Climatological Variability of Fire Weather in Australia

ANDREW J. DOWDY

Bureau of Meteorology, Docklands, Victoria, Australia

(Manuscript received 15 June 2017, in final form 6 October 2017)

ABSTRACT

Long-term variations in fire weather conditions are examined throughout Australia from gridded daily data from 1950 to 2016. The McArthur forest fire danger index is used to represent fire weather conditions throughout this 67-yr period, calculated on the basis of a gridded analysis of observations over this time period. This is a complementary approach to previous studies (e.g., those based primarily on model output, reanalysis, or individual station locations), providing a spatially continuous and long-term observations-based dataset to expand on previous research and produce climatological guidance information for planning agencies. Long-term changes in fire weather conditions are apparent in many regions. In particular, there is a clear trend toward more dangerous conditions during spring and summer in southern Australia, including increased frequency and magnitude of extremes, as well as indicating an earlier start to the fire season. Changes in fire weather conditions are attributable at least in part to anthropogenic climate change, including in relation to increasing temperatures. The influence of El Niño–Southern Oscillation (ENSO) on fire weather conditions is found to be broadly consistent with previous studies (indicating more severe fire weather in general for El Niño conditions than for La Niña conditions), but it is demonstrated that this relationship is highly variable (depending on season and region) and that there is considerable potential in almost all regions of Australia for long-range prediction of fire weather (e.g., multiweek and seasonal forecasting). It is intended that improved understanding of the climatological variability of fire weather conditions will help lead to better preparedness for risks associated with dangerous wildfires in Australia.

1. Introduction

Fire weather indices can be used to represent the combined influence of different meteorological factors and fuel information of relevance to risks associated with wildfires (known as bushfires in Australia). The McArthur forest fire danger index (FFDI; [McArthur 1967](#)) is a common measure used in many regions of Australia for examining the influence of near-surface weather conditions on fire behavior (as detailed in the data and methods section), with the Australian Bureau of Meteorology (BoM) routinely issuing forecasts of FFDI for use by fire management (including firefighting) authorities throughout Australia.

The purpose of this study is to examine the climatological variability of fire weather conditions throughout Australia based on a long period (i.e., 67 yr) of gridded FFDI data, with a focus on broadscale spatial and temporal features. This approach is intended to be complementary to previous studies including those based

primarily on model output as well as those based on station data that are necessarily focused on a number of individual point locations. For example, various recent studies have examined FFDI values in Australia from a climatological perspective, including based on station data ([Lucas 2010](#); [Fox Hughes 2011](#); [Clarke et al. 2013](#)), numerical weather prediction (NWP) model output ([Dowdy et al. 2009](#)), and global climate model output ([Williams et al. 2001](#); [Whetton et al. 2015](#)) as well as finer-scale downscaling from reanalyses and climate model output ([Grose et al. 2014](#); [Louis 2014](#); [Brown et al. 2016](#); [Clarke et al. 2016](#)). Although station data are useful for understanding the fire weather at a given location, they may not be ideal for understanding aspects of the spatial variability in fire weather conditions throughout a given region, while also noting issues associated with the relatively limited number of stations with a long time period of homogenous wind observations ([Jakob 2010](#); [Lucas 2010](#)), which can add uncertainty for spatial analyses of long-term changes. Spatial variations in fire weather conditions can be examined using approaches such as fine-resolution NWP or downscaling methods, while noting uncertainties associated with such approaches due to being primarily

Corresponding author: Andrew Dowdy, andrew.dowdy@bom.gov.au

based on modeling. Consequently, this study is novel in its examination of fire weather conditions based on a gridded analysis of observations over a long period (from 1950 to 2016) throughout Australia.

El Niño–Southern Oscillation (ENSO) can have a significant influence on fire weather conditions in Australia (Williams and Karoly 1999; Williams et al. 2001; Long 2006; Nicholls and Lucas 2007; Dowdy et al. 2016). Building on previous studies such as these, the influence of ENSO is examined here for individual seasons of the year based on a long time period of gridded FFDI data so as to examine both the seasonal and spatial characteristics of ENSO–fire weather relationships throughout Australia.

Extremely dangerous fire weather conditions can occur in Australia, including in temperate regions of southern Australia during the austral summer (Luke and McArthur 1978; Russell-Smith et al. 2007; Teague et al. 2009; Bradstock 2010; Sullivan et al. 2012; Murphy et al. 2013; Sullivan and Matthews 2013). There is a growing need to better understand climatological variations in extreme weather conditions, such as those leading to extreme fire danger and wildfires, particularly given the scientific consensus that global warming is unequivocally occurring because of anthropogenic influences and has enhanced fire danger in parts of the world (Seneviratne et al. 2012; IPCC 2013; Whetton et al. 2015; Abatzoglou and Williams 2016). Improved climatological knowledge of fire weather conditions in Australia, including the factors that influence its variability (e.g., large-scale natural modes of variability and the influence of anthropogenic climate change), is therefore an important research priority that could have benefits for a range of fields such as emergency management, planning, insurance, health, agriculture, climate change adaptation, and disaster risk reduction.

Details of the datasets and analyses used are provided in data and methods (section 2). A climatological examination of extreme fire weather conditions based on percentile measures and return period calculations is presented in section 3a. Long-term trends are examined in section 3b, with the influence of ENSO on fire weather conditions examined in section 3c. Results are discussed in section 4.

2. Data and methods

Daily values of the McArthur Mark V FFDI (McArthur 1967; Noble et al. 1980), are used for this study throughout the time period from 1950 to 2016. The FFDI is calculated here based on temperature T (°C), relative humidity RH (%), and wind speed v (km h^{−1}) on a given day, as well as a dimensionless number representing fuel availability called the drought factor (DF; Griffiths 1999), as shown in Eq. (1). This formulation is a

rearrangement of the commonly used formulation (Noble et al. 1980) so as to improve computational efficiency (including avoiding calculating the natural logarithm of DF within the exponential, while not changing the resultant FFDI value), which can be beneficial when applied to large gridded climatological data such as for this study:

$$\text{FFDI} = \exp(0.0338T - 0.0345\text{RH} + 0.0234v + 0.243147) \times \text{DF}^{0.987}. \quad (1)$$

The drought factor is partly based on a temporally accumulated soil moisture deficit, calculated here using the Keetch–Byram drought index (KBDI; Keetch and Byram 1968), as described by Finkele et al. (2006). The KBDI is based on a memory of antecedent temperature and rainfall data, so as to provide an estimate of the soil moisture below saturation up to a maximum field capacity (in an agricultural sense where the soil micropores are full but the macropores are empty) of 203.2 mm (i.e., 8 in., corresponding to KBDI = 203.2, representing the driest conditions) and a minimum of 0 mm (corresponding to KBDI = 0, representing the wettest conditions). Although there are a number of uncertainties associated with the KBDI estimate of fuel moisture, such as not including the influence of wind or humidity in contrast to some fuel moisture measures such as those of the Canadian Fire Weather Index (FWI) System (Van Wagner 1987; Dowdy et al. 2009), the KBDI is a common measure used in Australia for input to the FFDI and therefore is selected for use here given its broadscale relevance for fire management applications in Australia. Temperature and precipitation data are used here from 1948 onward, such that the KBDI and drought factor have a 2-yr period in which to accumulate their modeled representation of the soil moisture on a given day, prior to the start of the period for which FFDI values are examined in this study (i.e., 1 January 1950).

Although the FFDI is commonly used in Australia, there are a range of other indices that are available, such as the FWI System that has been applied widely throughout many climatic zones of the world (Van Wagner 1987; Dowdy et al. 2009; Field et al. 2015), as well as the National Fire Danger Rating System (NFDRS) used in the United States (Deeming et al. 1977). Additionally, indices such as the Haines index are also sometimes considered by fire agencies in relation to the potential influence of tropospheric stability and moisture on fire behavior (Haines 1988; Mills and McCaw 2010).

The input variables for calculating the FFDI values used in this study consist primarily of a gridded analysis of observations from the Australian Water Availability Project (AWAP; Jones et al. 2009), with all analysis in this

study using this AWAP grid of 0.05° in both latitude and longitude throughout Australia. The input variables for the FFDI used here from the AWAP data include daily maximum temperatures as well as vapor pressure at 1500 local time (used here together with temperature to calculate relative humidity near the time of maximum temperature) and daily accumulated precipitation totals for the 24-h period to 0900 local time each day. Because of the lack of suitable gridded wind observations for Australia, 6-hourly NCEP–NCAR reanalysis (Kalnay et al. 1996) data are used for surface wind speeds, with the 0600 UTC value used here (representing midafternoon wind speeds over the longitude range spanned by Australia). The reanalysis wind fields are bilinearly interpolated to the AWAP grid, with bias correction subsequently applied to provide a better match to the NWP-based 0600 UTC value of the 10-min average wind speeds used operationally by BoM for issuing forecasts of the FFDI [i.e., quantile–quantile matching for the bias correction, limited to a maximum change of 10% from the original reanalysis wind speed and trained over all days in the period 2005–15 using the “ACCESS” NWP model (Puri et al. 2013)]. Although other gridded wind datasets have been produced for the Australian region, the NCEP–NCAR data are the best available for the long study period examined here, given the relatively limited number of stations that have wind data of suitable quality (Jakob 2010; Lucas 2010) and noting that datasets based on spatial interpolation of station wind data such as McVicar et al. (2008) have additional limitations for the purposes of this study in only providing daily average wind speeds with a start date from the year 1975. It is also noted that the density of the ground-based observations used to produce the AWAP dataset is variable throughout Australia. In particular, there is relatively sparse data availability in parts of the central and western desert regions of the Australia continent, such that care is taken here when interpreting and discussing results for these regions.

The focus of this study is on broadscale temporal variations in fire weather conditions for regions throughout Australia, based on a relatively long period of gridded FFDI data. The analysis and interpretation of results are primarily focused on temperate and subtropical regions of Australia (rather than the central deserts and tropical north of Australia) as these regions are where the FFDI is most widely used. It is also noted that other fire weather indices, such as those representing grassland conditions, have greater relevance in the more northern regions and that there is considerable regional variation in the key drivers of burned area and other measures of fire activity (Russell-Smith et al. 2007).

Seasonal mean values of daily FFDI are calculated individually at each grid point as well as for each year of

available data. This is done based on 3-month periods for December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). The resultant time series of seasonal FFDI values is used to examine long-term changes in fire weather conditions. Long-term changes in seasonal mean FFDI values are calculated here based on comparing the first and second halves of a given time period for statistically significant differences in the seasonal FFDI values. This method does not rely on the assumption of a linear trend over the time period. This is a novel aspect of the study design, relating to having a long period of available data (spanning more than six decades), allowing climatological mean values to be examined for a number of different time periods with minimal influence from natural variability (e.g., variations at interannual to decadal scales). This analysis of long-term changes in fire weather presented here is based on seasonal values from 1951 to 2016 (i.e., 66 yr, from December 1950 to November 2016).

The influence of ENSO (as represented by the Niño-3.4 index), an ocean–atmosphere coupled mode with strong interaction between the Walker circulation and the Pacific Ocean (Rasmusson and Carpenter 1982; Latif et al. 1998), on fire weather conditions is examined throughout Australia based on the time series of seasonal FFDI values. Three-month averages of Niño-3.4 are used here for DJF, MAM, JJA, and SON for each year from 1951 to 2016, obtained from the National Oceanic and Atmospheric Administration (NOAA) (from <http://www.cpc.ncep.noaa.gov/>).

The sample Pearson’s correlation coefficient r is used to examine the dependence between ENSO and fire weather conditions, based on concurrent seasonal correlations of the FFDI and Niño-3.4 datasets. The 95% confidence level is used throughout this study to examine the significance of the correlations as well as of the long-term climatological changes, determined using a nonparametric bootstrap method based on 500 random permutations of the data.

Extreme values are examined based on a number of different metrics, including for relatively moderate measures as represented by the 90th, 95th, and 99th percentiles as well as more severe conditions as represented by the 1-, 5-, and 10-yr return periods (sometimes also referred to as average recurrence interval): for example, the 1-yr return period is equal to the 99.7th percentile, that is, $100 - (1/365.25)100 = 99.7$. The approach used here is complementary to alternative methods based on extreme value theory, such as using statistical modeling to simulate the shape of the upper tail of the data distribution (e.g., Louis 2014), given that extreme values are examined here based on the frequency of occurrence of daily FFDI values throughout the entire study period (noting that this is

FIG. 1. Extreme fire weather conditions throughout Australia, as represented by six different measures. FFDI values are shown corresponding to the (a) 90th, (b) 95th, and (c) 99th percentiles as well as the (d) 1-, (e) 5-, and (f) 10-yr return periods. These values are calculated individually for each grid location based on the daily values from 1950 to 2016. The black contours represent intervals of 20, as shown in the key.

another benefit of having over six decades of available data). Figures 1 and 2 use a ± 4 -gridpoint spatial averaging in both latitude and longitude, so as to focus on regional-scale features of the extreme conditions shown in those figures, with no averaging applied to the other figures presented in this study (Figs. 3–6, on the analyses of trends and ENSO relationships).

3. Results

a. Climatological maps for various occurrence frequencies

Figure 1 shows extreme FFDI values corresponding to a number of different occurrence frequencies. The

results are based on daily values throughout the 67-yr period of available data (from 1950 to 2016) calculated individually for each gridpoint location.

The spatial features show some similarities between the different occurrence frequencies, particularly for the percentile-based measures, with the larger FFDI values typically occurring in the more inland regions of the Australian continent. Although coastal regions generally have relatively low values, extremely high FFDI values can also reach coastal regions in some rare cases as shown by the multiyear return period values (Figs. 1e,f), particularly around the western and southern parts of the continent, as well as in some parts of eastern Australia.

FIG. 2. The mean number of days per month that the FFDI is above the annual 90th percentile. The 90th percentile is calculated for each individual grid location, based on all days throughout the period 1950–2016. Results are shown for the months from July to June, with contours for values of 4, 8, and 12.

Relatively low values occur in many of the eastern locations along the Australian continent, corresponding to elevated regions of the Great Dividing Range near the eastern Australian coastline. However, these regions still experience dangerous fire weather conditions, highlighting the point that a particular value of the FFDI can indicate a different level of danger in different locations. Consequently, these spatially continuous results indicate that the percentile (or similarly, the return period) of a fire weather index value can be a useful quantity to consider when examining fire weather conditions over varied climatic regions, similar to results and discussion presented previously by Dowdy et al. (2010). For example,

from Fig. 1, considering the spatial variations of the contour lines it is evident that a FFDI value of 40 in some regions of southeast Australia indicates close to record high values (e.g., exceeding the 10-yr return period value), whereas in some other regions of central Australia this represents conditions that occur relatively frequently (e.g., similar to the 90th percentile value).

The spatial variability in these extreme values shown in Fig. 1 is also valuable for highlighting regions with exceptionally high values of FFDI. Locations with values above 100 are generally in the central parts of the Australian continent away from the coast. However, there are some locations near the coast where the 10-yr

FIG. 3. Long-term changes in seasonal mean FFDI values. This is shown for the change from the first half (1951–83) to the second half (1984–2016) of the study period during (a) DJF, (b) MAM, (c) JJA, and (d) SON. This is also shown for the change from the third quarter (1983–99) to the fourth quarter (2000–16) of the study period during (e) DJF, (f) MAM, (g) JJA, and (h) SON. The colored regions represent locations where the magnitude of the change is significant at the 95% confidence level.

return period (Fig. 1f) of the FFDI is above 100, including for the south, southeast, and central-west coasts of continental Australia.

Figure 2 shows the mean number of days per month that the FFDI is above the 90th-percentile value, where

the 90th percentile is based on all days throughout the year for the period 1950–2016, calculated for each individual grid location. This highlights the months of the year when dangerous fire weather conditions typically occur at a given location. The results are shown here for

FIG. 4. As in Fig. 3, but for long-term changes in the number of daily FFDI values per season greater than the 90th percentile value at a given location.

the months from July to June, so as to highlight the temporal evolution of the fire weather conditions from before until after the austral summer period (i.e., the period around the months from December to February). The results presented here are not directly comparable with studies that have examined climatological variations in fire activity, noting seasonality differences between fire weather and fire activity as

discussed by studies such as [Russell-Smith et al. \(2007\)](#), given that the FFDI is an indicator of fire weather conditions whereas fire occurrence depends on many factors (including fuel conditions and ignition sources).

From about December to February, the southern parts of Australia typically experience their highest FFDI values, while noting that high values also occur during March in some of the southern extremities

FIG. 5. Time series for the period 1951–2016 based on results averaged over southern Australia (south of 30°S). This is shown for mean FFDI values during the (a) DJF and (b) SON seasons. This is also shown for the average number of days per season that the FFDI is above the 90th percentile at a given grid location during the (c) DJF and (d) SON seasons.

(including Tasmania and coastal regions of the Australian continent in the southwest and southeast). Another notable feature is a narrow region running along the central east coast of Australia that experiences its highest FFDI values relatively early in the year. The highest values in that region (i.e., the central eastern seaboard of Australia) occur from September to November, whereas at similar latitudes in nearby regions to the west the highest values occur from November to January. The seasonal changes are broadly consistent with spatiotemporal variations in the influences of the broadscale drivers of climate variability experienced in Australia, including the influences of the monsoon and trade winds on the more northern regions of the continent as well as fronts, low pressure systems, and blocking highs on the more southern regions. These drivers can influence fire weather

climatology and variability through their influence on weather variables such as those that the FFDI are based on [including temperature and rainfall, as detailed in Whetton et al. (2015; their sections 4.1 and 5.2.3)]. Additionally, these results presented in Fig. 2 show broad similarities to those based on 8 yr of NWP output (Dowdy et al. 2009) including for the general spatial features and monthly variability, while noting that the 67-yr period of available data used here provides a considerable degree of confidence in the features shown as an accurate representation of the long-term climatology for each month of the year.

b. Long-term changes in fire weather

Figure 3 shows locations where a long-term change is apparent based on time series of seasonal FFDI data

FIG. 6. Correlations between seasonal values of Niño-3.4 and FFDI for the time period from 1951 to 2016. The correlations are calculated individually for (a) DJF, (b) MAM, (c) JJA, and (d) SON. Correlations are also shown between seasonal values of Niño-3.4 and the number of days per season that the FFDI is above its 90th percentile at a given location, calculated individually for (e) DJF, (f) MAM, (g) JJA, and (h) SON. The colored regions represent locations where the magnitude of the correlation is significant at the 95% confidence level.

(i.e., seasonal mean values of daily FFDI, calculated for individual years). Results are calculated individually for four different seasons (DJF, MAM, JJA, and SON) for the time periods from 1951 to 2016 (i.e., from December

1950 to November 2016) and from 1983 to 2016 (i.e., from December 1982 to November 2016). Only changes that are significant at the 95% confidence level are shown.

Statistically significant long-term changes are generally positive in sign (i.e., increases in FFDI values over these time periods). Relatively widespread regions of increased FFDI values occur in some cases, such as for the more recent time period in southeast Australia during the SON season (Fig. 3h). The main region where a decrease in FFDI values has occurred is in northern Australia during DJF where rainfall has increased substantially in recent years (Whetton et al. 2015), also noting that this is during the wet season in the tropical northern regions of Australia when fire activity is uncommon (Russell-Smith et al. 2007).

Figure 4 is similar to Fig. 3, but for the number of days per season that are above the 90th percentile (i.e., the values shown in Fig. 1a). The results show some differences to those based on the mean FFDI values. For example, the recent increase during the JJA season in western Australia based on the mean FFDI values (from Fig. 3g) is not apparent based on the number of days above the 90th percentile (Fig. 4g). However, it is noted that there are very few days above the 90th percentile in this region during these months (Fig. 2), with this period being when dangerous fire weather conditions are typically only experienced in the far-north coastal regions of Australia (noting some increases apparent for those regions from Fig. 4g). Additionally, the vast majority of the island of Tasmania has recent increases in the number of days above the 90th percentile in DJF since around the year 2000 (Fig. 4e), in contrast to the case for the mean FFDI values (Fig. 3e). Some similarities are also apparent between the results based on the number of days above the 90th percentile and those based on the mean FFDI values, including recent increases in southern Australian regions during SON.

To further examine these results from Figs. 3 and 4, including the recent increases since around the year 2000 for southern Australia, Fig. 5 presents time series of spatially averaged values throughout southern Australia (south of 30°S), presented for the mean FFDI values in that region, as well as for the mean number of days per season that the FFDI is above the 90th percentile at a given grid location in that region. Results are shown individually for the DJF and SON seasons, based on data from 1951 to 2016 (i.e., from December 1950 to November 2016).

The mean FFDI time series for DJF in southern Australia shows some indication of a long-term increase over the study period (Fig. 5a, similar to the spatial changes indicated previously from Fig. 3e), as do the mean values for SON (Fig. 5b, similar to the spatial changes indicated previously from Fig. 3h). Recent increases are also apparent in the number of days above the 90th percentile for both DJF (Fig. 5c) and SON

(Fig. 5d), similar to the changes shown previously in Figs. 4e and 4h, respectively. These increases are all associated with more frequent high values in recent decades than earlier decades, with many of the highest values on record occurring since the year 2002, including for the mean FFDI values (Fig. 5b) as well as for the number of days above the 90th percentile (Fig. 5d). These recent extreme cases for SON (i.e., cases shown in Fig. 5d since about the year 2000 with values around 20 days or higher) are similar in magnitude to the typical values for DJF prior to that time period (i.e., the mean value from 1951 to 1999 in Fig. 5c is 21 days), suggesting a seasonal expansion in the timing of when extreme fire weather conditions could be likely to occur in this region. This long-term change for weather conditions during spring (SON) in southern Australia is broadly consistent with previous studies based on other datasets and methods in indicating a trend toward an earlier start to the fire season (e.g., Jolly et al. 2015) with such increases in the seasonal window conducive to burning also likely to promote increased opportunities for the occurrence of large fires.

For spring (SON in Fig. 5b), the mean FFDI during the period from 1951 to 1999 is 14, increasing to 17 during the period from 2000 to 2016 (i.e., representing a change of 21% since the start of this century). Similarly for the number of days above the 90th percentile in spring (Fig. 5d), the change over those time periods is from 2.6 to 3.5 days (i.e., an increase of 35%). For the input variables to the FFDI, the changes in daily mean values over those time periods and region are from 23.0° to 24.2°C for temperature, from 1.3 to 1.2 mm for rainfall, from 38% to 34% for relative humidity, from 6.64 to 6.68 m s⁻¹ for wind speed, and from 65 to 76 for KBDI. Although it is difficult to deconstruct the exact individual contributions to the trend in FFDI given the multiple influencing factors [e.g., from Eq. (1) including noting that relative humidity and KBDI are in part dependent on air temperature], these results indicate that the increased FFDI values are associated with the combination of a number of factors. This includes higher values for temperature, wind speed, and KBDI (representing the temporally integrated measure used for representing soil moisture conditions here) as well as lower values for rainfall and relative humidity, all of which are consistent in sign with a tendency toward higher values of the FFDI.

In contrast to the extremely high values shown in Fig. 5, there is little indication of a long-term increase in the occurrence of the extremely low values. Consequently, this trend toward increased magnitudes for the higher values corresponds to a general increase in interannual variability in recent decades. For example, the standard deviation of values shown in Fig. 5d has

increased by about 54% since the start of this century, from 4.1 days for the period from 1951 to 1999 to 6.3 days for the period from 2000 to 2016.

The nonstationarity in the occurrence of extreme values evident from these results has implications for quantifying fire weather risk, including in relation to preparedness for hazardous conditions in the current climate, as well as in relation to planning and disaster risk reduction efforts for future time periods. It is also noted that the temporal changes are nonlinear over the study period, highlighting the benefits of using datasets available over a long period of time as well as analysis methods that do not assume linear changes (as is the case for the results presented in Figs. 3 and 4).

c. Influence of ENSO on the variability of Australian fire weather

Spatial maps of the correlation between Niño-3.4 (as a measure of the state of ENSO) and mean FFDI values are shown in Fig. 6. The correlations are presented for locations where the relationship is significant at the 95% confidence level. Correlations are calculated individually for each grid point and for each season, based on the period from 1951 to 2016 (i.e., from December 1950 to November 2016). Results are also shown based on the number of days that the FFDI is above its 90th percentile.

Large regions where significant relationships occur between Niño-3.4 and seasonal mean FFDI values are apparent, with almost all locations having a significant correlation for at least one season. These correlations are positive in sign, indicating that higher FFDI values are generally associated with El Niño conditions (characterized by high values of Niño-3.4) and lower FFDI values with La Niña conditions (characterized by low values of Niño-3.4). The influence of ENSO on the number of days that the FFDI is above its 90th percentile shows some differences to the case for the mean FFDI values. In particular, there are relatively few regions with significant relationships during JJA (Fig. 6g) as compared with the case for the mean FFDI values (Fig. 6c), while noting that this period of the year generally does not have many days above the 90th percentile (from Fig. 2).

There are some regions where the ENSO–FFDI relationship is not very strong in a given season. This includes for some fire-prone regions, such as the southwest of the continent during spring for the mean values (Fig. 6d) and the number of days above the 90th percentile (Fig. 6h). Given that ENSO is predictable up to several months in advance in some cases, results such as those shown in Fig. 6 suggest that although many regions of Australia could potentially benefit from the development of long-range fire weather forecasts (i.e.,

based on model predictions of ENSO conditions or FFDI values at lead times from weeks to seasons), the usefulness of such applications would likely vary regionally throughout Australia as well as temporally throughout the year.

4. Discussion

The results presented here provide new insight on the climatological variability of daily fire weather conditions, as represented by FFDI values based on a gridded analysis of observations throughout Australia. The 67-yr period of data used for this study allows a considerable degree of confidence in the features apparent in these climatologies, including in relation to broadscale temporal and spatial variations.

Spatial variations in extreme values were examined based on measures ranging from the 90th percentile up to the 10-yr return period. From a fire behavior perspective, such knowledge is important for planning applications as well as for input to simulations of wildfire that need to consider potential threats to communities under “extreme” or “catastrophic” conditions (e.g., Blanchi et al. 2010). Furthermore, the findings also demonstrate that the spatial variability in these different measures of extremes (i.e., the percentiles and return periods) are also valuable for highlighting regions where relatively moderate magnitude values of FFDI may actually be considered as representing dangerous fire weather conditions for a particular region, even though this value of FFDI may occur relatively frequently and not represent dangerous fire weather conditions in other regions of Australia.

Long-term changes in FFDI values are apparent, with substantial increases in recent years in the frequency of dangerous fire weather conditions particularly during spring and summer in southern Australia. It was found that these increases in southern Australia are predominantly due to an increased frequency of occurrence of the higher FFDI values in recent decades, including numerous examples since the year 2000 that are higher than anything recorded previously (Figs. 5a–d) together with increased variability (i.e., standard deviation) of fire weather conditions from one year to the next, noting that knowledge of changes such as these is important for fire management authorities to consider in relation to preparedness for risks associated with extreme fire events.

Although previous studies based on different datasets and methods have also indicated a general long-term change in fire weather conditions characterized by FFDI values increasing with time in many regions of Australia, the results presented here additionally show some differences to previous studies. For example, Clarke et al.

(2013) reported that the largest increases in FFDI occurred in spring and autumn, whereas the results presented here (e.g., from Fig. 4) indicate that the trends during spring (SON) are notably stronger than autumn (MAM). Differences such as these could plausibly be associated with different methods and study periods, noting that they examined 38 locations in Australia using linear regression over a 38-yr period (1973–2010).

A benefit of the long time period used here, from 1950 to 2016, is that it allows substantial confidence when examining the nonstationarity in extreme fire weather conditions (e.g., although extremes are rare by definition, this time period results in a reasonable sample size for the extreme measures examined here). A notable aspect of the study findings is that the long-term increases in the mean and extreme fire weather conditions are nonlinear over the study period, with the largest magnitude changes occurring in the most recent time periods including for the southern parts of Australia during spring and summer (Fig. 5).

The long-term changes in fire weather conditions (Figs. 3 and 4) are broadly consistent with observed long-term trends in temperature throughout Australia as well as in rainfall in some cases. For example, the climatology of a wide range of meteorological features was recently examined throughout Australia based on a synthesis of various different observations and analyses (including based on the AWAP dataset as used here) as well as climate modeling from global and regional downscaling models (Whetton et al. 2015), showing significant anthropogenic climatological changes have occurred in Australia in line with expectations based on increasing concentrations of greenhouse gases in the atmosphere (IPCC 2013). The observed daily maximum temperature for Australia has increased by about 1.0°C since the year 1910, noting that a large amount of this increase occurred during the second half of the twentieth century (Bureau of Meteorology and CSIRO 2016), with models also indicating with very high confidence a continued long-term increase throughout this century in daily maximum temperature for all regions of Australia and for all seasons of the year (Whetton et al. 2015).

Changes in the other input variables to the FFDI are generally less certain than for temperature (including for relative humidity and wind speed). However, cool season rainfall has decreased and is projected to continue to decrease in southern Australia in general, with some indications that this decrease has already occurred based on observations in some regions (e.g., for the southwest region of Australia as well as parts of Victoria in southeast Australia), while wetter conditions have occurred in recent decades in the northwest of Australia (Whetton et al. 2015; Bureau of Meteorology and

CSIRO 2016; Hope et al. 2017). The time period from 1997 to 2009 had lower-than-normal rainfall in parts of southern Australia and is sometimes referred to as the Millennium Drought (Hope et al. 2017), while also noting that the severe fire weather conditions that have occurred in recent decades are not confined to that time period (e.g., many of the extremely high values in each panel of Fig. 5 occur since the year 2010).

The long period of available data (spanning more than six decades) allows climatological analysis with minimal influence from natural variability (e.g., internal climate fluctuations associated with ENSO and other sources of interannual- to decadal-scale variability), with the long-term climate change signal for Australian fire weather conditions being clearly apparent based on the results presented here (e.g., from Figs. 3 and 4). For the example shown in Fig. 5, on the recent FFDI increases in southern Australia during spring, all input variables for the FFDI were found to have changes in sign consistent with increasing FFDI, including increasing temperatures for which anthropogenic climate change influences are well established (IPCC 2013; Whetton et al. 2015; Bureau of Meteorology and CSIRO 2016).

The influence of ENSO on fire weather conditions has been examined in numerous studies, including for various individual regions of Australia (Williams and Karoly 1999; Williams et al. 2001; Long 2006; Nicholls and Lucas 2007), other regions of the world (Swetnam and Betancourt 1990; Veblen et al. 1999; Beckage et al. 2003; Holz and Veblen 2011; Spessa et al. 2015), and globally (Dowdy et al. 2016). Furthermore, a previous study (Harris et al. 2008) found significant relationships between ENSO and fire activity in southeast Australia, while noting this was considering fire occurrence data rather than fire weather indices such as the FFDI. Complementary to previous studies, the results presented here highlight a number of variations in the influence of ENSO on fire weather conditions, including between different seasons and regions. Although such findings suggest considerable scope for further examinations into physical processes linking ENSO and fire weather variability [e.g., variations in extreme fire weather conditions associated with approaching cold fronts in southern Australia (Reeder and Smith 1987; Mills 2005; Fiddes et al. 2016)], the correlations are predominantly positive in sign between the Niño-3.4 and the FFDI measures examined here. This corresponds to more severe fire weather conditions generally occurring for El Niño than La Niña conditions for each of the four seasons examined here. These results for the FFDI are consistent with a recent study examining these four seasons (Dowdy et al. 2016) that showed similar seasonal relationships for the Australian region between ENSO

and a different measure of fire weather conditions: the FWI (Van Wagner 1987; Field et al. 2015).

Results such as these (e.g., from Fig. 6) show that there is strong potential for long-range forecasting (e.g., on subseasonal to seasonal time scales) of fire weather in Australia, given that ENSO can be predictable several months in advance in some cases (Latif et al. 1998). Further work toward realizing this potential could build on the results presented here by examining the degree of skill in predicting FFDI values at long lead times (e.g., from weeks to months in advance), including based on statistical methods such as correlations similar to Fig. 6 but for various different time lags, as well as based on FFDI values derived from dynamical models used operationally for seasonal prediction services.

The findings of this study will have benefits for a range of different applications, such as helping to inform fire authorities and planning agencies in relation to climatological variations in the risk of dangerous wildfire conditions for regions throughout Australia. This includes spatial variations in the risk of extreme conditions, variations associated with long-term trends in fire weather conditions, and shorter-term modes of atmospheric and oceanic variability such as ENSO. The results presented here will also help provide broadscale climatological guidance for assessing modeling efforts to understand the influence of future projected climate change on fire weather conditions, including through providing a benchmark for assessing historical variations in gridded fire weather conditions throughout Australia. An improved ability to understand and prepare for dangerous wildfires is intended to lead to greater resilience in relation to wildfire impacts on built and natural environments, with benefits for a wide range of groups such as industry, government, insurance, and emergency services.

Acknowledgments. This research was supported by the Australian Government's National Environmental Science Programme. Data are available on request from the Bureau of Meteorology.

REFERENCES

- Abatzoglou, J. T., and A. P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Natl. Acad. Sci. USA*, **113**, 11 770–11 775, <https://doi.org/10.1073/pnas.1607171113>.
- Beckage, B., W. J. Platt, M. G. Slocum, and B. Panko, 2003: Influence of the El Niño Southern Oscillation on fire regimes in the Florida Everglades. *Ecology*, **84**, 3124–3130, <https://doi.org/10.1890/02-0183>.
- Blanchi, R., C. Lucas, J. Leonard, and K. Finkele, 2010: Meteorological conditions and wildfire-related house loss in Australia. *Int. J. Wildland Fire*, **19**, 914–926, <https://doi.org/10.1071/WF08175>.
- Bradstock, R. A., 2010: A biogeographic model of fire regimes in Australia: Current and future implications. *Global Ecol. Biogeogr.*, **19**, 145–158, <https://doi.org/10.1111/j.1466-8238.2009.00512.x>.
- Brown, T. J., G. Mills, S. Harris, D. Podnar, H. J. Reinbold, and M. G. Fearon, 2016: A bias corrected WRF mesoscale fire weather dataset for Victoria, Australia 1972–2012. *J. South. Hemisphere Earth Syst. Sci.*, **66**, 281–313, <https://doi.org/10.22499/3.6003.00004>.
- Bureau of Meteorology and CSIRO, 2016: State of the climate 2016. Tech. Rep., 22 pp., <http://www.bom.gov.au/state-of-the-climate/State-of-the-Climate-2016.pdf>.
- Clarke, H., C. Lucas, and P. Smith, 2013: Changes in Australian fire weather between 1973 and 2010. *Int. J. Climatol.*, **33**, 931–944, <https://doi.org/10.1002/joc.3480>.
- , A. J. Pitman, J. Kala, C. Carouge, V. Haverd, and J. P. Evans, 2016: An investigation of future fuel load and fire weather in Australia. *Climatic Change*, **139**, 591–605, <https://doi.org/10.1007/s10584-016-1808-9>.
- Deeming, J. E., R. E. Burgan, and J. D. Cohen, 1977: The National Fire Danger Rating System—1978. USDA Forest Service General Tech. Rep. INT-39, 63 pp.
- Dowdy, A. J., G. A. Mills, K. Finkele, and W. de Groot, 2009: Australian fire weather as represented by the McArthur forest fire danger index and the Canadian forest fire weather index. CAWCR Tech. Rep. 10, 84 pp., http://www.bushfirecrs.com/sites/default/files/managed/resource/ctr_010.pdf.
- , —, —, and —, 2010: Index sensitivity analysis applied to the Canadian forest fire weather index and the McArthur forest fire danger index. *Meteor. Appl.*, **17**, 298–312, <https://doi.org/10.1002/met.170>.
- , R. D. Field, and A. C. Spessa, 2016: Seasonal forecasting of fire weather based on a new global fire weather database. *Proc. Fifth Int. Fire Behaviour and Fuels Conf.*, International Association of Wildland Fire, 1–6, <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170003345.pdf>.
- Fiddes, S. L., A. B. Pezza, and J. Renwick, 2016: Significant extratropical anomalies in the lead up to the Black Saturday fires. *Int. J. Climatol.*, **36**, 1011–1018, <https://doi.org/10.1002/joc.4387>.
- Field, R. D., and Coauthors, 2015: Development of a global fire weather database. *Nat. Hazards Earth Syst. Sci.*, **15**, 1407–1423, <https://doi.org/10.5194/nhess-15-1407-2015>.
- Finkele, K., G. A. Mills, G. Beard, and D. A. Jones, 2006: National daily gridded soil moisture deficit and drought factors for use in prediction of forest fire danger index in Australia. Bureau of Meteorology Research Centre Research Rep. 119, 68 pp.
- Fox-Hughes, P., 2011: Impact of more frequent observations on the understanding of Tasmanian fire danger. *J. Appl. Meteor. Climatol.*, **50**, 1617–1626, <https://doi.org/10.1175/JAMC-D-10-05001.1>.
- Griffiths, D., 1999: Improved formula for the drought factor in McArthur's forest fire danger meter. *Aust. For.*, **62**, 202–206, <https://doi.org/10.1080/00049158.1999.10674783>.
- Grose, M. R., P. Fox-Hughes, R. M. B. Harris, and N. L. Bindoff, 2014: Changes to the drivers of fire weather with a warming climate—A case study of southeast Tasmania. *Climatic Change*, **124**, 255–269, <https://doi.org/10.1007/s10584-014-1070-y>.
- Haines, D. A., 1988: A lower atmosphere severity index for wildland fires. *Natl. Wea. Dig.*, **13**, 23–27.
- Harris, S., N. Tapper, D. Packham, B. Orlove, and N. Nicholls, 2008: The relationship between the monsoonal summer rain and dry-season fire activity of northern Australia. *Int. J. Wildland Fire*, **17**, 674–684, <https://doi.org/10.1071/WF06160>.
- Holz, A., and T. T. Veblen, 2011: Wildfire activity in rainforests in western Patagonia linked to the southern annular mode. *Int.*

- J. *Wildland Fire*, **21**, 114–126, <https://doi.org/10.1071/WF10121>.
- Hope, P., B. Timbal, H. Hendon, M. Ekström, and N. Potter, 2017: A synthesis of findings from the Victorian Climate Initiative (VicCI). Bureau of Meteorology Rep., 56 pp., <http://www.bom.gov.au/research/projects/vicci/docs/2017/VicCI-SynR-MR.pdf>.
- IPCC, 2013: *Climate Change 2013: The Physical Science Basis*. Cambridge University Press, 1535 pp., <https://doi.org/10.1017/CBO9781107415324>.
- Jakob, D., 2010: Challenges in developing a high-quality surface wind-speed data-set for Australia. *Aust. Meteor. Oceanogr. J.*, **60**, 227–236, <https://doi.org/10.22499/2.6004.001>.
- Jolly, W. M., M. A. Cochrane, P. H. Freeborn, Z. A. Holden, T. J. Brown, G. J. Williamson, and D. M. J. S. Bowman, 2015: Climate-induced variations in global wildfire danger from 1979 to 2013. *Nat. Commun.*, **6**, 7537, <https://doi.org/10.1038/ncomms8537>.
- Jones, D. A., W. Wang, and R. Fawcett, 2009: High-quality spatial climate data-sets for Australia. *Aust. Meteor. Oceanogr. J.*, **58**, 233–248.
- Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471, [https://doi.org/10.1175/1520-0477\(1996\)077<0437:TNYP>2.0.CO;2](https://doi.org/10.1175/1520-0477(1996)077<0437:TNYP>2.0.CO;2).
- Keetch, J. J., and G. M. Byram, 1968: A drought index for forest fire control. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station Res. Paper SE-38, 35 pp.
- Latif, M., and Coauthors, 1998: A review of the predictability and prediction of ENSO. *J. Geophys. Res.*, **103**, 14 375–14 393, <https://doi.org/10.1029/97JC03413>.
- Long, M., 2006: A climatology of extreme fire weather days in Victoria. *Aust. Meteor. Mag.*, **55**, 3–18.
- Louis, S. A., 2014: Gridded return values of McArthur forest fire danger index across New South Wales. *Aust. Meteor. Oceanogr. J.*, **64**, 243–260, <https://doi.org/10.22499/2.6404.001>.
- Lucas, C., 2010: On developing a historical fire weather data-set for Australia. *Aust. Meteor. Oceanogr. J.*, **60**, 1–14, <https://doi.org/10.22499/2.6001.001>.
- Luke, R. H., and A. G. McArthur, 1978: *Bushfires in Australia*. Australia Government Publishing Service, 359 pp.
- McArthur, A. G., 1967: *Fire Behaviour in Eucalypt Forests*. Australia, Forestry and Timber Bureau, Leaflet 107, Forestry and Timber Bureau, 36 pp.
- McVicar, T. R., T. G. Van Niel, L. T. Li, M. L. Roderick, D. P. Rayner, L. Ricciardulli, and R. J. Donohue, 2008: Wind speed climatology and trends for Australia, 1975–2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output. *Geophys. Res. Lett.*, **35**, L20403, <https://doi.org/10.1029/2008GL035627>.
- Mills, G. A., 2005: A re-examination of the synoptic and mesoscale meteorology of Ash Wednesday 1983. *Aust. Meteor. Mag.*, **54**, 35–55.
- , and L. McCaw, 2010: Atmospheric stability environments and fire weather in Australia—Extending the Haines index. CAWCR Tech. Rep. 20, 151 pp., http://cawcr.gov.au/technical-reports/CTR_020.pdf.
- Murphy, B. P., and Coauthors, 2013: Fire regimes of Australia: A pyrogeographic model system. *J. Biogeogr.*, **40**, 1048–1058, <https://doi.org/10.1111/jbi.12065>.
- Nicholls, N., and C. Lucas, 2007: Interannual variations of area burnt in Tasmanian bushfires: Relationships with climate and predictability. *Int. J. Wildland Fire*, **16**, 540–546, <https://doi.org/10.1071/WF06125>.
- Noble, I. R., A. M. Gill, and G. A. V. Bary, 1980: McArthur's fire-danger meters expressed as equations. *Aust. J. Ecol.*, **5**, 201–203, <https://doi.org/10.1111/j.1442-9993.1980.tb01243.x>.
- Puri, K., and Coauthors, 2013: Implementation of the initial ACCESS numerical weather prediction system. *Aust. Meteor. Oceanogr. J.*, **63**, 265–284, <https://doi.org/10.22499/2.6302.001>.
- Rasmusson, E. M., and T. H. Carpenter, 1982: Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Wea. Rev.*, **110**, 354–384, [https://doi.org/10.1175/1520-0493\(1982\)110<0354:VITST>2.0.CO;2](https://doi.org/10.1175/1520-0493(1982)110<0354:VITST>2.0.CO;2).
- Reeder, M. J., and R. K. Smith, 1987: A study of frontal dynamics with application to the Australian summertime “cool change.” *J. Atmos. Sci.*, **44**, 687–705, [https://doi.org/10.1175/1520-0469\(1987\)044<0687:ASOFDW>2.0.CO;2](https://doi.org/10.1175/1520-0469(1987)044<0687:ASOFDW>2.0.CO;2).
- Russell-Smith, J., and Coauthors, 2007: Bushfires “down under”: Patterns and implications of contemporary Australian landscape burning. *Int. J. Wildland Fire*, **16**, 361–377, <https://doi.org/10.1071/WF07018>.
- Seneviratne, S. I., and Coauthors, 2012: Changes in climate extremes and their impacts on the natural physical environment. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, C. B. Field et al., Eds., Cambridge University Press, 109–230.
- Spessa, A. C., and Coauthors, 2015: Seasonal forecasting of fire over Kalimantan, Indonesia. *Nat. Hazards Earth Syst. Sci.*, **15**, 429–442, <https://doi.org/10.5194/nhess-15-429-2015>.
- Sullivan, A. L., and S. Matthews, 2013: Determining landscape fine fuel moisture content of the Kilmore East “Black Saturday” wildfire using spatially-extended point-based models. *Environ. Modell. Software*, **40**, 98–108, <https://doi.org/10.1016/j.envsoft.2012.08.008>.
- , L. McCaw, M. G. Da Cruz, S. Matthews, and P. Ellis, 2012: Fuel, fire weather and fire behaviour in Australian ecosystems. *Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World*. CSIRO Publishing, 51–77.
- Swetnam, T. W., and J. L. Betancourt, 1990: Fire-Southern Oscillation relations in the southwestern United States. *Science*, **249**, 1017–1020, <https://doi.org/10.1126/science.249.4972.1017>.
- Teague, B., R. McLeod, and S. Pascoe, 2009: The fires and the fire-related deaths. Vol. 1, Victorian Bushfires Royal Commission Final Rep., 360 pp., <http://royalcommission.vic.gov.au/Commission-Reports/Final-Report/Volume-1/High-Resolution-Version.html>.
- Van Wagner, C. E., 1987: Development and structure of the Canadian Forest Fire Weather Index System. Forestry Tech. Rep. 35, 37 pp., <http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/19927.pdf>.
- Veblen, T. T., T. Kitzberger, R. Villalba, and J. Donnegan, 1999: Fire history in northern Patagonia: The roles of humans and climatic variation. *Ecol. Monogr.*, **69**, 47–67, [https://doi.org/10.1890/0012-9615\(1999\)069\[0047:FHINPT\]2.0.CO;2](https://doi.org/10.1890/0012-9615(1999)069[0047:FHINPT]2.0.CO;2).
- Whetton, P., M. Ekström, C. Gerbing, M. Grose, J. Bhend, L. Webb, and J. Risbey, Eds., 2015: Climate change in Australia: Projections for Australia's NRM regions. CSIRO and Bureau of Meteorology Tech. Rep., 218 pp., https://www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/cms_page_media/168/CCIA_2015_NRM_TechnicalReport_WEB.pdf.
- Williams, A. A. J., and D. J. Karoly, 1999: Extreme fire weather in Australia and the impact of the El Niño–Southern Oscillation. *Aust. Meteor. Mag.*, **48**, 15–22.
- , —, and N. Tapper, 2001: The sensitivity of Australian fire danger to climate change. *Climatic Change*, **49**, 171–191, <https://doi.org/10.1023/A:1010706116176>.