFDI shown in Figure 2. The interannual variability shows the same pattern, with higher values generally found during El Niño years and an overall upward trend. Figure 5 shows the spatial pattern of the trends and Table II shows the magnitude of the trend at each station. The spatial pattern of the trends is very similar to that of ΣFFDI, with strong upward trends identified across the southeast portion of the continent. A few stations that did not have significant trends in ΣFFDI showed significant trends in annual 90th percentile FFDI, especially along the New South Wales and Queensland coasts. Five stations recorded an annual increase of 0.27 or greater, which equates to a rise since 1973 of at least 10 points in the value exceeded on the 36 highest fire danger days of the year. No significant decreases were observed. Trends in annual 95th percentile levels were also computed (not shown). As a general rule, trends are larger at the high percentile levels, which suggests that the overall shape of the distribution is changing, rather than merely shifting to the right due to a change in the mean.

Trends in the multi-station mean ΣFFDI and 90th percentile FFDI show similar sensitivity to the selection of start and end points (Figure 6). The trend in both measures remains positive when 1, 5 and 10 years are removed from the start or end of the record. However, the trend is no longer significant when the end point occurs 10 years earlier. This gives an indication of the magnitude of the apparent 'jump' in values in the post-2000 years. In the case of ΣFFDI, delaying the start date by 5 years results in a trend whose lower 95% confidence bound is just below 0, which points to a period of relatively low fire weather conditions during the mid-1970s. Randomly removing individual stations has no material effect on trends until well in excess of 50% are removed (data not shown). This fits in with the suggestion of a spatial coherence in the signal between individual station time series shown in Figures 2 and 4.

3.2. Seasonal statistics

The spatial distribution of trends in seasonal 90th percentile FFDI for each of the four meteorological seasons is shown in Figure 7. Table III shows the values at individual stations for both the median and 90th percentile FFDI. The seasonal patterns show a wider variety of changes compared to the annual values shown previously. During winter, trends in both median and 90th percentile FFDI are almost uniformly positive, the exception being Brisbane Airport. For the 90th percentile FFDI

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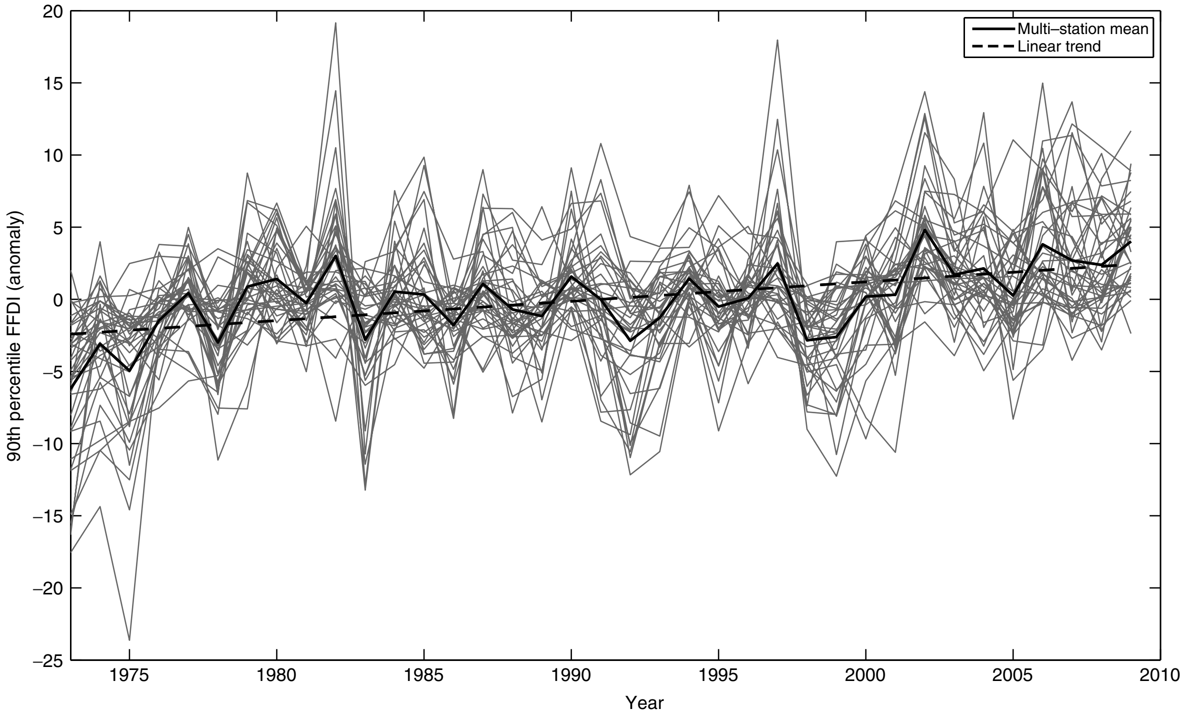

Figure 4. Time series of annual 90th percentile FFDI anomaly at each station. The thick line indicates the multi-station mean. The thick dotted line indicates the linear trend.

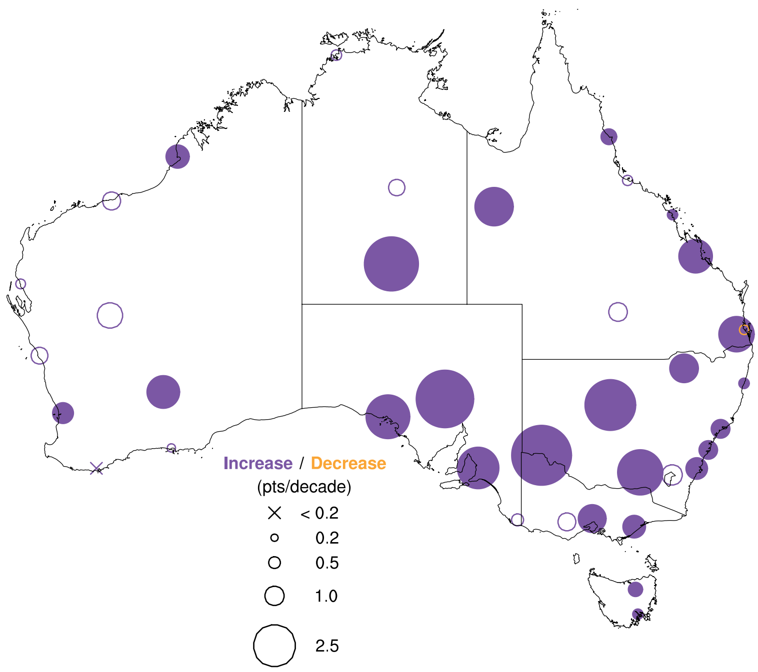

Figure 5. Map of trend in annual 90th percentile FFDI. Marker size is proportional to the magnitude of trend. Reference sizes are shown in the legend. Filled markers represent trends that are statistically significant. The marker for Laverton has been moved west to avoid overlap with Melbourne Airport. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

(median FFDI), 17 (15) stations recorded significantly positive trends, and an additional 4 (6) at the $p < 0.10$ level. The stations with significant trends are spread out across the country, although the largest trends are found northwards of about 31 °S. Smaller trends, significant or otherwise, are found in the southeast and in northern coastal Queensland.

The largest trends overall are seen in spring, for both median and 90th percentile FFDI. Most significant changes in FFDI are found in the southern half of mainland Australia, particularly in the southeast. Tasmania is an exception here. Many non-significant, but large-valued, trends are noted in the central latitudes of the country. In several cases, these are significant

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Table II. Trends (points/decade) in annual cumulative and 90th percentile FFDI and seasonal median and 90th percentile FFDI. Shading indicates trends are significant at the 95% level.

Station	Annual ∑ FFDI	Annual 90%	Seasonal 50%				Seasonal 90%			
			JJA	SON	DJF	MAM	JJA	SON	DJF	MAM
Adelaide	330	2.49	0.13	0.66	1.09	0.70	0.41	2.21	2.47	2.49
Albany Airport	30	0.00	0.09	0.15	−0.30	0.06	0.23	0.32	−0.43	0.33
Alice Springs	638	3.33	0.96	2.31	1.55	2.36	1.34	3.09	1.08	2.62
Amberley	317	2.08	0.98	0.61	0.49	1.28	2.23	1.63	0.66	1.6
Brisbane Airport	0	−0.36	−0.15	−0.15	−0.10	0.23	0.34	0.94	−0.51	−0.05
Broome	50	1.27	0.83	0.07	−0.17	0.05	2.21	0.55	−0.43	1.39
Cairns	49	0.77	0.22	0.21	−0.34	0.36	0.56	0.51	−0.36	1.2
Canberra	170	1.07	0.14	0.61	−0.43	0.92	0.25	1.1	−0.07	1.83
Carnarvon	60	0.37	0.44	0.23	−0.25	0.25	1.64	0.43	−0.65	0.94
Ceduna	282	2.64	0.36	0.84	0.55	0.85	1.42	3.78	1.74	3.31
Charleville	122	0.96	0.84	1.10	−1.46	1.20	1.52	1.51	−1.61	1.38
Cobar	564	3.11	0.57	2.08	1.30	1.05	1.65	3.43	1.74	1.13
Coffs Harbour	48	0.42	0.13	−0.08	0.12	0.21	0.25	0.16	0.45	0.34
Darwin	59	0.42	0.64	0.40	−0.07	0.04	0.46	0.21	−0.12	0.23
Esperance	94	0.27	0.13	0.21	0.10	0.15	0.44	0.43	0.07	0.73
Geraldton	126	0.84	0.63	0.68	0.16	0.74	1.81	2.04	−1.5	2.48
Hobart	48	0.41	0.19	0.25	0.11	0.27	0.24	0.38	0.49	0.42
Kalgoorlie	323	1.90	0.80	1.84	0.61	0.53	1.94	2.69	1.87	1.12
Launceston Airport	85	0.67	0.07	0.21	0.41	0.42	0.15	0.38	0.16	0.87
Laverton	183	0.91	0.29	0.69	0.09	0.17	0.3	2.1	0.77	0.26
Mackay	105	0.41	0.05	0.19	−0.05	0.35	0.2	0.16	0.21	0.42
Meekatharra	346	1.41	1.20	2.27	0.40	0.73	1.63	1.86	1.05	−0.01
Melbourne Airport	312	1.58	0.40	1.06	0.37	0.43	0.85	3.32	1.58	0.89
Mildura	645	3.72	0.57	1.99	1.67	1.20	0.95	4.17	2.77	2.62
Moree	231	1.63	0.91	0.98	0.05	1.21	2.16	2.3	0.62	1.24
Mt Gambier	70	0.52	0.01	0.18	−0.06	0.14	0.11	1.07	0.34	0.91
Mt Isa	323	2.28	1.28	2.00	−0.76	1.32	1.4	1.88	0.26	1.5
Nowra	153	1.16	0.51	0.62	0.16	0.69	0.71	1.83	−0.07	1.28
Perth Airport	160	1.11	0.32	0.59	0.89	0.75	1.06	1.77	0.78	1.56
Port Hedland	82	0.92	0.95	0.04	0.13	0.67	1.53	1.05	−0.24	1.32
Rockhampton	343	1.96	0.53	0.94	0.25	0.90	2.15	1.91	0.74	2.07
Sale	193	1.23	0.39	0.82	0.16	0.64	0.9	1.79	0.02	1.23
Sydney Airport	27	0.96	0.18	0.48	0.22	0.31	0.31	2.34	0.64	0.57
Tennant Creek	240	0.81	0.80	0.89	−0.23	1.24	0.1	0.42	−1.39	0.58
Townsville	1	0.40	0.05	0.07	−0.18	0.71	0.38	0.06	−0.17	1.01
Wagga	439	2.74	0.22	1.49	1.09	1.30	0.32	2.85	2.21	1.46
Williamtown	87	0.97	0.11	0.24	0.35	0.22	0.65	1.86	0.4	−0.02
Woomera	689	3.56	0.92	2.67	2.33	1.38	2.31	4.58	3.08	2.58

at the $p < 0.10$ level. While median trends are smaller than 90th percentile trends in almost all cases, southeastern New South Wales shows a striking disparity in this regard. In the tropical north, trends in both the median and 90th percentile FFDI are small during this season.

The fewest significant trends are observed during DJF (the summer), with only 3 (5) stations significant for the seasonal 90th percentile FFDI (median FFDI). These are found in southern portions of the country, at Adelaide, Mildura and Woomera, with Ceduna and Perth included for the median. Generally weak and insignificant negative trends are seen during this season in the northern portions of the country. Significant trends are more frequent during MAM and are seen along eastern Australia from coastal north QLD extending southwards into Tasmania. A greater number of significant trends are seen in the median than 90th percentile FFDI during autumn, especially in southeastern NSW. Prominent trends in the 90% level are also noted in a region centred on South Australia. Sites along the west coast also show significant trends.

4. Discussion and conclusions

4.1. Trends in fire weather

Fire weather, as depicted by the FFDI, has increased across much of Australia since 1973. Statistically significant increases in annual cumulative FFDI, observed at two fifths of the sites in the data set, are concentrated in the south and southeast of Australia. The largest absolute changes occur in the hot, arid interior of the continent, although some of the largest proportional increases

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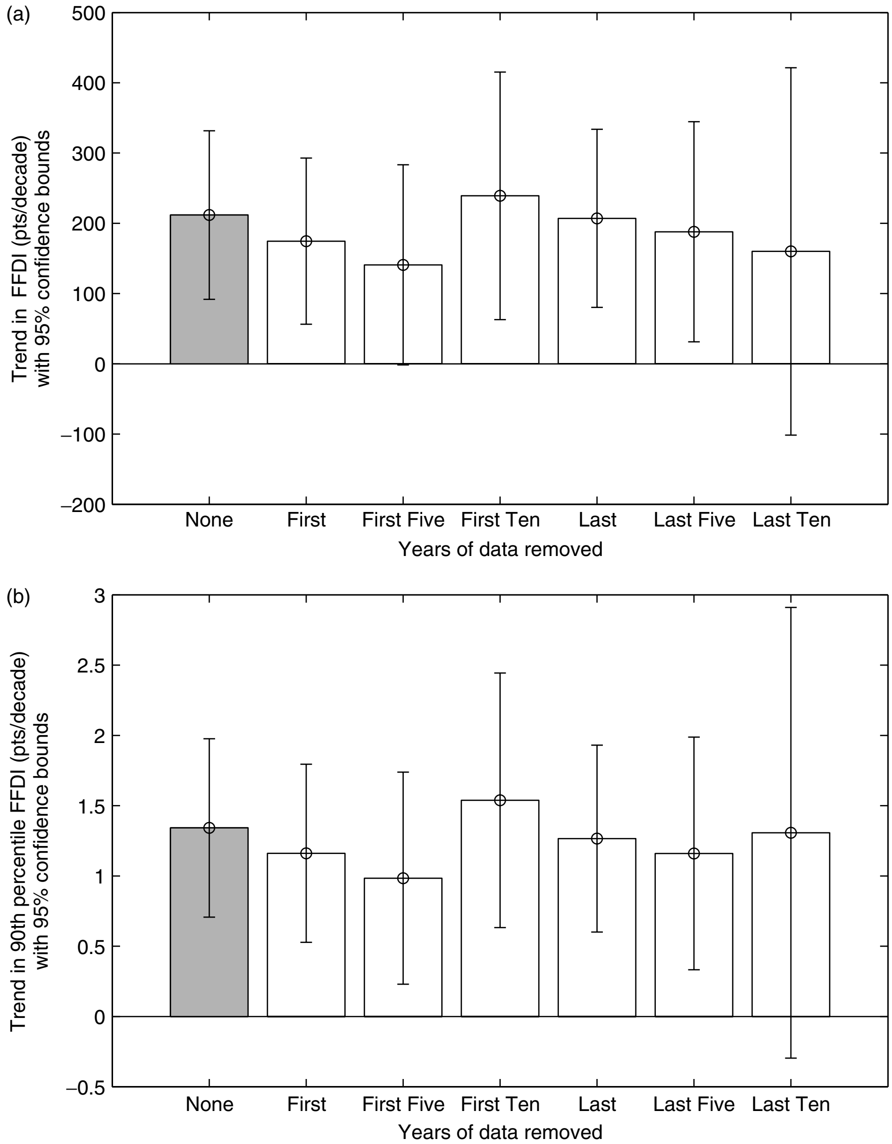

Figure 6. Sensitivity of multi-station mean trend values in (a) annual cumulative FFDI and (b) annual 90th percentile FFDI (points/decade) to variation in the start and end points of the time series. Whiskers indicate 95% confidence intervals for trend values.

occurred in coastal areas, where average annual cumulative FFDI is relatively low – Melbourne and Adelaide recorded increases of 49% or more over the duration of the record. Although no significant decreases in annual cumulative FFDI were observed, large areas did not record a significant increase: much of the north and west of the country, as well as most of the eastern seaboard.

While annual cumulative FFDI provides a good standalone estimate of changes to fire weather, it masks their distribution and timing. The upper tails are changing more quickly than the centre, such that changes to the annual 90th percentile FFDI account for 20–30% of the total change on average. It is at these upper tails of the FFDI distribution that fire weather conditions are greatest. There are also distinct seasonal changes and associated spatial patterns, even in regions which do not show a significant increase in the annual figures. The largest changes by magnitude have occurred in the spring, with large changes on southern parts of the mainland, particularly Victoria, South Australia and New South Wales. An increase in the upper tails of the distribution is particularly dominant here. There are similarities here with temperature trends in Australia since 1960, which have increased the most in spring and the least in summer (CSIRO and Bureau of Meteorology, 2010). Based on the weather station data used in this study, relative humidity shows a similar pattern of larger increases in spring. The bias towards larger increases in spring compared to other seasons is slightly more pronounced for temperature than for relative humidity and FFDI.

The fewest significant trends are observed in summer. Trends in the 90th percentile summer FFDI are large across the south, but often not significant because of the large interannual variability. In the tropical north, weak negative trends occur during summer, which is not part of the fire season. Widespread changes occur in both autumn and spring, but are of larger magnitude during spring. Changes in the winter are comparatively small

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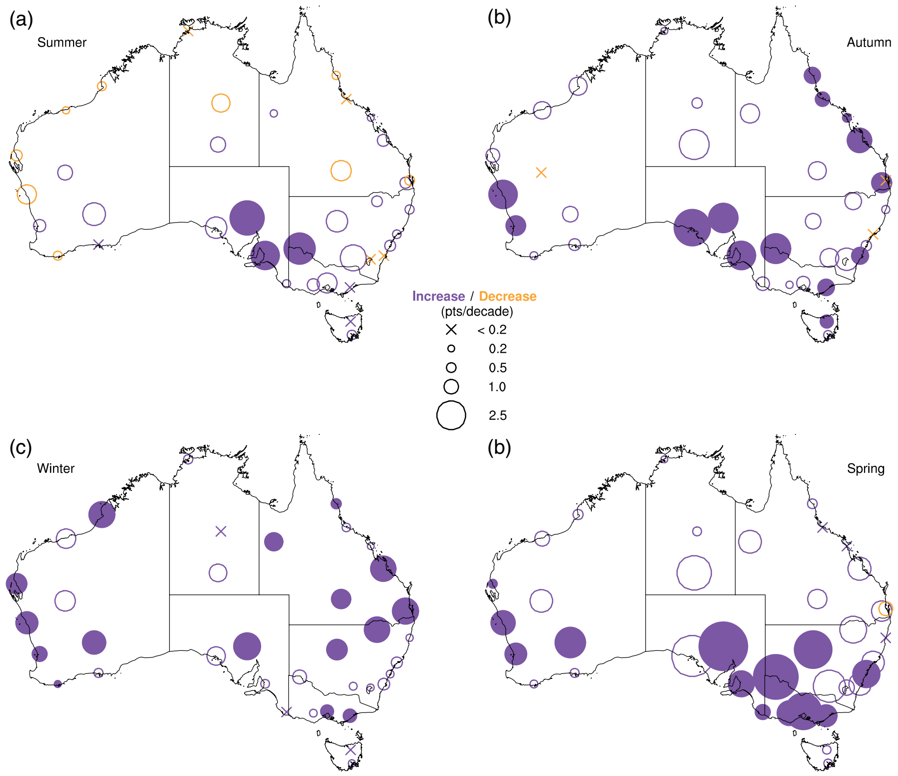

Figure 7. Map of trend in seasonal median FFDI. Marker size is proportional to the magnitude of trend. Reference sizes are shown in the legend. Filled markers represent trends that are statistically significant. The marker for Laverton has been moved west to avoid overlap with Melbourne Airport. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

but widespread, and occur at lower latitudes than the bulk of spring and autumn increases. The general spatial coherence of these changes suggests that these are not effects of 'spurious significance' but real phenomena. At most locales, the largest trends are observed in the season before the peak of the fire season, which indicates a lengthening fire season across southern Australia. An increase in fire season length has also been found in Ontario, Canada, due in contrast to a delayed end to the fire season (Woolford *et al.*, 2010). It should be noted that FFDI values are a nonlinear indication of fire weather conditions; the magnitude of change must be interpreted with respect to local baseline values and fire danger rating thresholds.

There are a number of difficulties in separating the contribution from each of the variables constituting FFDI towards the observed trends. One method, adapted from Lucas (2010b; see also Dowdy *et al.*, 2010), is to take the partial derivative of the FFDI equation with respect to each variable (they are differently weighted) and substitute the change in each variable, as derived from ordinary least squares regression. This approach suggests that decreases in relative humidity have played the largest role in the average changes observed here and that the direct effect of temperature has played a relatively small role (data not shown). In southeastern Australia, drought factor – an estimate of fuel dryness – appears to be a significant factor in the observed trends. This observation is particularly noteworthy in Victoria (e.g. Laverton, Melbourne and Mildura), where severe drought conditions have prevailed between 1996 and late-2010 (Murphy and Timbal 2008; Timbal 2009). However, this method is based on average changes and does not capture influences across the distribution, particularly at the important upper end. It must also rule out wind speed, as the methodology used here to correct inhomogeneities in the wind record has the effect of removing any trends. Moreover, the decreasing trend in relative humidity is influenced by the data set commencing during a relatively wet period. Ultimately, any attempt at attributing changes in FFDI to individual variables must recognize that the variables are not independent. Relative humidity and temperature are strongly linked and it is possible that changes in relative humidity are more attributable to temperature than actual water vapour amounts. In addition, while the drought factor is based largely on recent rainfall, temperature is also a contributing factor in its calculation.

These increases in FFDI do not necessarily equate to an increased chance of wildland fire occurrence. The changes will have manifested differently depending on local fire dynamics. In the north and widespread arid regions, wildland fire is limited more by fuel availability than the immediate weather (Bradstock, 2010). Rainy years – such as the strong La Niña event of 2010 – can bring enhanced fire danger in the following year(s). This can lead to a situation where 1 or 2 years of very low cumulative FFDI are followed by a period of increased fire weather conditions, such as the central Australian fires in the 1970s and early 2000s (Griffin

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Table III. 1973–2010 mean values (in points FFDI) for ΣFFDI, annual 90th percentile FFDI and seasonal median and 90th percentile FFDI.

Station	Annual ∑FFDI	Annual 90%	Seasonal 50%				Seasonal 90%			
			JJA	SON	DJF	MAM	JJA	SON	DJF	MAM
Adelaide	2875	18.6	1.9	4.3	10.3	5.7	5.7	15.7	28.2	17.5
Albany Airport	1414	8.6	1.0	1.9	6.1	3.9	3.3	5.0	11.9	10.8
Alice Springs	9329	45.8	12.1	26.6	29.6	17.7	25.5	48.1	51.4	36.9
Amberley	3378	17.9	7.1	8.6	4.7	5.7	17.6	21.8	14.1	14.0
Brisbane Airport	2068	10.6	5.1	5.5	3.4	3.9	13.0	12.3	8.5	8.8
Broome	4496	27.1	17.0	8.2	4.2	8.3	29.9	30.7	9.3	24.8
Cairns	1919	10.8	5.9	5.9	1.1	1.6	11.1	12.3	7.4	7.5
Canberra	2693	17.3	2.4	4.1	8.5	4.8	5.7	14.7	27.1	13.7
Carnarvon	3658	18.1	6.1	8.6	8.9	8.1	16.6	18.3	18.7	18.2
Ceduna	4984	30.9	4.9	8.3	10.2	7.9	17.0	35.4	39.5	26.9
Charleville	6582	34.5	9.8	20.1	18.8	13.9	19.3	38.6	40.3	28.5
Cobar	5191	29.5	4.9	12.7	20.2	10.5	11.8	30.7	39.8	22.5
Coffs Harbour	1397	7.8	3.4	3.4	2.0	1.5	8.5	9.0	6.6	5.4
Darwin	3510	22.1	14.9	8.3	0.6	5.1	27.1	17.6	5.3	17.9
Esperance	1905	10.2	1.9	3.3	6.3	4.7	6.9	9.0	12.8	13.1
Geraldton	4412	27.5	2.7	6.5	13.1	10.4	10.1	18.8	42.6	31.4
Hobart	1458	7.9	1.6	2.6	4.2	2.9	4.1	7.0	10.7	7.6
Kalgoorlie	6059	34.1	6.7	16.7	22.3	11.2	17.0	37.2	44.9	27.6
Launceston Airport	1396	9.0	1.0	2.3	6.2	3.0	2.3	5.9	13.3	8.8
Laverton	2185	12.7	2.3	3.2	5.6	3.9	6.0	11.8	21.1	12.3
Mackay	1110	6.5	3.0	5.1	1.8	1.7	6.6	8.4	7.0	5.1
Meekatharra	8467	44.9	10.0	26.6	35.0	17.9	22.7	47.1	56.5	36.8
Melbourne Airport	2591	15.1	2.4	3.5	6.8	4.5	5.9	13.2	25.0	14.3
Mildura	5121	29.4	4.8	12.2	20.2	10.1	12.1	31.6	40.1	24.1
Moree	4696	24.5	5.9	10.8	11.9	10.2	12.9	28.6	27.6	20.7
Mt Gambier	2097	12.7	0.9	2.2	7.7	3.7	2.6	7.6	22.5	13.6
Mt Isa	8447	41.0	18.0	29.4	14.2	17.1	28.7	47.6	40.4	30.8
Nowra	2022	11.2	3.2	3.5	3.4	2.9	9.1	15.0	11.7	8.6
Perth Airport	3805	24.8	1.3	4.8	16.2	9.0	5.8	14.4	35.1	24.2
Port Hedland	7722	38.5	17.2	22.3	11.3	15.2	32.1	46.0	30.5	32.0
Rockhampton	3329	16.9	8.1	9.7	6.0	7.3	17.3	21.1	14.2	14.5
Sale	2010	10.9	2.1	3.0	5.3	3.5	5.9	10.0	15.8	10.2
Sydney Airport	2370	12.7	3.0	4.3	4.2	2.9	10.3	15.2	12.9	9.0
Tennant Creek	8710	41.6	20.3	31.5	18.3	19.8	31.2	47.8	45.4	36.6
Townsville	2883	13.7	7.6	8.2	2.9	5.6	16.1	13.8	10.0	11.6
Wagga	3639	23.8	1.8	4.1	15.8	7.0	5.0	18.5	36.8	18.8
Williamtown	2100	12.8	2.6	4.2	4.4	2.4	9.8	16.7	15.8	8.9
Woomera	7615	40.9	8.1	19.6	27.9	14.9	20.1	46.8	50.8	31.4

et al., 1983; Edwards *et al*., 2008). Conversely, the Black Saturday forest fires of February 2009 in Victoria, in the country's temperate southeast, were driven by some of the highest FFDI values on record, against a background of severe drought conditions in the preceding months and years (McCaw *et al*., 2009; National Climate Centre, 2009). Regional differences in fire frequency will also lead to different sample sizes from which to detect potential impacts of changes in fire weather. In the north, some parts of the tropical savanna woodlands and grasslands burn on an annual basis, while fires in temperate heathlands and dry sclerophyll forests have inter-fire intervals of 7 to 30 years (Beeton *et al*., 2006). Fires in wet sclerophyll forests are less frequent but often of extremely high intensity when they do occur, especially in the southern temperate areas.

4.2. Natural variability and climate change

The observed trends in fire weather occurred against a backdrop of considerable interannual variability. A primary mechanism driving this variability across Australia is ENSO. There is a strong positive relationship between El Niño events and fire weather conditions in southeast and central Australia (Williams and Karoly, 1999; Verdon *et al*., 2004; Lucas, 2005). Despite the strong relationships, ENSO only explains 15–35% of the year to year variance in FFDI (Lucas *et al*., 2007). A link has recently been found between positive Indian Ocean Dipole (pIOD) events, which have trended upwards since 1950, and significant fire seasons in the country's southeast (Cai *et al*., 2009). Another possible driver of variability is the Southern Hemisphere Annular Mode (SAM). The effect of SAM on Australia varies with the season; the positive

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phase of SAM corresponds with generally higher summer rainfall in north-central and south-east Australia and lower winter rainfall in south-east and south-west Australia (Hendon *et al*., 2007).

Sources of interannual variability are in turn subject to longer term interdecadal circulation variations such as the Interdecadal Pacific Oscillation (IPO; Folland *et al*., 1999; Power *et al*., 1999). Long-term fluctuations with a period of around 20 years are apparent at a few stations in southeast Australia with data extending back to the 1940s (Lucas *et al*., 2007). These longer time series also highlight the importance of start date selection in a highly variable climate. The 1940s were a period of relatively high fire danger and the observed trends since then are much lower. Although we find the choice of start and end dates has a relatively small effect on the positive trends in fire danger, the fact remains that the period 1973–1975 was one of the wettest across Australia.

Is climate change a plausible contributor to the trends observed here? Studies of the impacts of elevated atmospheric carbon dioxide on future fire weather show considerable global variation, including decreases in some areas, but the potential for large increases in many areas (e.g. increases of up to 95% in a daily fire severity rating by 2070 in western Canada during summer; Nitschke and Innes, 2008; see Flannigan *et al*., 2009 for other examples). A number of early Australian studies on the effects of climate change using global climate model (GCM) simulations found widespread increases in fire weather under increased atmospheric carbon dioxide (Beer and Williams, 1995; Cary and Banks, 1999; Williams *et al*., 2001; Cary, 2002). Building on the work of Hennessy *et al*. (2005), Lucas *et al*. (2007) projected increases in annual FFDI of up to 30% by 2050 over historical levels in southeast Australia, and up to a trebling in the number of days per year where the uppermost values of the index are exceeded. The largest changes occurred in the arid and semi-arid interior of NSW and northern Victoria, with the smallest changes in coastal areas and Tasmania. They also found that in many cases, fire weather conditions during the 2000s far exceeded the projections for 2050. The southeast of Australia is a hotspot for future increases in fire weather conditions according to other studies, in terms of both FFDI (Clarke *et al*., 2011) and a synoptic marker of extreme fire events (Hasson *et al*., 2009). Observed increases in FFDI over southeast Australia match these projections well. Another area of agreement is Tasmania, which has recorded little to no increases in FFDI and was projected to continue to do so by Lucas *et al*. (2007). There is less consistency in projections for other areas: in tropical northeast Australia, some studies have projected no change or decreases in mean and extreme FFDI (Clarke *et al*., 2011) while others located the largest increases in this region (Pitman *et al*., 2007). Observations for tropical north Australia correspond more closely to the former, with smaller increases or no significant trends in much of tropical northern Australia. Detailed spatial projections are lacking for much of central and Western Australia.

These projections should be interpreted in light of known flaws in climate models' ability to simulate important modes of variability (Guilyardi *et al*., 2009) and their interaction (Cai *et al*., 2011). There is further uncertainty about the potential effect climate change will have on these modes and thus indirectly on future fire weather conditions. For instance, it is believed that climate change will impact the physical processes that underpin ENSO, but it is not known whether this will lead to more or less events or a change in their intensity (Collins *et al*., 2010). An additional source of doubt in future projections of the probability of wildland fire occurrence is the response of fuel load to climate change, with potentially competing effects of increased carbon dioxide fertilization and changes in both magnitude and variability of temperature and precipitation (Medvigy *et al*., 2010; Zhang *et al*., 2010; Matthews *et al*. 2011). As discussed above, the relative importance of fire weather with respect to other limiting factors (such as fuel load) in determining overall chance of wildland fire occurrence depends on prevailing fire regimes.

The total change predicted by the trends is typically smaller than the range of interannual variability, which can be quite large depending on the location and season. Despite this, there is a consistency between the increases in FFDI observed since 1973 and projections of increased fire weather conditions due to climate change. One hypothesis, after Lucas *et al*. (2007) is that we are currently experiencing an upswing in fire weather conditions due to some natural forcing with an interdecadal time scale, and that this is being exacerbated by the subtle, ongoing effects of climate change. In this respect, it is noteworthy that the 2010/2011 fire season has seen some of the lowest measures of FFDI on record in some areas. Additional data in the coming years will reveal whether this is a natural fluctuation in the face of a steadily increasing trend, or part of a longer lasting decline in FFDI values.

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