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# Index sensitivity analysis applied to the Canadian Forest Fire Weather Index and the McArthur Forest Fire Danger Index

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**ABSTRACT:** A number of different methodologies are developed for examining the sensitivities of an index. These methodologies are applied to examine the characteristics of the Canadian Fire Weather Index (FWI) and the McArthur Forest Fire Danger Index (FFDI) using 8 years of gridded data throughout Australia. Percentile changes in input conditions show that the indices are similar to each other in that they are both most sensitive to wind speed, then secondly to relative humidity and thirdly to temperature. On a finer scale, a combination of the relationship between the indices and their partial derivatives shows that the FFDI is relatively less sensitive to wind speed and rainfall, and more sensitive to temperature and relative humidity, than the FWI. A method based on equilibrium values of the indices shows that the FFDI has a temperature threshold set by recent rainfall above which its sensitivity increases, resulting in some non-linearity in its relationship with the FWI. The sensitivity differences between the indices mean that the indices are complementary in that they each respond to a somewhat different set of conditions, as is shown by examining a number of recent fire events. The fire events also reveal that index values associated with dangerous fire behaviour can vary greatly between different regions. Methods to reduce the consequences of this variation are examined, including the use of index percentiles. Copyright © 2009 Royal Meteorological Society

KEY WORDS forecasting; indices; wildfire; bushfire; extreme; percentiles

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## 1. Introduction

A number of methodologies are presented for examining the sensitivities of an index, including the use of percentile changes in input parameters to determine the relative importance of each parameter, a method for comparing the sensitivities of two different indices through a combination of the relationship between the indices and their partial derivatives, as well as a method based on equilibrium values of an index that provides a different perspective from which to examine the formulation of an index. These methods are applied to two different fire weather indices, although the methods are general enough that they could readily be applied to most other indices.

Indices are used in many different fields for a wide range of purposes. A common use of indices is in the forecasting of extreme events. By definition, extreme events occur infrequently which means that large amounts of data are often not available for developing an index. Additionally, indices are often developed using a somewhat limited data set and then applied more broadly (e.g. an index may be developed primarily in a particular region and then applied across a wider geographic range). The interpretation of an index value to forecast an event must therefore be undertaken with care. Doswell III *et al.* (1996) stress the importance of understanding the various different ingredients that influence a forecast event. To make the best use of an index, it is important to have a sound understanding of the sensitivities of an index to its various input parameters as these provide a greater understanding of the underlying processes that influence the occurrence of an event.

A common application of indices is to assess fire danger, and in Australia the McArthur Forest Fire Danger Index (FFDI) (McArthur, 1967) is widely used as a basis for issuing fire weather warnings. The Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987; Lawson and Armitage, 2008) is being used increasingly in many different countries throughout the world (Dudfield, 2004; de Groot *et al.*, 2006; Taylor and Alexander, 2006). The FWI has performed well in comparative studies between a range of different index systems (Viegas *et al.*, 1999) and has also been shown to perform well in certain conditions in Australia (Cruz and Plucinski, 2007). The considerable international interest in the FWI System is a motivation for examining how it behaves under Australian conditions. To this effect, this paper compares the sensitivities of the FWI with those of the FFDI.

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Eight years of daily data are used to calculate gridded fields of the FWI and the FFDI throughout Australia. Numerical weather prediction (NWP) data have predominantly been used in contrast to station based data, since NWP data more readily allow for a consistent spatial distribution of data throughout Australia. The FWI fields are compared with an equivalent set of FFDI fields (calculated from the same set of meteorological inputs). Climatological fields of these indices allow regional variations in the sensitivities of the indices to be investigated both analytically (based on the different distributions of the index climatologies) and by means of examining a number of severe fire events. Methods to reduce the consequences of these variations are examined, including the use of index percentiles.

An overview of the indices is provided in Section 2, followed by a description of the data and analysis methods used in Section 3. The relationship between the indices is examined in Section 4, predominantly based on percentiles of the indices. A sensitivity analysis of the indices to their input parameters is presented in Section 5. A number of severe fire events are examined in Section 6 by applying the results of the previous sections.

## 2. Overview of the Indices

### 2.1. Overview of the Forest Fire Danger Index (FFDI)

The FFDI is a key tool for assessing fire danger in Australia. It has an associated set of classification thresholds ranging from low to extreme as shown in Table I. The formulation of the FFDI (e.g. Noble *et al*., 1980) is based on the current day's maximum temperature (°C), $T$, the wind speed (km h$^{-1}$), $v$, and relative humidity (%), $RH$, and a component representing fuel availability called the Drought Factor, $DF$, as shown in Equation (1):

$$FFDI = 2e^{(-0.45+0.987\ln(DF)-0.0345RH+0.0338T+0.0234v)} \quad (1)$$

The Drought Factor has a range from 0 to 10 and is partly based on the soil moisture deficit, calculated here as the Keetch-Byram Drought Index (KBDI) (Keetch and Byram, 1968), and the effects of recent rainfall (including the rainfall amount and time), as detailed by Griffiths (1998). The KBDI is an estimate of the soil moisture below saturation up to a maximum field capacity (in an agricultural sense where the soil micro-pores are full but the macro-pores are empty) of 203.2 mm (i.e. 8 in.) and a minimum of 0 mm.

Table I. Forest Fire Danger Index (FFDI) values for each fire danger rating class (Luke and McArthur, 1986).

| Fire danger rating | FFDI range |
|---|---|
| Low | 0–5 |
| Moderate | 5–12 |
| High | 12–24 |
| Very high | 24–50 |
| Extreme | 50+ |

### 2.2. Overview of the Forest Fire Weather Index (FWI)

The FWI System was developed in 1970s, with revised versions issued in 1976, 1984 and 1987. The FWI formulation cannot be expressed as a single equation as simply as is the case for the FFDI. The Australian implementation used here is based on the 1987 version of the formulation (Van Wagner, 1987), with modifications to its day length dependency to make it a continuous function in both latitude and time of year, potentially allowing it to be applied globally (as detailed in Dowdy *et al*., 2009).

The FWI System is based on the effects of weather parameters on forest floor fuel moisture conditions and generalized fire behaviour in a standard jack pine stand (Van Wagner, 1974). It requires calibration of its classification thresholds to suit local climatic conditions which is usually accomplished through an analysis of historical fire weather data (e.g. de Groot *et al*., 2005).

The meteorological inputs to the FWI System are noon Local Standard Time values of temperature, relative humidity, wind speed and the past 24 h rainfall. The meteorological inputs are used as inputs for three fuel moisture codes representing three classes of forest fuel (each with different drying rates, nominal fuel depth and nominal fuel loads): the Fine Fuel Moisture Code (FFMC) representing the moisture content of fine fuels and litter on the forest floor, the Duff Moisture Code (DMC) representing the moisture content of loosely compacted decomposing organic matter, and the Drought Code (DC) representing the moisture content of deep compact organic matter of moderate depth. The three fuel moisture codes are each calculated with a daily time-step and include their previous day's value as an input to the current day's value. It is through this feedback mechanism that antecedent information is incorporated into the FWI System and the drying rates of the fuel classes are determined.

The three fuel moisture codes are used as inputs to two intermediate fire behaviour indices: the Initial Spread Index (ISI) and the Buildup Index (BUI). The ISI estimates the combined influence of wind speed and the FFMC on fire spread. It is a simple exponential function which doubles the FWI for increments in wind speed of about 20 km h$^{-1}$. The BUI is a combination of the DMC and the DC, and represents the availability of the deeper or larger-sized fuel. The ISI and the BUI are combined to determine the value of the FWI, which represents the peak daily intensity of the spreading fire as the energy output rate *per* unit length of fire front.

## 3. Data Requirements

The FFDI and FWI systems are both based on daily values of temperature, relative humidity, wind speed and the past 24 h rainfall. Temperature, wind speed and relative humidity data have been obtained for this study from NWP forecasts, while rainfall data have been acquired from an observational data set.

### 3.1. Observational rainfall analyses

The gridded analysis of daily rainfall observations used here to calculate both the FFDI and FWI systems is valid for 0900 h (local time including daylight saving) and has a resolution of 0.25° in both latitude and longitude across Australia (Weymouth *et al*., 1999). It has been produced from about 5000–6000 observational reports throughout Australia although in some areas, mainly the central desert regions of Australia, the rainfall observation network is very sparse and so these areas are therefore not used for the analyses presented in this study. These regions are sparsely vegetated and so their omission does not significantly limit the aims of this study.

### 3.2. NWP forecast data

Due to a lack of available gridded observations of temperature, relative humidity and wind speed, short range forecasts have been used for these parameters from MESOLAPS (for details Puri *et al*., 1998). The MESOLAPS forecasts have a resolution of 0.125° in both latitude and longitude, but have been resampled (compressed) for the purposes of this study to match the 0.25° resolution of the observed rainfall data. Consequently, the indices used in this study have a resolution of 0.25° in both latitude and longitude throughout Australia (which is approximately a grid of about 25 km by 25 km).

The Bureau of Meteorology archive of MESOLAPS forecasts is available from 10 October 1999 onwards. Forecasts are produced each day at analysis times of 0000 and 1200 UTC. Forecasts are available at multiple terrain-following vertical sigma (i.e. pressure scaled by surface pressure) levels for 3 h intervals, out to 48 h past the analysis time.

The FWI System requires data valid at noon Local Solar Time (LST) to estimate the daily peak fire conditions. Noon LST corresponds to about 0200 UTC in eastern Australia and 0400 UTC in Western Australia. The 3 h forecast from the 0000 UTC analyses has been used to represent the noon LST values required by the FWI System since it is the closest available forecast to this time throughout Australia. The FFDI uses the maximum daily temperature to calculate the daily peak fire conditions. The 6 h forecast from the 0000 UTC analyses has been used for the FFDI, except in cases where the 0300 UTC temperature is greater than the 0600 UTC temperature in which case the 0300 UTC forecast has been used.

A known issue with the MESOLAPS forecasts is that they tend to underestimate wind speeds as compared with observations. To reduce this bias, wind speed is calculated here as the average of the 10 m wind speed and the gust speed (calculated as the peak wind speed in the mixed layer). This wind speed has been used in Australia for daily forecasts of FFDI based on MESOLAPS forecasts since 2006, following the analysis of meteograms such as those described in Mills (2005).

Complete sets of input data are available from 1 October 1999 onwards. However, it is necessary to initialize the indices with a significant amount of historical input data. It is for this reason that the first 3 months of data (i.e. from October to December 1999) have been used to allow the indices to 'spin-up', which means that the indices have only been used for this study from 1 January 2000 onwards. A historical record of the FFDI and FWI systems is therefore available from 1 January 2000 onwards. The calculation of the indices is an ongoing process, although this study is only based on data up to 31 December 2007, resulting in an 8 year data set.

This paper investigates the FFDI and FWI systems at gridded locations throughout Australia. In addition to this, it focuses on six locations in particular (as shown in Figure 1). These locations are concentrated in Australia's temperate zone since this is where the vast majority of devastating bushfires occur (e.g. those associated with loss of life). The locations were chosen partly because they cover a wide range of different geographical and climatic regions, and also because a significant fire event occurred at each of these locations during the period of available data (as investigated in Section 6).

It should be kept in mind that the results presented in this paper may not necessarily match what would be obtained from single station data since the data used in this study are derived from gridded analysis of forecast fields (with data from the nearest grid point to each location being used). Due to the lack of gridded observation of wind speed, relative humidity and temperature,

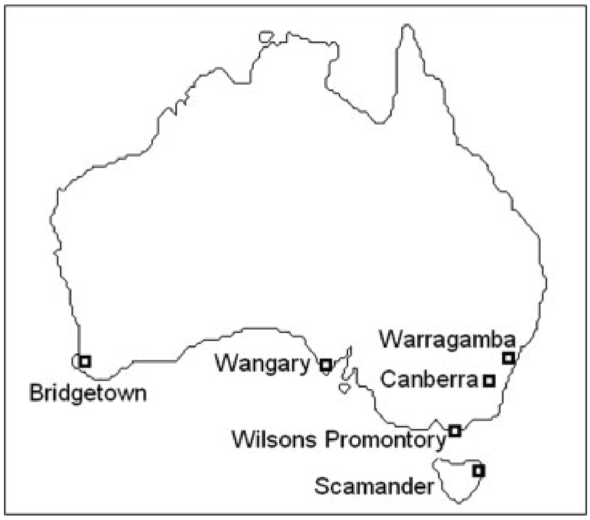


Figure 1. Map of Australia showing the locations of Warragamba in New South Wales (33.75 °S, 150.5 °E), Canberra in the Australian Capital Territory (35.25 °S, 149.25 °E), Wangary in South Australia (34.5 °S, 135.5 °E), Bridgetown in Western Australia (34.0 °S, 116.0 °E), Wilsons Promontory in Victoria (38.75 °S, 146.25 °E) and Scamander in Tasmania (41.5 °S, 148.25 °E).

 

it is not possible to determine if a statistically significant bias exists between fire weather indices based on NWP or observed data. Finkele *et al*. (2006) discuss the differences to be expected between gridded analyses and station observations, observing that differences in rainfall can sometimes be significant, such as in complex terrain or for convective small-scale rain events, whereas differences tend to be smaller for other parameters such as temperature which have greater spatial homogeneity.

## 4. The Relationship Between the Indices

The relationship between the FWI and FFDI is examined in this section, predominantly based on index percentiles. Regional variations in the relationship between the indices are also examined. This provides a background context in which to examine the sensitivities of the indices (in Section 5).

### 4.1. The national median relationship

A relationship between the FWI and FFDI based on the percentiles of the indices is developed in this section. Examples of the percentiles of the FWI and FFDI, calculated separately for each grid point throughout Australia, are shown in Figure 2. The percentiles are based on 8 years of data and are used here to provide an indication of broad-scale climatological features. Both indices show reasonably similar patterns of spatial variability to each other with higher index values predominantly occurring throughout the central and southern-central regions of mainland Australia, with the lower values generally occurring in Tasmania, southwestern Western Australia, eastern Victoria and around the Great Dividing Range.

A relationship between the indices can be determined by matching a FWI value to a FFDI value, based on selecting the FWI value that has the same percentile as a given FFDI value. This is shown in Figure 3 for three different FFDI values, calculated separately for each grid point throughout Australia. This method could be used to estimate warning classification thresholds for the FWI in Australia, rather than matching fire behaviour to index values (e.g. de Groot *et al*., 2006).

There is reasonably little spatial variation in the FWI values for each value of FFDI shown in Figure 3. The main variation is that the FWI tends to be higher than the national median in some regions, such as parts of Tasmania, south-west Western Australia, Victoria and the Great Dividing Range. These regions correspond reasonably well to the regions where the index percentiles are relatively low (from Figure 2), suggesting that the FWI tends to indicate more severe fire weather conditions than the FFDI in these regions.

The method of matching the percentiles of the indices (as shown in Figure 3) was repeated for a wide range of different FFDI values. For each different FFDI value, the median and standard deviation of the FWI values were calculated over all grid points. The median FWI values

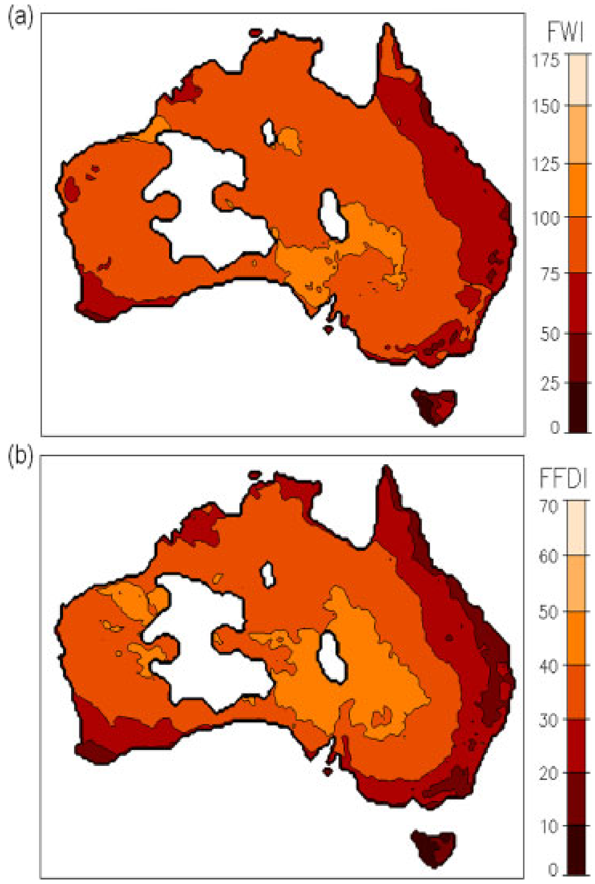


Figure 2. The 95th percentiles of the FWI (a) and FFDI (b) based on daily values of the indices during the years 2000–2007. The inland blank areas indicate where the indices have not been calculated due to distance from rainfall observations. This figure is available in colour online at wileyonlinelibrary.com/journal/met

and standard deviations calculated using this method are shown in Figure 4, calculated individually for each different FFDI value. Figure 4 shows that the national median relationship between the FWI and the FFDI is nonlinear, since no single straight line can represent the data to within the error bars. However, the data can be well represented by two different linear fits to different sections of the data (shown as the dotted lines in Figure 4) given by:

$$FWI = \begin{cases} 2.8FFDI - 0.3 & FFDI \leq 20 \\ 2.2FFDI + 10.8 & FFDI > 20 \end{cases} \quad (2)$$

While there is considerable spread about this line of best fit at the higher end of the range (with the FWI values having a standard deviation throughout Australia of about 15%), least-absolute-deviation fits are used (throughout this study) instead of least-square fits to avoid overweighting the influence of outliers.

### 4.2. Regional variations in the relationship between the indices

The spatial variation of the relationship between the indices is investigated here using scatter plots of the

 

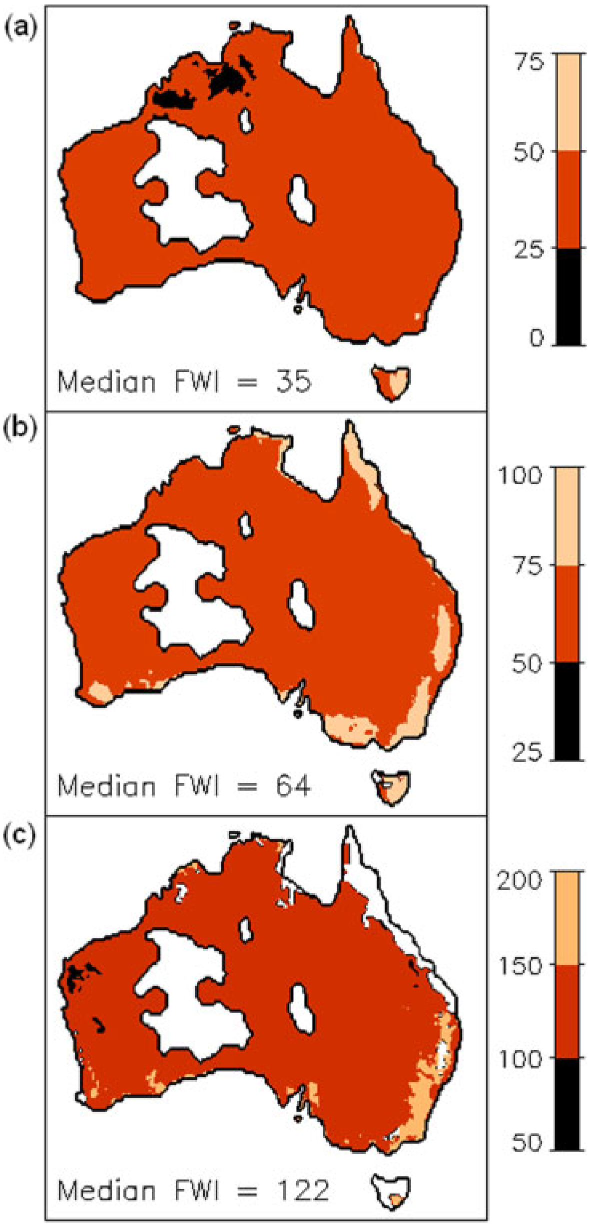


Figure 3. The FWI values that have the same frequency of occurrence (i.e. the same percentile) as a particular FFDI value. This is shown for FFDI values of 12 (a), 24 (b) and 50 (c), representing the transitions to High, Very High and Extreme Fire Danger classifications, respectively. The FWI values are calculated separately for each grid point throughout Australia, based on daily values from the years 2000 to 2007. Areas are left blank where the FFDI did not reach its listed value during the period of available data (as is the case throughout most of Tasmania for FFDI = 50), in addition to the regions where index values are not calculated due to sparse rainfall observations (as shown in Figure 2). The national median of the FWI values calculated over all grid points is shown for each of the three panels. This figure is available in colour online at wileyonlinelibrary.com/journal/met

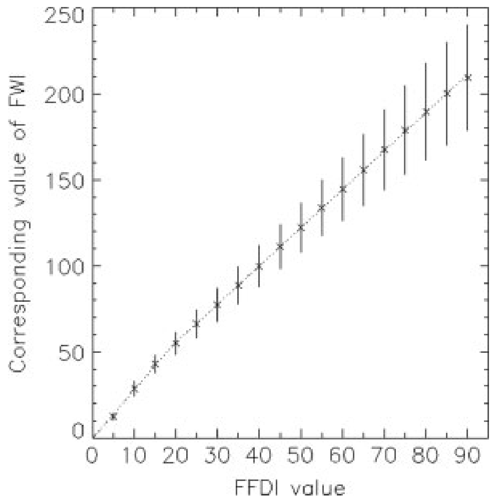


Figure 4. The national median relationship between the FWI and FFDI. The relationship was produced by matching the percentiles of the indices at each individual grid point throughout Australia, then calculating the national median FWI value corresponding to each FFDI value. The standard deviations of the FWI values throughout Australia are shown as vertical lines above each point as well as below each point. The dotted line represents a combination of two linear fits to the data, one for FFDI $\leq 20$ and one for FFDI $> 20$, as described by Equation (2).

FWI *versus* the FFDI. This is shown in Figure 5 for the six different locations (Figure 1). Although considerable spread is evident in Figure 5, there is also an obvious correlation between the FWI and FFDI values at each of the six locations. This correlation is reasonably consistent with the national median relationship between the indices given by Equation (2), although some variation between the locations is apparent. For the six locations shown in Figure 5, the slopes of linear fits to the data for $FFDI \leq 20$ range from 2.6 at Warragamba up to 3.9 at Scamander.

A similarity between the different locations is that the slopes of linear fits to the data for $FFDI \leq 20$ at each location are all higher than for $FFDI > 20$ (with the exception of Scamander which has very few days where $FFDI > 20$). This indicates that the non-linearity of the relationship between the FWI and FFDI occurs at individual locations as well as for Australia as a whole (cf. Figure 4).

There are many examples in Figure 5 where considerable differences occur between the indices. For example, there are numerous days at all six locations where one index is below its 98th percentile even though the other index is significantly higher than its 98th percentile. This shows that significant differences exist between the indices in their sensitivities to their input parameters.

## 5. Sensitivity Analysis

It was seen in the previous section that the relationship between the FWI and FFDI is both nonlinear and spatially variable, and that there are many examples where the indices show significant differences to each other. To understand features such as these, and thereby understand the individual indices themselves in greater detail, the sensitivities of the indices need to be understood.

A number of methods are presented in this section for examining the sensitivities of an index, including a method for comparing the sensitivities of two different indices through a combination of the relationship

 

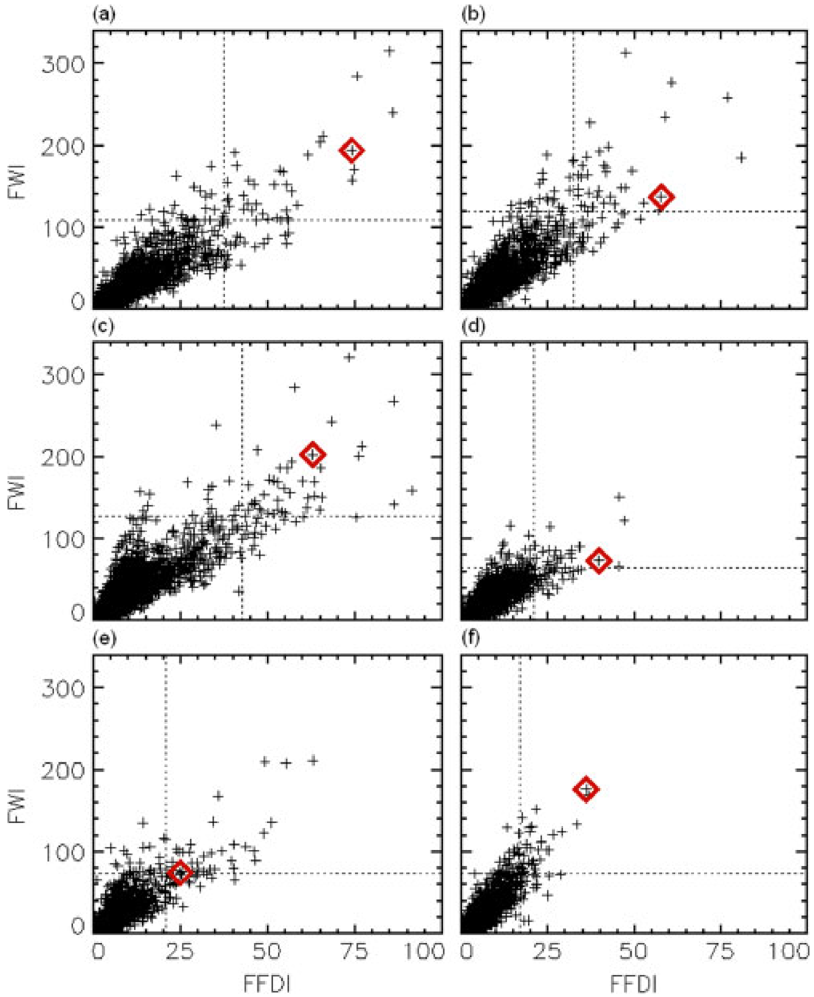


Figure 5. Daily values of the FWI *versus* the FFDI for Warragamba (a), Canberra (b), Wangary (c), Bridgetown (d), Wilsons Promontory (e) and Scamander (f). The 98th percentiles of both indices are shown as dashed lines for each of the six locations. The day of a severe fire event is highlighted by a '◊' at each location (as investigated in Section 6). This figure is available in colour online at wileyonlinelibrary.com/journal/met

between the indices and their partial derivatives (Section 5.1), a method to determine the relative importance of each parameter based on percentile changes in input parameters (Section 5.2), as well as a method based on equilibrium values of an index that provides a different perspective from which to examine the formulation of an index (Section 5.3).

### 5.1. Index derivatives

Partial derivatives of the indices are used in this section to examine the sensitivities of the indices to their individual input parameters. The partial derivatives are then combined with the relationship between the indices to develop a method for comparing the sensitivities of two different indices to each other.

The derivative of an index with respect to a single input parameter (i.e. the partial derivative) is a measure of the sensitivity of the index to that input parameter. The partial derivatives of the FFDI calculated from Equation (1) are:

$$\left(\frac{\partial FFDI}{\partial T}\right)_{RH,DF} = 0.0338FFDI \tag{3}$$

$$\frac{\partial FFDI}{\partial v} = 0.0234FFDI \tag{4}$$

$$\left(\frac{\partial FFDI}{\partial RH}\right)_{T} = -0.0345FFDI \tag{5}$$

$$\left(\frac{\partial FFDI}{\partial DF}\right)_{T} = 0.987\frac{FFDI}{DF} \tag{6}$$

where the subscripts indicate the variables that are held constant when calculating the partial derivatives (which is necessary since the Drought Factor and relative humidity both depend on temperature).

The formulation of the FWI System includes many complexities such as conditional discontinuities. This means that calculating the derivatives of the FWI mathematically is not as easy as for the FFDI. For this reason, partial derivatives are calculated here as the change in an index value due to a unit change in an individual input parameter (i.e. a finite difference method). Since unit changes in input parameters are used instead of infinitesimal changes, the derivatives represent a generalized value within the unit change.

Table II. Partial derivatives of the Forest Fire Weather Index (FWI) with respect to temperature, wind speed, relative humidity or rainfall.

| | Location | | | | | |
|---|---|---|---|---|---|---|
| | Warragamba | Canberra | Wangary | Bridgetown | Wilsons Prom. | Scamander |
| Temperature (°C) | 1.7 | 2.0 | 2.3 | 1.7 | 1.9 | 1.6 |
| Wind speed (km $h^{-1}$) | 3.9 | 4.5 | 5.2 | 3.6 | 3.9 | 3.4 |
| Relative humidity (%) | −2.3 | −1.8 | −2.9 | −1.8 | −2.1 | −1.8 |
| Rainfall (mm $day^{-1}$) | −7.8 | −9.5 | −7.9 | −9.7 | −8.9 | −10.4 |

Table III. As for Table II, but for the Forest Fire Danger Index (FFDI).

| | Location | | | | | |
|---|---|---|---|---|---|---|
| | Warragamba | Canberra | Wangary | Bridgetown | Wilsons Prom. | Scamander |
| Temperature (°C) | 1.9 | 1.9 | 2.6 | 1.5 | 1.4 | 1.0 |
| Wind speed (km $h^{-1}$) | 1.2 | 1.3 | 1.8 | 1.1 | 1.0 | 0.6 |
| Relative humidity (%) | −1.8 | −1.8 | −2.5 | −1.5 | −1.4 | −0.9 |
| Rainfall (mm $day^{-1}$) | −2.5 | −2.3 | −3.4 | −2.0 | −1.5 | −0.7 |

To calculate derivatives using this method, all of the input parameters are initially set equal to their 95th percentiles at each location (including the FFMC, DMC and DC of the FWI, the KBDI of the FFDI, as well as temperature and relative humidity) or their 5th percentiles (for relative humidity and rainfall), as listed in Dowdy *et al.* (2009), and day length is calculated based on 1 January. A unit increase is then made to a single meteorological input parameter (for temperature, relative humidity, wind speed or rainfall). The index and its subcomponents (such as the FFMC, DMC and DC of the FWI, and the KBDI of the FFDI) are then recalculated. This method shows the sensitivity of the indices to short-term changes in an input parameter (i.e. from one day to the next day), rather than the sensitivity to long-term changes (as is the focus of Section 5.3).

The derivatives of the indices with respect to rainfall have been calculated using a 5.1 mm $day^{-1}$ increase in rainfall (instead of using a unit increase in rainfall, i.e. 1 mm $day^{-1}$), with the resultant change in the index value being divided by 5.1, since small amounts of rainfall are not considered to be significant due to canopy interception or surface runoff (Van Wagner, 1987; Finkele *et al.*, 2006).

Derivatives calculated using this method are shown in Tables II and III for the FWI and FFDI, respectively, at the six locations shown in Figure 1. The FWI derivatives are more consistent between the different locations than the FFDI derivatives, varying between locations by a factor of 1.4 for temperature, 1.5 for wind speed, 1.6 for relative humidity and 1.3 for rainfall. In contrast, the FFDI derivatives vary by a factor of about 3–5 between the six locations. The reason for the large variation between locations in the sensitivity of the FFDI to its input parameters is that the FFDI derivatives are all directly proportional to the value of the FFDI, as is shown by Equations (3)–(6), combined with the fact that the 95th percentile of the FFDI is about three times smaller at Scamander than at Wangary. Other studies have also noted the increased sensitivity of the FFDI with increasing values of FFDI (e.g. Sullivan, 2001).

The sensitivity differences between the indices can be expressed as the relative change in one index, as compared with the change produced in the other index, resulting from a change in an input parameter. This is calculated here by comparing the slope of the national median relationship between the indices with the ratio of their derivatives. Using this method, the disproportionate change, $X$, in the FWI is given by:

$$X_{FWI} = \left[ \frac{\Delta FWI}{\Delta FFDI} - \frac{\delta FWI}{\delta FFDI} \right] \Delta FFDI \qquad (7)$$

where $\Delta FWI$ and $\Delta FFDI$ are the changes in the indices due to a unit change in an input parameter (such that $\frac{\Delta FWI}{\Delta FFDI}$ represents the ratio of the derivatives of the indices), and $\frac{\delta FWI}{\delta FFDI}$ is the slope of the relationship between the indices (from Equation (2)).

Similarly, the disproportionate change in the FFDI (relative to the FWI) is given by:

$$X_{FFDI} = \left[ \frac{\Delta FFDI}{\Delta FWI} - \frac{\delta FFDI}{\delta FWI} \right] \Delta FWI \qquad (8)$$

Values of $X_{FWI}$ and $X_{FFDI}$ are shown in Tables IV and V, respectively, based on the derivatives of the indices shown in Tables II and III. Note that magnitudes are approximately doubled between Tables IV and V, reflecting the larger numerical values of the FWI.

Tables IV and V show that high temperatures and low humidities favour high FFDI values, while high wind speeds and low rainfall favour high FWI values. This is

 

Table IV. The disproportionate change in the Forest Fire Weather Index (FWI) (relative to the FFDI) produced by a unit change in temperature, wind speed, relative humidity or rainfall.

| | Location | | | | | |
|---|---|---|---|---|---|---|
| | Warragamba | Canberra | Wangary | Bridgetown | Wilsons Prom. | Scamander |
| Temperature (°C) | −2.5 | −2.2 | −3.4 | −1.6 | −1.2 | −0.6 |
| Wind speed (km $h^{-1}$) | 1.3 | 1.6 | 1.2 | 1.2 | 1.7 | 2.1 |
| Relative humidity (%) | 1.7 | 2.2 | 2.6 | 1.5 | 1.0 | 0.2 |
| Rainfall (mm $day^{-1}$) | −2.3 | −4.4 | −0.4 | −5.3 | −5.6 | −8.9 |

Table V. As for Table IV, but for the disproportionate change in the Forest Fire Danger Index (FFDI) (relative to the Forest Fire Weather Index (FWI)).

| | Location | | | | | |
|---|---|---|---|---|---|---|
| | Warragamba | Canberra | Wangary | Bridgetown | Wilsons Prom. | Scamander |
| Temperature (°C) | 1.1 | 1.0 | 1.6 | 0.7 | 0.5 | 0.3 |
| Wind speed (km $h^{-1}$) | −0.6 | −0.7 | −0.6 | −0.5 | −0.8 | −0.9 |
| Relative humidity (%) | −0.8 | −1.0 | −1.2 | −0.7 | −0.4 | −0.1 |
| Rainfall (mm $day^{-1}$) | 1.0 | 2.0 | 0.2 | 2.4 | 2.5 | 4.0 |

the case at all six locations, although the magnitudes of the values show some variation between locations. Some of the relatively low values shown in Table V, such as for temperature and relative humidity at Scamander, can be explained by the FFDI derivatives being proportional to the value of the FFDI (Equations (3)–(6)) combined with the fact that the 95th percentile of the FFDI is lowest at Scamander of the six locations. However, even with the lower sensitivity of the FFDI at Scamander, the FFDI is still more sensitive to temperature and relative humidity than the FWI there.

The index sensitivities examined here are based on index values defined by the 95th percentiles of their input parameters (or 5th percentiles for relative humidity and rainfall) at each of the six locations. This produces index values at the upper end of the typical range which occur during summer at each of the six locations. Since these locations were selected to represent a diverse range of geographic and climatic regions, the resultant index values represent a diverse range of different conditions, with FFDI (FWI) values of 53 (137) at Warragamba, 54 (161) at Canberra, 75 (193) at Wangary, 45 (128) at Bridgetown, 42 (138) at Wilsons Prom and 26 (119) at Scamander. It was shown that for all of these sets of conditions, the FFDI is more sensitive to temperature and relative humidity, and less sensitive to wind speed and rainfall, than the FWI. To examine this further, Figure 6 shows scatter plots of the indices with days highlighted where the wind speed was above its 95th percentile at a particular location. The high wind speeds correspond to the vast majority of days where the FWI is disproportionately large. In contrast, high values of temperature (as shown in Figure 7) or low values of relative humidity (as shown in Figure 8) correspond to the vast majority of days where the FFDI is disproportionately large. It is therefore apparent that these sensitivity differences between the indices can account for the large amount of scatter that can be seen in Figure 5.

### 5.2. Relative sensitivities of each input parameters

This section examines the relative importance of each input parameter. This was not possible to do using the results of the previous section since each input parameter has its own distinct units. In this section, the change in an index value due to a percentile change in an input parameter is examined. This allows for direct comparisons to be made between different parameters, regardless of what units they are measured in, since percentile changes can be considered equally likely to occur for different parameters.

The change in an index value due to a percentile change in an input parameter is shown in Tables VI and VII for the FWI and FFDI, respectively. All input parameters are initially set equal to their 95th percentiles and then one input parameter is changed from its 95th to 99th percentile (with the exception of relative humidity which is changed from its 5th to 1st percentiles), as listed in Dowdy *et al*. (2009). Changes in rainfall have not been used, since a daily rainfall of 0 mm represents both the 5th and 1st percentiles at all locations.

Tables VI and VII show that the FWI and FFDI are similar to each other in that they are both most sensitive to wind speed, then secondly to relative humidity and thirdly to temperature. This order of importance of the input parameters is consistent for both the FWI and the FFDI. This has been calculated for changes in these parameters at the upper end of their ranges, although the fact that the order is consistent at all six locations shows that this result is applicable to a wide range of different conditions (for example, the initial FFDI values used range from 26 at Scamander to 75 at Wangary).

 

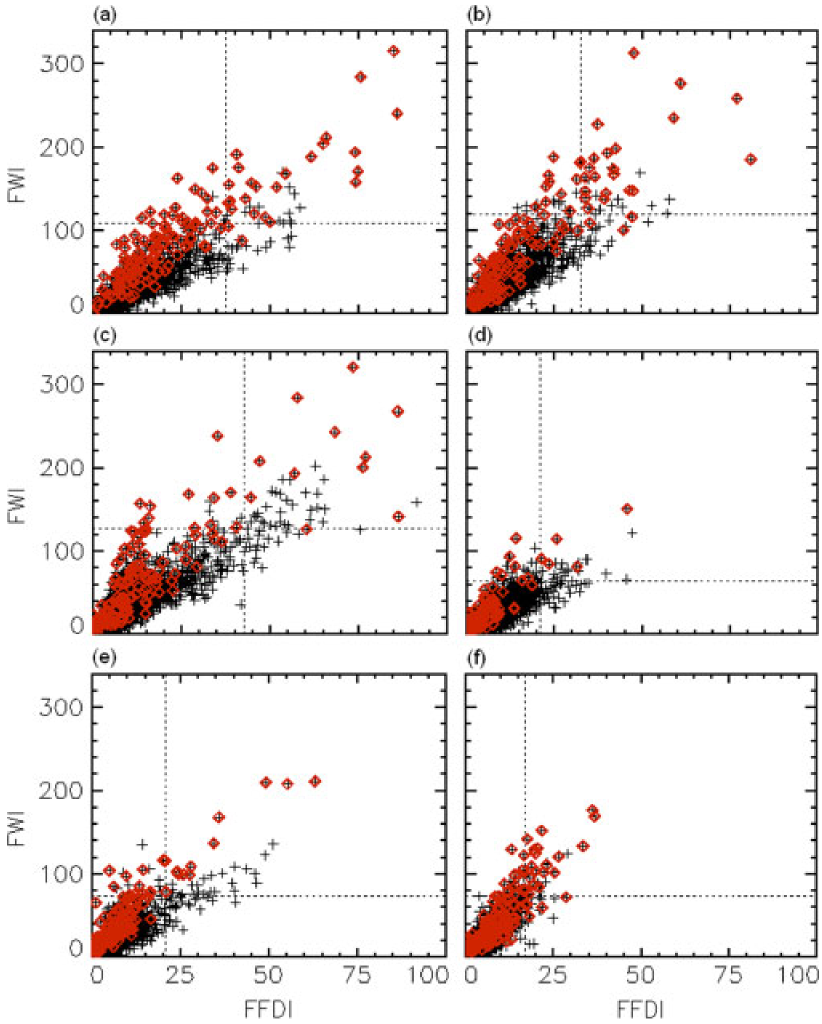


Figure 6. As for Figure 5, but with days highlighted by a '◊' to indicate where noon wind speeds are higher than their 95th percentiles. This figure is available in colour online at wileyonlinelibrary.com/journal/met

## 5.3. Equilibrium values

The sensitivities of the indices to long-term changes in an input parameter are examined in this section using equilibrium values of the indices. Equilibrium values of the indices are produced by setting all of the input parameters to be unchanging in time, so that the index eventually reaches a reasonably constant value (a variation from one day to the next of less than 1% of the index value has been used in this study). This removes the influence of the time lags which result from the feedback mechanisms whereby index components from the previous day are used as inputs for the current day (as occurs for the FFMC, DMC and DC of the FWI System, and the Drought Factor for the FFDI).

The equilibrium values show how the indices respond to long-term changes in their input parameters (e.g. to a prolonged period of high temperatures such as a heat wave), as well as how they could be expected to perform in different climatic regions. Figure 9 shows equilibrium values of the FWI plotted against equilibrium values of the FFDI. The equilibrium values are produced as the end result of 100 days of unchanging input conditions. The different points shown in Figure 9 represent different values of temperature and rainfall. Four different values of rainfall are shown (denoted by '+': 0 mm day$^{-1}$, '*': 1 mm day$^{-1}$, '◊': 2 mm day$^{-1}$ and '$\Delta$': 3 mm day$^{-1}$), as well as temperatures from 20 to 40 °C in 1 °C steps (with higher values of temperature corresponding to the higher index values). In all cases the relative humidity is 20%, the wind speed is 30 km h$^{-1}$, the day of the year is January 1, the latitude is 30 °S and the annual rainfall is 1000 mm.

The spread in the points shown in Figure 9 indicates that increasing temperature (for constant values of rainfall) favours high FFDI values, and that decreasing rainfall (for constant values of temperature) favours high FWI values. These sensitivity differences are for long-term changes in an input parameter. They are in the same direction to the sensitivity differences shown in Tables IV and V based on index derivatives (which represent changes in input parameters from one day to the next) with the main difference being that the sensitivity of the FWI to a long-term change in rainfall is considerably larger than for a short-term change in rainfall.

 

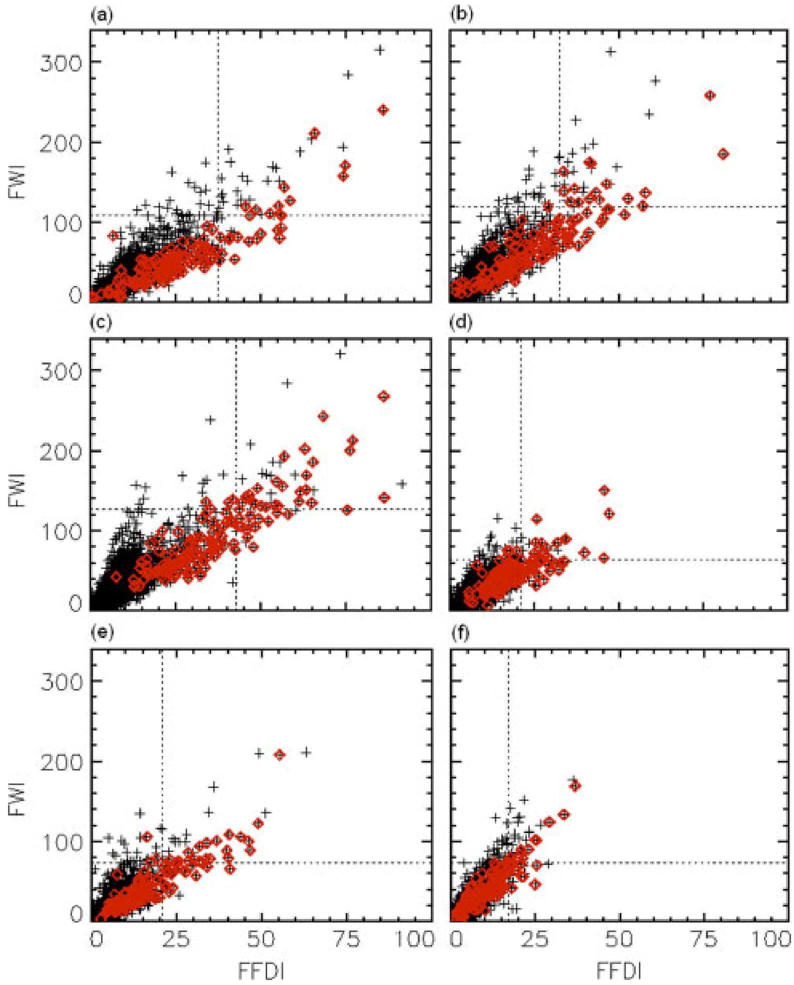


Figure 7. As for Figure 5, but with days highlighted by a '◊' to indicate where noon temperatures are higher than their 95th percentiles. This figure is available in colour online at wileyonlinelibrary.com/journal/met

A change in slope is apparent in Figure 9 at around $FFDI = 15$, corresponding to the point where the evapotranspiration term of the Drought Code used in the FFDI becomes larger than the effective rainfall term of the FFDI (Equation (4) in Finkele *et al*., 2006). This is effectively a temperature threshold, set by recent rainfall, above which the FFDI increases more rapidly due to an increased soil moisture deficit. This threshold does not occur in the formulation of the FWI, resulting in the nonlinearity apparent in Figure 9.

Figure 10 is similar to Figure 9, except that the wind speed and relative humidity are varied, while the temperature and rainfall are the same for all points. Four different values of relative humidity are shown (denoted by '×': 40%, '□': 35%, 'Δ': 30%, '◇':25% and '*': 20%), and wind speeds from 30 to 50 km $h^{-1}$ in 1 km $h^{-1}$ steps (with higher wind speeds corresponding to higher index values). In all cases the temperature is 35 °C, the rainfall is 2 mm $day^{-1}$, the day of the year is January 1, the latitude was 30 °S and the annual rainfall is 1000 mm.

The spread in the points in Figure 10 shows that increasing wind speeds (for constant relative humidity) favour high FWI values, while decreasing relative humidities (for constant wind speed) favour high FFDI values. This difference in sensitivity between the indices to long-term changes in wind speed and relative humidity is once again in the same direction as for short-term changes in input parameters (from Tables IV and V).

## 6. Severe Fire Events

The results of previous sections are applied here to examine a number of severe fire events:

- 25 December 2001 at Warragamba in New South Wales (Emergency Management Australia, 2008);
- 18 January 2003 at Canberra in the Australian Capital Territory (McLeod, 2003);
- 11 January 2005 at Wangary in South Australia (Bureau of Meteorology, 2005);
- 23 March 2005 at Bridgetown in Western Australia (McCaw, 2008; McCaw and Smith, 2008);
- 2 April 2005 at Wilsons Promontory in Victoria (Bureau of Meteorology, 2007), and
- 11 December 2006 at Scamander in Tasmania (Forestry Tasmania, 2007; Emergency Management Australia, 2008).

 

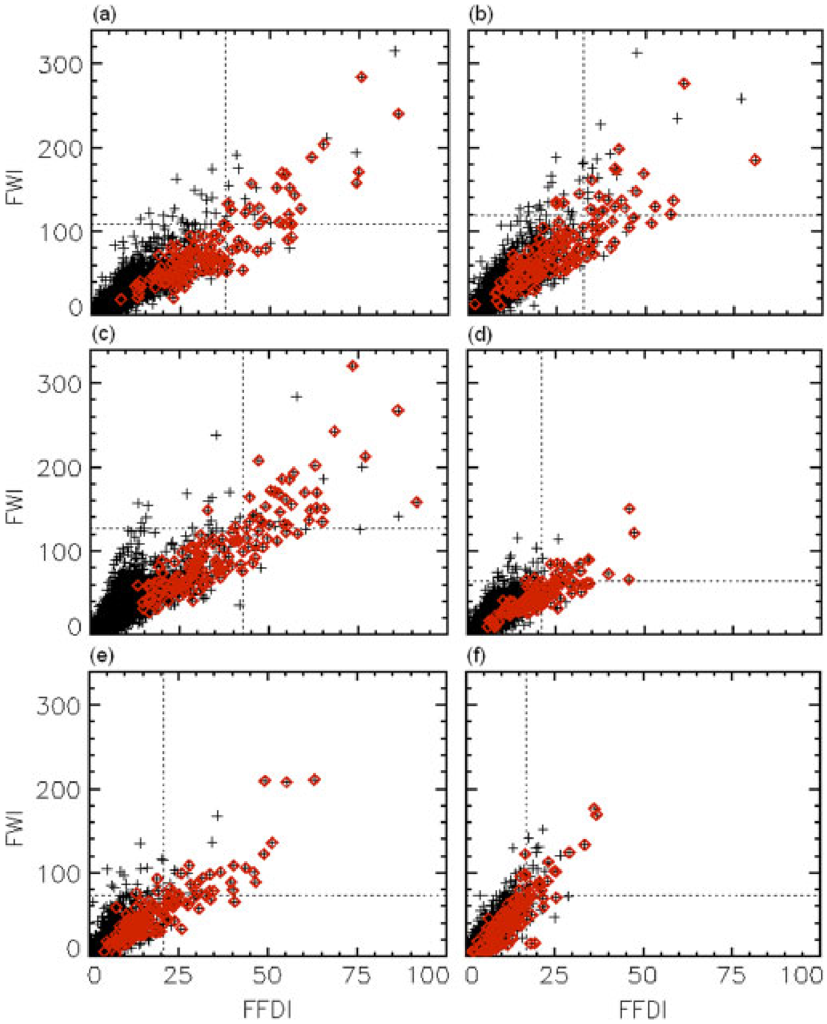


Figure 8. As for Figure 5, but with days highlighted by a '◊' to indicate where relative humidities are lower than their 5th percentiles. This figure is available in colour online at wileyonlinelibrary.com/journal/met

Table VI. The change in the fire weather index (FWI) due to a percentile change in an input parameter.

| | Location | | | | | |
|---|---|---|---|---|---|---|
| | Warragamba | Canberra | Wangary | Bridgetown | Wilsons Prom. | Scamander |
| Temperature (°C) | 5.7 | 6.1 | 10 | 6.6 | 9.5 | 5.8 |
| Wind speed (km $h^{-1}$) | 60 | 65 | 77 | 68 | 67 | 45 |
| Relative humidity (%) | 16 | 21 | 30 | 17 | 21 | 11 |
| FFMC | 16 | 18 | 21 | 17 | 17 | 7.2 |
| DMC | 8.5 | 5.9 | 1.7 | 2.6 | 17 | 12 |
| DC | 3.1 | 1.4 | 0.27 | 0.91 | 3.2 | 3.2 |

FFMC, Fine fuel moisture code; DMC, Duff moisture code; DC, Drought code.

Index values for each of these events are shown in Figure 5 (for the days listed above at the nearest grid point to each location). Although the FFDI and FWI show some similarities to each other in terms of how they represent the six events (e.g. their percentiles are all above 98), considerable differences between the two indices are also apparent. For example, the FFDI is slightly lower for the Scamander event ($FFDI = 36$) than for the Bridgetown event ($FFDI = 40$), whereas the FWI is considerably higher for the Scamander event ($FWI = 176$) than for the Bridgetown event ($FWI = 73$).

An ingredients-based approach is useful for examining the reasons for differences such as this. For example, time series for a 50 day period around the time of the Scamander fire (shown in Figure 11) indicate that the Scamander event is largely driven by high wind speeds (accompanied by temperatures that are relatively moderate by Australian standards). Based on the sensitivity analyses

 

Table VII. As for Table VI, but for the Forest Fire Danger Index (FFDI).

| | Location | | | | | |
|---|---|---|---|---|---|---|
| | Warragamba | Canberra | Wangary | Bridgetown | Wilsons Prom. | Scamander |
| Temperature (°C) | 6.1 | 5.4 | 10.8 | 5.6 | 7.1 | 3.4 |
| Wind speed (km $h^{-1}$) | 19 | 19 | 23 | 23 | 16 | 9.2 |
| Relative humidity (%) | 11 | 13 | 22 | 12 | 14 | 4.8 |
| Drought factor | 1.8 | 1.6 | 1.3 | 0.0 | 2.7 | 3.2 |

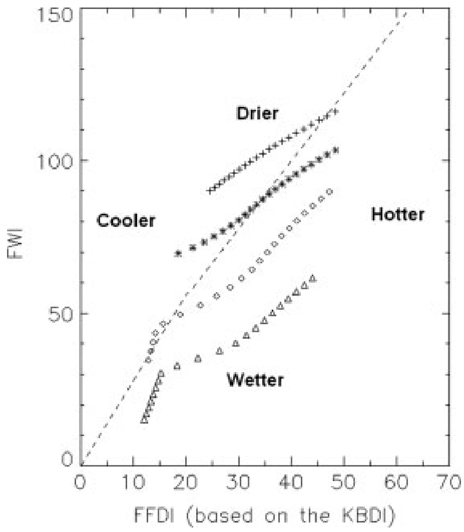


Figure 9. Equilibrium values of the FWI and FFDI for different temperature and rainfall conditions. The dotted line shows the national median relationship between the FWI and FFDI from Equation (2).

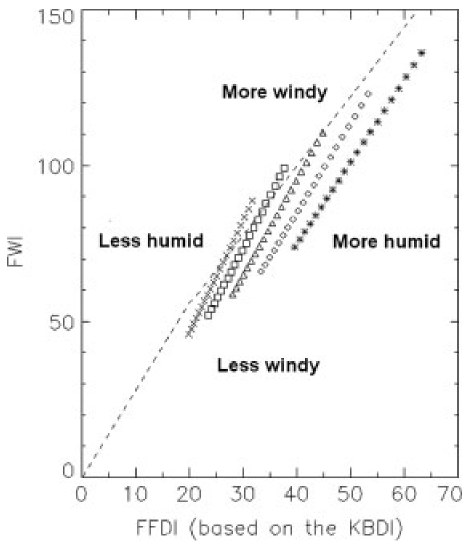


Figure 10. Equilibrium values of the FWI and FFDI for different relative humidity and wind speed conditions. The dotted line shows the national median relationship between the FWI and FFDI from Equation (2).

presented in the previous section, these conditions would be expected to favour high FWI values relative to the FFDI. In contrast to the Scamander event, the Bridgetown event (as detailed in Figure 12) is largely driven by high temperatures (accompanied by wind speeds that are not remarkably high), favouring high FFDI values relative to the FWI.

Apart from differences such as this, the indices are similar to each other in that they both vary by about a factor of three between the six events, even though severe fire behaviour occurred in all cases (including the breaking of containment lines and the occurrence of crown fires). This suggests that the significance of a particular index value, where significance is assessed in terms of the ranking of the magnitude of the index relative to its climate at that location, may be different in some locations than in others. In contrast to the index values, the index percentiles are more consistent between locations, being above 98 for all six events (for both the FWI and the FFDI).

## 7. Conclusion

A number of methodologies have been presented for examining how an index represents a given set of conditions. Percentile changes in input conditions revealed that the FWI and FFDI are similar to each other in that they are both most sensitive to wind speed, then secondly to relative humidity and thirdly to temperature. Thus, in a broad sense, the FWI and FFDI could be expected to show similar climatological patterns to each (as was apparent from Figure 2).

A finite difference method was used for calculating partial derivatives of the indices with respect to their input parameters, since the index formulation of the FWI did not allow derivatives to be calculated in a straight forward manner. The partial derivatives were combined with the relationship between the indices (produced based on matching the percentiles of the two indices to each other) to show that the sensitivities of the indices are somewhat different to each other on a fine scale, with the FFDI being relatively more sensitive to temperature and relative humidity, and less sensitive to wind speed and rainfall, than the FWI. Scatter plots were used to show that the sensitivity differences between the indices can account for the significant variations which frequently occur between the indices.

Equilibrium values of the indices were shown to be able to provide information about the sensitivities of the indices that was not apparent from other methods. For example, equilibrium values showed that the FFDI has a temperature threshold set by recent rainfall above which

 

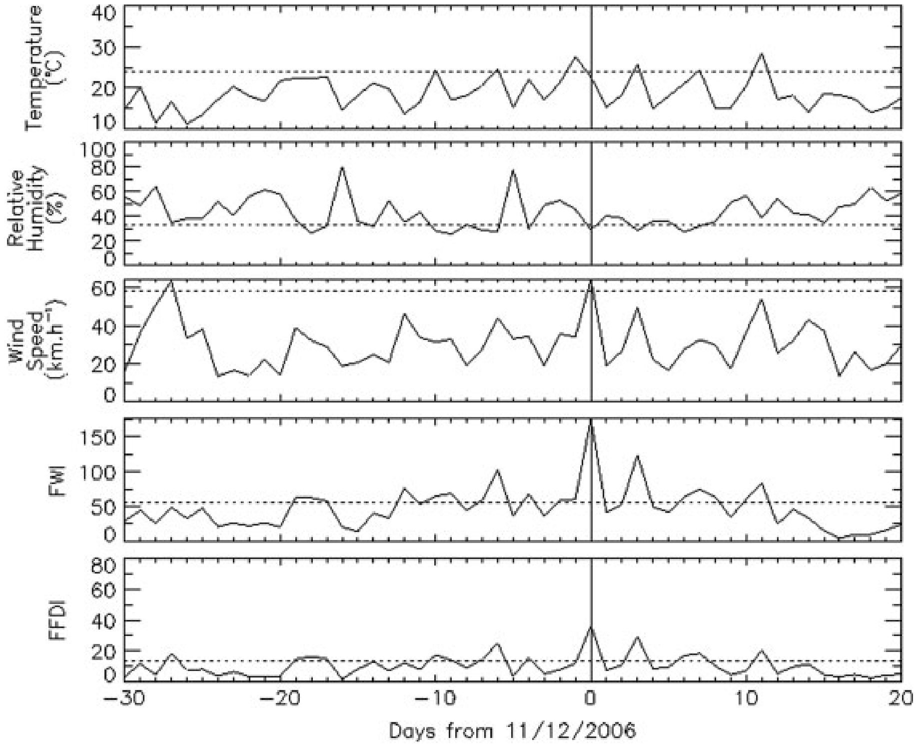


Figure 11. Time series of the FWI and FFDI at Scamander for days around 11 December 2006, shown together with NWP forecast noon values of temperature, relative humidity and wind speed. Dotted lines represent the 95th percentiles of each parameter at this location (or the 5th percentile for relative humidity).

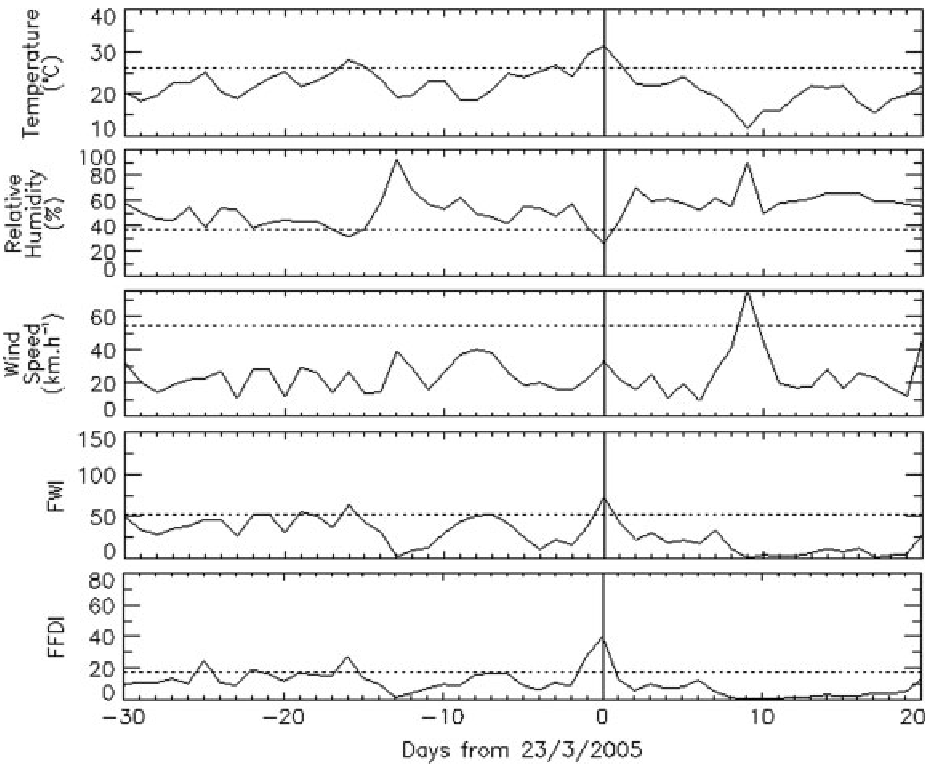


Figure 12. As for Figure 11, but for the Bridgetown fire event of 23 March 2005.

its sensitivity increases, resulting in some non-linearity in its relationship with the FWI. The equilibrium values of the indices also showed that some geographical variation in the relationship between the indices is to be expected, since the indices differ in their sensitivity to long-term changes in input parameters.

The variation in the relationship between the indices has a standard deviation throughout Australia of about

15% of the FWI value. The largest differences between the indices tend to occur in regions where index values are climatologically relatively low, where the FFDI generally indicates less severe conditions than the FWI. The likely reason for this was shown to be the fact that the derivatives of the FFDI are all directly proportional to the value of the FFDI, causing the sensitivities of the FFDI to decrease more quickly with decreasing index values than the FWI. This results in the FFDI generally indicating less severe conditions than the FWI in regions where index values are climatologically relatively lower.

The climatologies of the indices vary greatly across Australia, and even across relatively small regions of individual states. It was seen that many of the regions where the percentile values of FFDI and FWI are relatively low still correspond to regions where significant fire activity occurs (e.g. eastern Victoria, Tasmania and southwestern Western Australia). While Tasmania has reduced the numerical value of the FFDI threshold at which fire weather warnings are issued, due to the less extreme fire danger index climate of that state, such an approach is more problematic in states with a larger geographic variation in their fire danger index climatology. It is to be expected that the significance of an index value will show some degree of variation between different locations. For example, the FFDI and FWI are based on meteorological ingredients which means that the same index values (or identical meteorological parameters) may correspond to different fire activity in different vegetation types or fuel loads.

The assessment of an index in terms of its local climatology (using percentile values) reduces the regional variation in the significance on an index value, by highlighting conditions that are extreme relative to the local climatology. Index values associated with severe fire behaviour (i.e. the breaking of containment lines and the occurrence of crown fires) were found to vary by about a factor of three between the six recent fire events shown in Figure 5, while the index percentiles were above 98 in all cases. An index value with a percentile above 98 occurs only about 7 days a year on average at a given location. If a high index percentile occurs in a region where severe conditions are known to occur (such as the locations of the six fire events presented in Figure 5), it provides a good indication that severe conditions might be expected.

In spite of the similarity of the climatological distribution of percentiles of the FFDI and FWI over Australia, there are individual circumstances when one index may forecast a much higher value (in terms of its climatological distribution) than the other. These occasions tend to arise, as shown by some of the severe fire events examined here, when different ingredients are near the extreme limits of their distributions, and in these circumstances the differing relative sensitivities of the two indices do provide complementary information. The value of this complementary information is enhanced by an understanding of the relative sensitivities of the indices to their input parameters and the use of an ingredients-based approach to the interpretation of these differences.

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## References

Bureau of Meteorology. 2005. *Meteorological Report on the Wangary and Black Tuesday fires Lower Eyre Peninsula, 10–11 January 2005*. Bureau of Meteorology, South Australian Region: Adelaide, South Australia. October 2005.

Bureau of Meteorology. 2007. *Report on the April 2005 Wilsons Promontory Fire*. Bureau of Meteorology, Victorian Region: Melbourne, Victoria. June 2007.

Cruz MG, Plucinski MP. 2007. Billo road fire: report on fire behaviour and suppression activity. Report no. A.07.02, Bushfire Cooperative Research Centre: Melbourne.

Doswell CA III, Brooks HE, Maddox RA. 1996. Flash flood forecasting: an ingredients-based methodology. *Weather and Forecasting* **11**: 560–581.

Dowdy AJ, Finkele K, Mills GA, de Groot W. 2009. Australian fire weather as represented by the McArthur Forest Fire Danger Index and the Canadian Forest Fire Weather Index. CAWCR Technical Report No 10, Centre for Australian Weather and Climate Research: Docklands, Victoria, Australia.

Dudfield M. 2004. Art and science of forest and rural fire management. *Proceedings, AFAC/Bushfire CRC Annual Conference*, Perth, October 2004, 183–185.

Emergency Management Australia. 2008. Disasters database (http://www.ema.gov.au). Attorney General's Department – Commonwealth of Australia.

Finkele K, Mills GA, Beard G, Jones DA. 2006. National daily gridded soil moisture deficit and drought factors for use in prediction of forest fire danger index in Australia. Research Report No 119, Bureau of Meteorology Research Centre.

Forestry Tasmania. 2007. *2007 Annual Report*. Forestry Tasmania: Hobart, Tasmania, Australia.

Griffiths D. 1998. *Improved Formulae for the McArthur Forest Fire Danger Meter*. Meteorological Note 214. Bureau of Meteorology: Melbourne, Victoria.

de Groot WJ, Field RD, Brady MA, Roswintiarti O, Mohamad M. 2006. Development of the Indonesian and Malaysian fire danger rating systems. *Mitigation and Adaptation Strategies for Global Change* **12**(1): 165–180.

de Groot WJ, Wardati B, Wang Y. 2005. Calibrating the fine fuel moisture code for grass ignition potential in Sumatra, Indonesia. *International Journal of Wildland Fire* **14**: 161–168.

Keetch JJ, Byram GM. 1968. *A Drought Index for Forest Fire Control*. USDA Forest Service: Asheville, NC, USA. Research Paper SE-38.

Lawson BD, Armitage OB. 2008. *Weather guide for the Canadian Forest Fire Danger Rating System*. Natural Resources Canada, Canadian Forest Service: Edmonton, AB.

Luke RH, McArthur AG. 1986. *Bushfires in Australia*. Australian Government Publishing Service: Canberra.

McArthur AG. 1967. *Fire Behaviour in Eucalyptus Forests*. Department of National Development Forestry and Timber Bureau: Canberra, Leaflet 107.

McCaw L. 2008. *Fire in the bluegums*. Fire Australia. Winter 2008. Australasian Fire and Emergency Service Authorities Council: East Melbourne, Victoria.

McCaw L, Smith B. 2008. *Fire Behaviour in a 6 Year Old Eucalyptus globulus Plantation During Conditions of Extreme Fire Danger – A Case Study from South-Western Australia*. Bushfire Cooperative Research Centre: Melbourne (available at:

 

www.bushfirecrc.com/publications/downloads/Bluegum-plantation-fire-23-March-2005.pdf).

McLeod R. 2003. Inquiry into the operational response to the January 2003 bushfires in the ACT. Report No. 03/0537, ACT Government, Chief Minister's Department: Canberra.

Mills GA. 2005. On the subsynoptic-scale meteorology of two extreme fire weather days during the Eastern Australian fires of January 2003. *Australian Meteorological Magazine* **54**: 265–290.

Noble IR, Bary GAV, Gill AM. 1980. McArthur's fire-danger meters expressed as equations. *Australian Journal of Ecology* **5**: 201–203.

Puri K, Dietachmayer GD, Mills GA, Davidson NE, Bowen RA, Logan LW. 1998. The new BMRC Limited Area Prediction System (LAPS). *Australian Meteorological Magazine* **47**: 203–223.

Sullivan A. 2001. Review of the Operational Calculation of McArthur's Drought Factor. Client Report No. 921, CSIRO Forestry and Forest Products.

Taylor SW, Alexander ME. 2006. Science, technology, and human factors in fire danger rating: the Canadian experience. *International Journal of Wildland Fire* **15**: 121–135.

Van Wagner CE. 1974. *Structure of the Canadian Forest Fire Weather Index*. Canadian Forestry Service: Ottawa, ON, Publication No. 1333.

Van Wagner CE. 1987. Development and structure of the Canadian forest fire weather index system. Technical Report 35, Canadian Forestry Service: Ottawa, ON.

Viegas DX, Bovio G, Ferreira A, Nosenzo A, Sol B. 1999. Comparative study of various methods of fire danger evaluation in southern Europe. *International Journal of Wildland Fire* **9**(4): 235–246.

Weymouth G, Mills GA, Jones D, Ebert EE, Manton MJ. 1999. A continental-scale daily rainfall analysis system. *Australian Meteorological Magazine* **48**: 169–179.

 