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LETTER

Measurement of inter- and intra-annual variability of landscape fire activity at a continental scale: the Australian case

Grant J Williamson[1], Lynda D Prior[1], W Matt Jolly[2], Mark A Cochrane[3], Brett P Murphy[4] and David M J S Bowman[1]

[1] School of Biological Sciences, University of Tasmania, Private Bag 55, Hobart, Tasmania 7001, Australia
[2] USDA Forest Service, RMRS, Fire Sciences Laboratory, Missoula, MT 59808, USA
[3] Geospatial Sciences Center of Excellence, South Dakota State University, Brookings, SD 57007, USA
[4] Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin NT 0909, Australia

E-mail: grant.williamson@utas.edu.au

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Abstract

Climate dynamics at diurnal, seasonal and inter-annual scales shape global fire activity, although difficulties of assembling reliable fire and meteorological data with sufficient spatio-temporal resolution have frustrated quantification of this variability. Using Australia as a case study, we combine data from 4760 meteorological stations with 12 years of satellite-derived active fire detections to determine day and night time fire activity, fire season start and end dates, and inter-annual variability, across 61 objectively defined climate regions in three climate zones (monsoon tropics, arid and temperate). We show that geographic patterns of landscape burning (onset and duration) are related to fire weather, resulting in a latitudinal gradient from the monsoon tropics in winter, through the arid zone in all seasons except winter, and then to the temperate zone in summer and autumn. Peak fire activity precedes maximum lightning activity by several months in all regions, signalling the importance of human ignitions in shaping fire seasons. We determined median daily McArthur forest fire danger index ($FFDI_{50}$) for days and nights when fires were detected: $FFDI_{50}$ varied substantially between climate zones, reflecting effects of fire management in the temperate zone, fuel limitation in the arid zone and abundance of flammable grasses in the monsoon tropical zone. We found correlations between the proportion of days when FFDI exceeds $FFDI_{50}$ and the Southern Oscillation index across the arid zone during spring and summer, and Indian Ocean dipole mode index across south-eastern Australia during summer. Our study demonstrates that Australia has a long fire weather season with high inter-annual variability relative to all other continents, making it difficult to detect long term trends. It also provides a way of establishing robust baselines to track changes to fire seasons, and supports a previous conceptual model highlighting multi-temporal scale effects of climate in shaping continental-scale pyrogeography.

Introduction

Landscape fires play a crucial role in the Earth system, influencing vegetation distribution and structure, the carbon cycle and climate (Bowman *et al* 2009). Bradstock (2010) provides a conceptual framework to understand the constraints on landscape fire occurrence where all of the following four 'switches' must be simultaneously 'on': (1) sufficient biomass that is (2) dry enough to burn, with (3) weather conducive to fire-spread and (4) an ignition source . All switches are strongly affected by climate, and their relative importance in constraining fire activity varies among ecosystems, resulting in fundamentally different fire regimes (Bradstock 2010). Implicit in Bradstock's (2010) four switch model is a temporal hierarchy of climate effects from the decadal (fuel production), inter-annual (drought cycles), intra-annual or seasonal (periods of severe fire weather) to daily and hourly (heat waves and lightning storms) (Murphy et al 2011). Establishing baselines and detecting effects of climate change on fire activity requires consideration of all these temporal scales.

The potential importance of multi-scale temporal changes to fire activity is supported by recent research. Globally, there is concern that fire weather is worsening as temperatures rise and droughts become more frequent and intense (Hansen *et al* 2010, Dai 2013, Trenberth *et al* 2014). Analyses of meteorological data from 1979 to 2013 show that fire weather seasons are significantly lengthening across 25% of the Earth's vegetated surface, with a corresponding 19% increase in global mean fire season length (Jolly *et al* 2015). Lightning is a key ignition source of landscape fire (Bradstock 2010). It accounts for a disproportionately large area burnt, in part because lightning fires often start under extreme weather conditions, occur in clusters making fires difficult to extinguish and occur in remote regions where suppression is difficult (Price and Rind 1994, Attiwill and Adams 2013). In addition to causing longer-lasting and more severe fire weather, global climate change is also likely to increase fire activity through increasing thunderstorm activity (Price and Rind 1994, Reeve and Toumi 1999). Analysis of climate models has shown that thunderstorm occurrence may decrease under a future warmer climate yet thunderstorm intensity is likely to increase, with 10% more lightning for every °C of warming (Price 2009). A global study which combined modelled lightning projections under enhanced emissions scenarios with fire ignitions modelled through a land surface vegetation model (Krause *et al* 2014) found a 21.3% increase in cloud-to-ground lightning strikes over the coming century. This is predicted to increase the area burnt by lightning fires in Australia by 7.4%, concentrated in the north and in the arid interior. Amongst the many repercussions of increased fire activity due to longer fire seasons and increased lightning would be a release of more greenhouse gases to the atmosphere, intensifying the warming trend and creating a positive feedback with landscape fire.

Defining fire season onset and length is a complex problem constrained by fire records, meteorological data availability and their time depth. It is important to note that Jolly *et al* (2015) did not relate fire season onset and length to actual fire activity, but rather they estimated fire season length by counting the number of days above the median value of an ensemble of fire danger indices. Here, we develop an alternative approach to quantitatively describe fire seasons based on satellite detections of fire activity. Using actual fire activity has the advantage of integrating all factors that drive fire activity, namely weather, the availability of dry fuel and ignitions (Bradstock 2010, Krawchuk and Moritz 2011). The disadvantage, however, is the short period covered by the satellite record (since 2003), which makes it difficult to detect long-term trends.

Satellite detection provides insights into multi-temporal scales of fire activity at the diurnal, inter-, and intra-annual scales. While analyses of seasonal and inter-annual satellite-detected fire activity are well established (Giglio *et al* 2006a, 2006b, van der Werf *et al* 2006, Russell-Smith *et al* 2007, Archibald *et al* 2010), differentiation of diurnal patterns has received less consideration (but see Giglio 2007) although this is now possible using the four daily passes of the moderate-resolution imaging spectro-radiometer (MODIS) instruments on the Aqua and Terra Earth observation satellites. Differentiating day-time and night-time satellite-derived active fire detections (henceforth referred to as 'hotspots'; Giglio *et al* 2006a) is important because for much of the year, landscape fires will burn only during the day, and self-extinguish during the night due to lower temperatures, higher relative humidity and lower wind speeds. These are the periods targeted for prescribed burning. By contrast, night-time hotspots tend to be present only during the peak fire season, when the largest and most intense fires occur (Maier and Russell-Smith 2012), and if coincident with lightning this is the period when large, landscape fires could occur without human ignitions.

Australia has featured prominently in research into multi-scale temporal dynamics effects on fire, given it has vast areas of uncleared, native vegetation, which frequently burns (Murphy *et al* 2011). Continental-scale analyses have shown that Australian fire activity is largely driven by rainfall seasonality linked to summer monsoon activity (Russell-Smith *et al* 2007, Murphy *et al* 2013). Fires are most frequent and extensive in northern Australia, where the annual wet season promotes grass growth, followed by curing during the dry season. This is consistent with the strong global correspondence between the area burnt by fire and intra-annual variability in rainfall (Notaro 2008, Bowman *et al* 2014). In southern Australia, fires are less frequent, but can be much more intense (Murphy *et al* 2013) and cause loss of life and property (Attiwill and Adams 2013). These analyses also show the pronounced shift in timing of fire season, from winter-dominated in the north, to summer and autumn-dominated in the south of the continent (Russell-Smith *et al* 2007). However, there has been less consideration of inter-annual variability in fire weather and fire activity, despite the importance of the El Niño-Southern oscillation (ENSO) in shaping the ecology of the continent (Flannery 1997, Saji *et al* 1999, Orians and Milewski 2007). Intriguingly, Australia was the only vegetated continent for which Jolly *et al* (2015) did not detect a lengthening fire weather season. It was not clear why Australia was exceptional, but here we suggest that a contributing factor could be Australia's highly variable climate (Kershaw *et al* 2003). For example, the coefficient of inter-annual variation in rainfall is typically higher than for other continents (Fatichi *et al* 2012). It is plausible that this climatic variability masked any underlying trends in Australia's fire weather, particularly given the short instrumental record.

In this study, we use Australia as a model system to explore the coupling of fire and climate variation at the inter-annual, seasonal and daily scales. This is important both to provide regional baselines, as well as illuminating the peculiarities of Australia. Here, we revisit the Jolly *et al* (2015) dataset to ask whether inter-annual variability in fire season length is larger in Australia than the other continents, thereby making it more difficult to detect significant trends in fire season length. We also combine the fire activity dataset with meteorological data from across Australia and (a) define 61 climatic regions within the monsoon tropics, the arid and the temperate zones, and use these to describe spatial and seasonal variability in fire weather; (b) quantify inter-annual variability in fire weather; (c) assess the strength of the relationship between fire weather and day- and night-time fire activity in each climate zone by comparing weather conditions at the time when fires are burning, relative to when there is no fire activity; (d) having established the conditions when fires are most likely to occur in each climate zone, we show the spatiotemporal patterns of days with such conditions; and finally (e) examine how strongly fire weather across Australia is related to inter-annual climate modes (ENSO and the Indian Ocean dipole (IOD)).

Methods

Climate regionalisation

In order to examine fire activity across Australia, we objectively partitioned the continent into climatically similar regions based on long-term means of the following variables: annual precipitation, annual water balance, January maximum temperature, January precipitation, July minimum temperature, July precipitation, solar radiation and rainfall seasonality. This suite of climate variables captures the major drivers of plant productivity (growing season temperature and water availability) while being able to discriminate the seasonality of northern Australia, which has a winter dry season, from southern Australia, a wetter, cooler winter. These variables also incorporate important aspects of landscape-scale fire weather, including fuel drying based on rainfall, temperature and solar radiation. These means were generated for the period 1970–2000 on a 0.05° grid using ANUCLIM (version 6.1; Hutchinson and Xu 2011). Using these data, *k*-means clustering was then performed in R (R Core Team 2015), where latitude and longitude were included in order to ensure geographically constrained regions, followed by a 3×3 majority filter. Each of the 61 climate regions thus identified was classified as belonging to one of three climatic zones (monsoon tropical, arid, or temperate) based on the broad Köppen–Geiger groups A, B, and C, respectively (Kottek et al 2006) (figure 1; appendix S1).

Regional forest fire danger index (FFDI) analyses

We used the Scientific Information for Land Owners (SILO) patched-point meteorological dataset (Jeffrey *et al* 2001), which is based on daily data compiled from 4760 meteorological stations across Australia and spans the period from 1900 to 2011. The SILO data included daily maximum and minimum temperature, precipitation, pan evaporation, and maximum and minimum relative humidity. Mean daily wind speed, and synoptic wind speeds were obtained from the Australian Bureau of Meteorology for 1661 locations across Australia. These were interpolated on a daily time-step using thin plate spline surfaces, and joined to the SILO meteorological dataset. Few stations recorded wind prior to the mid-1950s (appendix S1), so wind interpolations prior to this date have a higher error.

The McArthur FFDI is an index of fire danger, linked to spread rate, spotting distance and controllability, and was first developed through observations of fire behaviour in Australian forests (McArthur 1966). The index is calculated from air temperature, dew point, wind speed, and a drought factor that incorporates the moisture content of fine fuels based on antecedent rainfall. Unlike modular systems such as the US National Fire Danger Rating System, and the Canadian Forest Fire Danger Rating System, the McArthur FFDI is based on a single, simple equation. FFDI was calculated for each meteorological station on a daily time-step according to the method of Noble et al (1980), using minimum daily relative humidity, maximum daily temperature and mean daily wind speed. These values therefore approximate daily maximum FFDI. For each station, we calculated the mean and inter-annual coefficient of variation of FFDI for each month.

Daily mean FFDI values were calculated for each region as follows. Polygons were created around each of the 4760 stations using Voronoi partitioning in the R package *dismo* (v.0.9-3; Hijmans *et al* 2013), where each polygon represented an area closest to the station, and daily FFDI values of each station were weighted by the polygon area to calculate daily area-weighted regional mean FFDI values. These regional daily means were pooled and used to calculate the 5%, 25%, 50%, 75% and 95% percentiles for each month and climate zone, using the package *quantreg* (v.5.05; Koenker 2013).

Regional landscape fire and lightning activity

The MODIS instruments on the Aqua and Terra Earth observation satellites detect fires at a temporal resolution of four passes daily (roughly 10:30 and 1:30 am and pm), during both day- and night-time, at a resolution of approximately 1 km (Giglio *et al* 2006a).

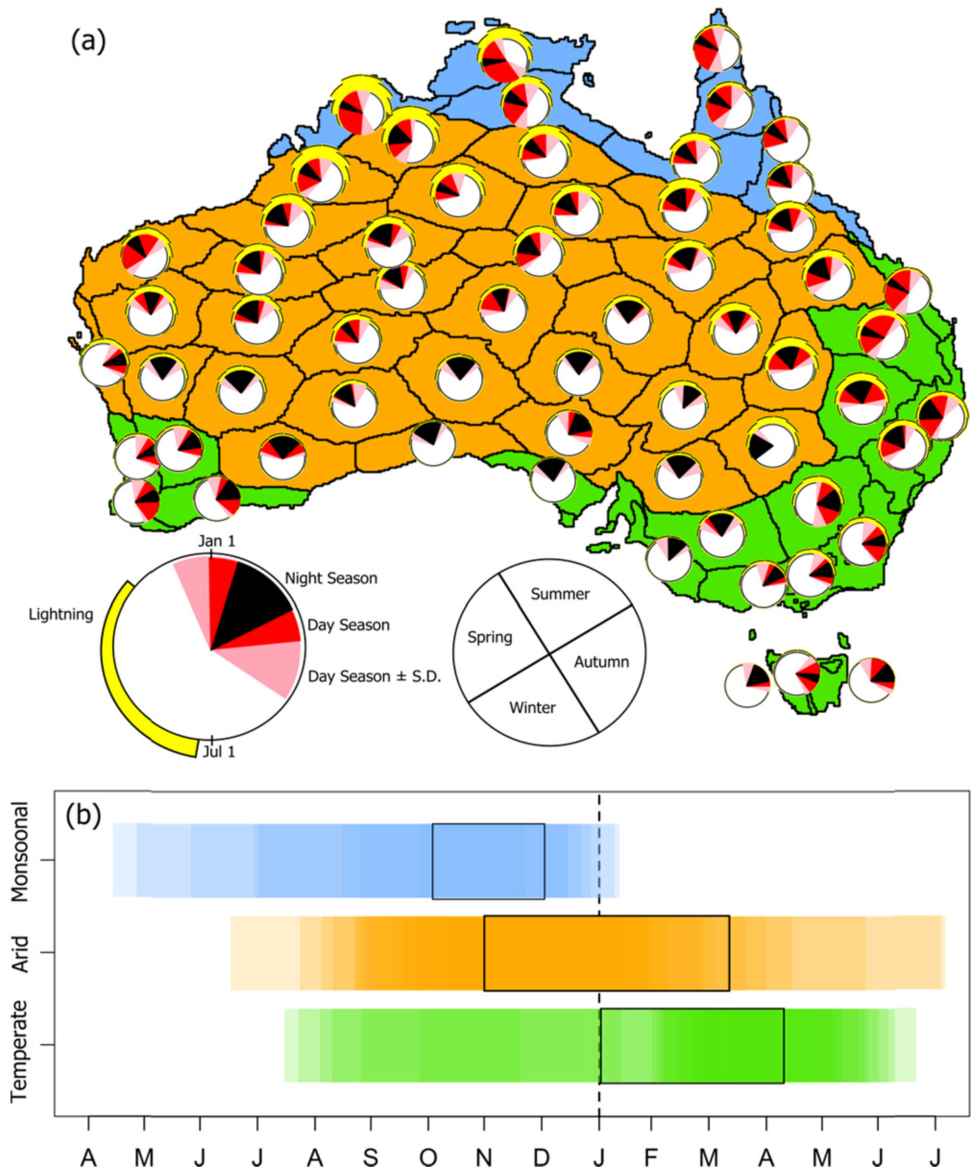

Figure 1. Geographical variation of seasonal fire activity, and its variability, across Australia. (a) Day- and night-time fire seasons, based on MODIS hotspot detections from 2000 to 2011, for the 61 climate regions in the three climate zones. Blue indicates the monsoon tropics, orange the arid zone and green the temperate zone. The circles represent the months of the year arranged in a clockwise direction, with 1 January at the top. The black slice indicates the night-time fire season, the red slices indicate day-time fire season, the pink is the standard deviation among years in day-time fire season start and end dates, and white signifies the period outside the fire season. The green outer ring indicates the density of lightning strikes. (b) Timing of the day-time fire seasons in the monsoon tropics, arid and temperate climate zones. Colour intensity indicates the proportion of regions in each climate zone with an active fire season. Rectangles show the period where the day-time fire season coincides with the top quartile of lightning occurrence. The dashed line indicates the start of the calendar year.

For each of the 61 climate regions, MODIS hotspot counts from 2000 to 2011 for the Terra satellite, and from 2002 to 2011 for the Aqua satellite, were summed for each day of the year, keeping day-time and night-time counts separate. From the day-time data we then created a local smooth polynomial curve using the *locpoly* function of the *KernSmooth* (Wand 2014) package in R (see appendix S2). The first day of the *fire year* was set as the day with the lowest fire activity, to ensure the fire activity period fell within a single fire year. The maximum value of the smooth function was determined, and the start and end of the *fire season* were defined as the days at which the smooth function increased above, and decreased below, 10% of this value (appendix S2). The same procedure was used with night-time MODIS hotspot counts to describe the start and end of the night-time fire season. In order to assess inter-annual variation in fire activity, the start, end and duration of the fire activity were also derived in the same way for each individual year in each region, and the coefficient of inter-annual variation was calculated.

We graphically assessed the degree of overlap between the day- and night-time fire seasons and frequent lightning activity in each climate zone. Monthly lightning activity data were obtained from the LIS/

OTD 2.5 Degree Low Resolution Monthly Time Series (NASA 2012) and pooled for each of the three climate zones. The 75th percentile of monthly lightning activity (strikes km^{-2} month^{-1}) was calculated for each climate zone. In order to show those months of the year when lightning strike rates are high in at least part of a climate zone, we identified the months for which at least one region in that zone had lightning activity above the 75th percentile. This was termed 'the peak lightning season' for that zone.

Regional climate influence on landscape fire activity

Each hotspot in Australia in the MODIS satellite record from 2000 to 2011 was attributed with the corresponding FFDI value for the nearest meteorological station on the date of the hotspot detection. The median FFDI values associated with day-time hotspots ($FFDI_{50}$), night-time hotspots (night $FFDI_{50}$) and days with no hotspots were then calculated for each of the three climate zones.

To examine the relationship between fire activity and fire weather in more detail, each day in each region was categorised into 5-unit FFDI bins, and the presence of hotspots was recorded. The proportion of days with day-time hotspots was then calculated for each FFDI bin in each region. These proportions were averaged across the regions within each climate zone, and standard deviation among regions within each climate zone was calculated. The procedure was repeated for night-time hotspots.

Inter-annual climate mode influence on fire weather

We investigated the strength of the relationship between fire weather and the inter-annual climate modes ENSO and the IOD. First, the complete SILO record from 1900 to 2011 was interrogated for each station to determine the proportion of days in each calendar month for which FFDI values exceeded $FFDI_{50}$ for that climate zone. Next, we obtained monthly records of the Southern Oscillation index (SOI), standardized according to the approach of Trenberth (1984), from the National Center for Atmospheric Research (2014). Monthly records of the HadISST-derived Indian Ocean dipole mode index (IODMI) were obtained from the Japan Agency for Marine-Earth Science and Technology (2014). SOI data was available from 1900 to 2011, while IOD data was available from 1959 to 2011. We then calculated the Pearson rank correlation for the number of days above $FFDI_{50}$ for each month, and a 12 month running mean of both the SOI and IOD. Maps of these monthly correlations were generated using Voronoi polygons around each station.

Inter-continental comparison of fire weather season length

We used the dataset compiled by Jolly *et al* (2015), who provide full details, to compare the inter-annual variability of fire season length amongst continents and biomes within continents. Briefly, eight broad biome classes were derived, based on the Ecoregions biome classification of Olson *et al* (2001). All datasets were masked using the vegetated land area. Daily weather data from each of three sub-daily global meteorological datasets were used to calculate all three of the US burning index (Bradshaw *et al* 1983), the Canadian fire weather index (van Wagner and Pickett 1985) and the McArthur FFDI (Noble *et al* 1980) for the period 1979–2013. Annual fire weather season length at each location (defined as the number of days each year when fire danger is above half its value range) was then derived for each of the nine climate data-fire index combinations and these values were averaged into an ensemble mean fire weather season length, which Jolly *et al* (2015) used to identify global, continental and continent × biome trends in fire weather season length over the last 35 years. Here, we interrogated the same dataset to calculate average fire season length and inter-annual standard deviation in fire season length for each continent, and biomes within continents. We considered absolute variability to be more important than relative variability because this represents the number of days during which fires are likely to occur, and resources will need to be available to potentially control fires. We restricted the latter comparison to the six biomes present in Australia (tropical forest, temperate broadleaf forest, tropical savannas and grasslands, temperate savannas and grasslands, Mediterranean shrublands, and xeric shrublands).

Results

Global context

Globally, Australia and Africa stand out as the continents with the longest fire weather seasons and the largest inter-annual standard deviations in length (figure 2). Australia showed the highest inter-annual variability of any continent and it also showed the highest biome-level variability of any continent for tropical forests, temperature broadleaf forest, and tropical savannas and grasslands (appendix S3(a)). However, a significant trend of lengthening fire weather season was detected in Africa but not in Australia (Jolly *et al* 2015, appendix S3(b)). The lack of an Australian trend appears related to its especially high variability in fire season length.

Patterns in fire activity

In all 61 climate regions, there are clearly identifiable fire seasons, given that there is a substantial part of a given year when there is little fire activity, a period when fires burn only in the day-time and a shorter period when fires burn at night as well as during the day (figure 1). There is a clear latitudinal gradient in fire activity from the monsoon tropics through the

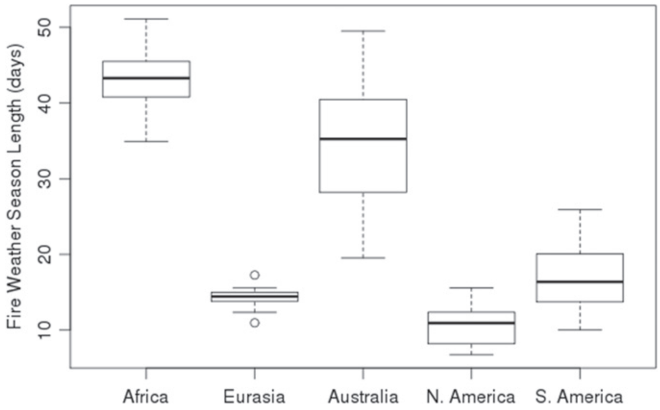

Figure 2. Global comparisons of area-weighted mean fire season length by continent, based on analyses of the dataset of Jolly *et al* (2015) where fire season length is defined in their work as the number of days each year when fire danger is above half its value range. Analyses for biomes within continents are shown in appendix S5.

Table 1. A comparison of the start, duration and variability of the day-time and night-time fire seasons among climate zones. The start, duration and inter-annual standard deviation were calculated for each region, then averaged for each climate zone (inter-regional standard deviation SD is not presented here).

Fire season	Climate zone	Season start (Julian day)	Inter-annual SD of start	Season length (days)	Inter-annual SD of length
Day-time	Monsoon tropics	182	43	174	26
	Arid	238	39	117	42
	Temperate	124	62	116	39
Night-time	Monsoon tropics	224	45	128	31
	Arid	262	40	92	32
	Temperate	139	55	101	42

arid to the temperate zone (appendix S4). The fire season is longer in the monsoon tropics than in the other climate zones (table 1). In the monsoon tropics, fire activity occurs in the winter and spring, in the arid zone the fire season is from spring to summer and in the temperate zone from summer to autumn (figure 1). There are limited periods of overlap between peak fire activity and the top quartile of lightning activity within each climate zone; the mean overlap is only 1.26 months (standard deviation of 1.1), suggesting that humans are the primary source of ignitions across the continent (figure 1(b)).

Relationship between fire activity and fire weather

In all climate zones, fire activity, especially at night-time, was low when FFDI was lower than ~10 (figure 3). It increased as FFDI increased to ~50, then tended to plateau as FFDI increased above that. However, our analysis also shows that fire activity is not simply a function of fire weather, given that there are substantial differences among climate zones in their relationships between hotspot activity and FFDI. There is much more fire activity in the monsoon tropics than the other climate zones, and a clear increase in fire activity with FFDI, such that there is fire activity almost every day once FFDI exceeds ~20, and every night when FFDI exceeds ~50 (figure 3). In the arid and temperate zones, regional fire activity is generally recorded on fewer than 60% of days, even when FFDI is very high, and the relationship between fire activity and FFDI is less clear.

As expected, $FFDI_{50}$ for night-time fires was higher than $FFDI_{50}$ for day-time fires (table 2). Night-time fire seasons were shorter than day-time ones in most climate regions (table 1; figure 1). However, in a few arid and temperate regions day-time and night-time fire seasons were similar in length. There were also substantial differences in $FFDI_{50}$ amongst the three climate zones for both day- and night-time fire activity (table 2). For example, the day-time $FFDI_{50}$ in the monsoon tropics is 15, compared with 24 in the arid zone and 14 in the temperate zone (table 2). Quantile regression showed the differences in FFDI values among the three climate zones, and for the type of hotspot (day-time hotspots, night-time hotspots and days when hot spots) were all significant ($P < 0.05$) (appendix S5).

Variability in fire weather and fire seasons

There are strong geographic and seasonal patterns in seasonal fire weather (figure 1; appendix S6). In the monsoon tropics, FFDI exceeds $FFDI_{50}$ (15) only in the winter and spring (figure 4, appendix S6(a)). In temperate Australia, $FFDI_{50}$ (14) is sometimes exceeded in the warmer spring, summer and autumn months. In these months, the most extreme FFDI values are

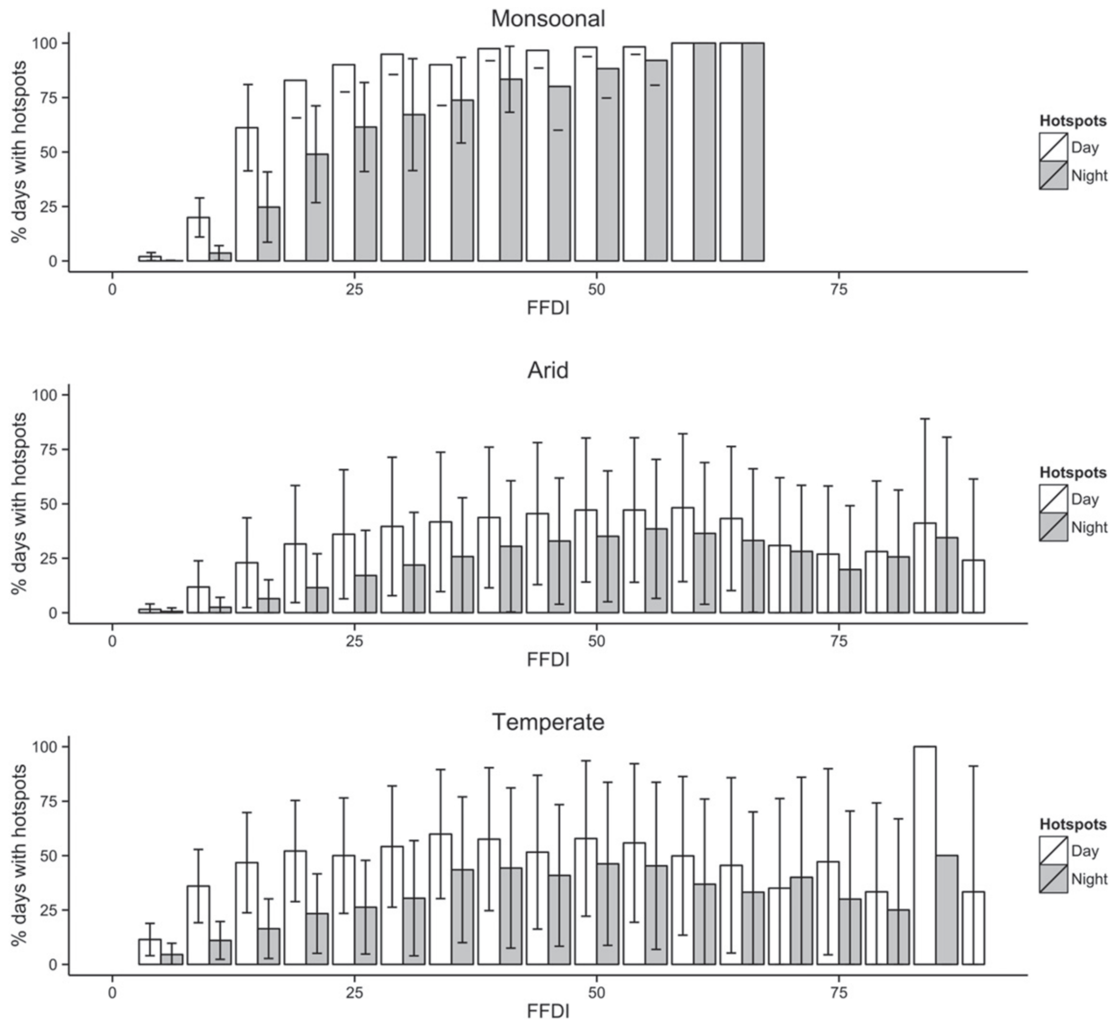

Figure 3. Occurrence of day time and night time hotspots in relation to the daily maximum FFDI. Bars show the percentage of days and nights in which hotspots were recorded in a region on days with that FFDI, averaged among regions within climate zones. Open bars indicate day-time hotspots, and grey bars, night-time hotspots. Error bars represent the standard deviation among regions.

Table 2. The mean of the median forest fire danger index (FFDI) of regions within the three climate zones for days with no hotspots, day-time hotspots and night-time hotspots. 95% confidence intervals are also shown. A quantile regression showed statistically significant differences ($P < 0.05$) in FFDI among climate zones for days with day-time, night-time and no hotspots.

Climate zone	Days with no hotspots	Days with day-time hotspots	Days with night-time hotspots
Monsoon tropics	6.2 ± 0.2	15.4 ± 0.3	18.5 ± 0.6
Arid	14.4 ± 0.2	23.6 ± 0.4	26.8 ± 0.7
Temperate	4.7 ± 0.1	13.9 ± 0.3	17.1 ± 0.6

comparable to those in the arid zone (figure 4). It is during these rare days of extreme FFDI that intense fires can occur in parts of the temperate zone where FFDI is usually low, such as the Southern extremities of Australia (appendix S6(a)). By contrast, in the arid zone, days with FFDI higher than $FFDI_{50}$ (24) occur frequently during all the spring and summer months (figure 4), and only in three months in the late autumn and winter are there days not exceeding this value.

Inter-annual variability in timing and duration of fire season was generally greatest in the temperate zone and least in the monsoon tropics. The onset of both the day- and night-time fire seasons was most variable in the temperate zone (table 1). The duration of the day-time fire season was most variable in the arid and temperate zones, and duration of the night-time fire season was most variable in the temperate zone. Similarly, inter-annual variation in FFDI during the fire season was lower in the monsoon tropics and arid zones, and contrasts with the high inter-annual variation in FFDI during spring and early summer in the temperate zone (appendix S6(b)). Some of this variability can be attributed to the effects of the inter-annual climate modes ENSO and IOD. The

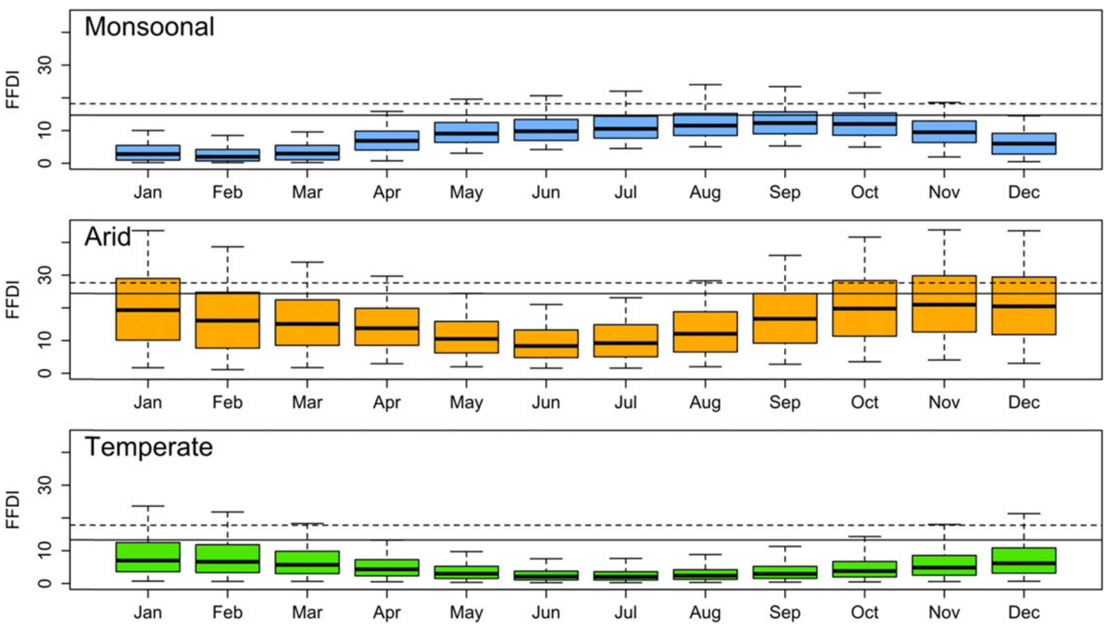

Figure 4. Variability in area-weighted regional mean daily FFDI values for each calendar month in each climate zone. Boxes span the 25th–75th percentiles, the line within the box shows the median, while whiskers indicate the 5th and 95th percentiles of the data. The solid horizontal line indicates $FFDI_{50}$ (the median FFDI for day-time hotspots) for that climate zone, and the dashed line represents the night-time $FFDI_{50}$.

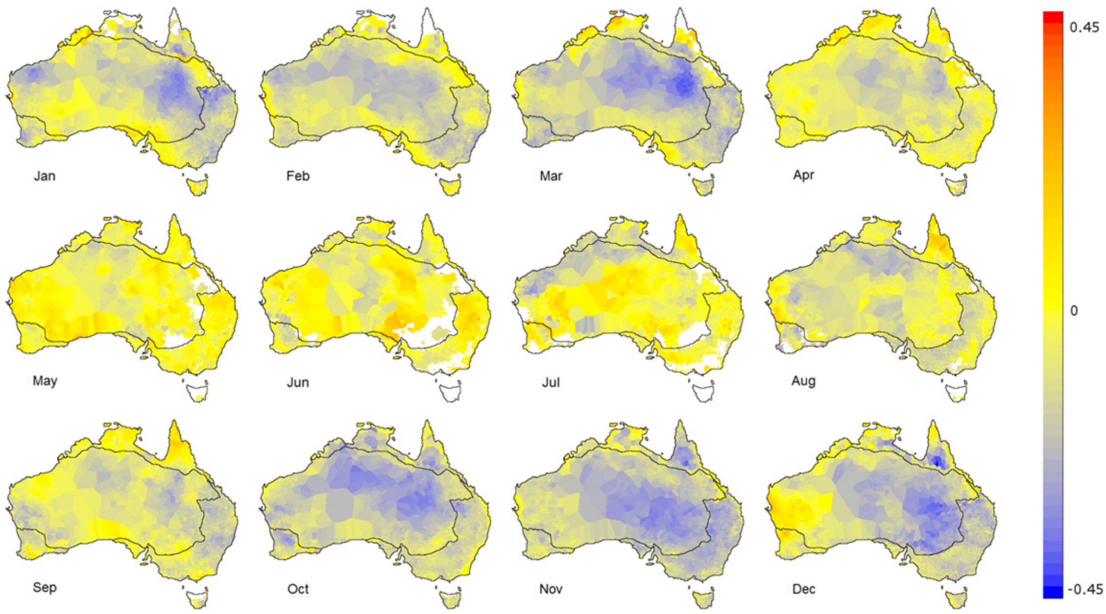

Figure 5. Correlations between the proportion of days above $FFDI_{50}$ and Southern Oscillation index (SOI). Maps show the spatial pattern of the Pearson correlation coefficient for the proportion of days in each month above $FFDI_{50}$ for that climate zone versus the 12 month running mean SOI for 1900–2011. $FFDI_{50}$ is the median FFDI on days with recorded fire activity. White polygons indicate there were too few days above the threshold for a correlation to be calculated. Note that negative values of SOI are associated with hot, dry conditions over much of Australia, leading to the observed negative correlations with FFDI (shown in blue).

negative phase of ENSO and the positive phase of IOD are associated with hot, dry weather conditions. As would be expected, negative correlations between SOI and the proportion of days when FFDI exceeds $FFDI_{50}$ were apparent across much of the arid zone during the summer months (figure 5). Similarly, in South-Eastern Australia there were positive correlations in the summer months between the IOD and the proportion of days when FFDI exceeds $FFDI_{50}$ (figure 6).

Discussion

Australia and Africa are the most fire-prone continents (Krawchuk and Moritz 2014), and have the longest fire

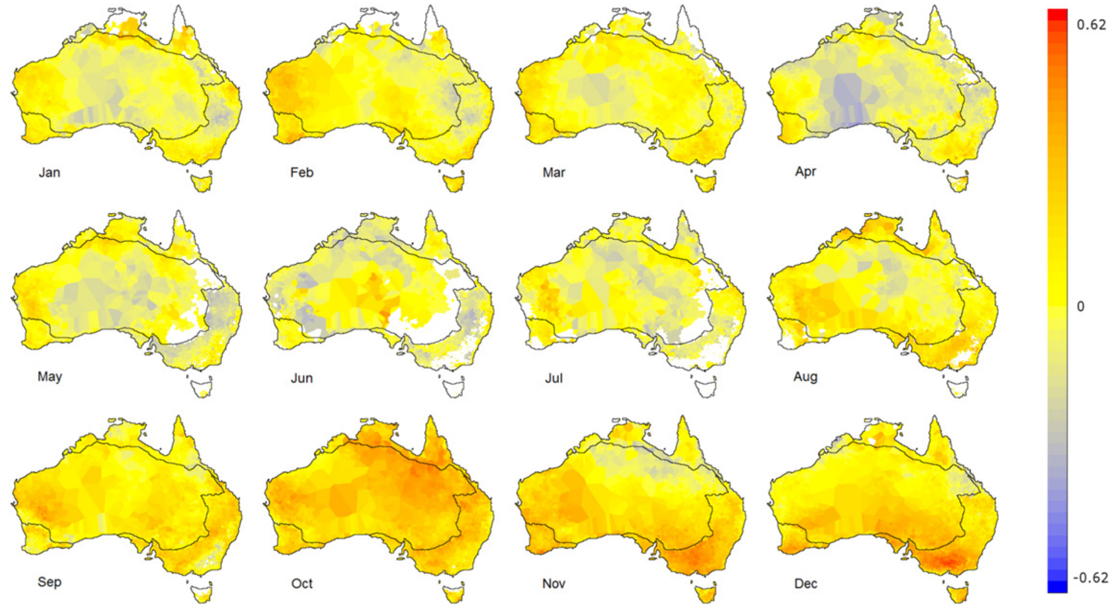

Figure 6. Correlations between the proportion of days above $FFDI_{50}$ and Indian Ocean dipole mode index (IODMI). Maps show the spatial pattern of the Pearson correlation coefficient for the proportion of days in each month above $FFDI_{50}$ for that climate zone versus the 12 month running mean IODMI for 1959–2011. $FFDI_{50}$ is the median FFDI on days with recorded fire activity. White polygons indicate there were too few days above the threshold for a correlation to be calculated. Note that positive values of the IODMI are associated with hot, dry conditions over much of Australia, leading to the observed positive correlations with FFDI (shown in red).

weather seasons with the largest inter-annual variability (shown here, using the dataset of Jolly *et al* 2015). Of all the vegetated continents, Australia has the lowest average rainfall, which is highly seasonally concentrated and highly variable among years in some regions (White *et al* 2003, Orians and Milewski 2007, Fatichi *et al* 2012). Australia's rainfall also exhibits interdecadal quasi-periodicity (White *et al* 2003, Meinke et al 2005), so that detection of short and medium-term trends is sensitive to the starting dates used. This means that very long-term records are required to detect underlying trends in the length of Australia's fire seasons.

Ours is one of the first comprehensive studies of spatial and temporal variability in fire activity and fire weather over an entire continent. Other researchers have examined spatial and seasonal patterns in Australia's fire activity (Russell-Smith *et al* 2007, Bradstock 2010, Murphy *et al* 2013), but they have not analysed diurnal or inter-annual variability. Like these other researchers, we have found the highest fire activity occurs in the monsoon tropics during the austral winter. There were diurnal contrasts in fire activity that differed among climate zones. In addition, we have shown that inter-annual variability in fire activity was largest in the temperate zone, where fuel loads generally do not limit fire activity but, rather, ignition availability, fire weather and fuel moisture content constrain landscape fires (Bradstock 2010, Boer and Bowman 2016).

Our analysis also corroborates previous Australian pyrogeographic analyses stressing the importance of the latitudinal climate gradient in shaping temporal patterns of landscape fire activity (Russell-Smith *et al* 2007, Murphy *et al* 2013). These patterns are reflected in differences in the weather conditions during which fires occur. In the monsoon tropics, very high fire activity is a predictable part of the annual dry season (April–November), given the consistent, moderately high FFDI values and the abundance of grassy fuels which cure during the dry season and regrow each wet season. Fire occurrence is more variable in the arid and temperate zones, but for different reasons. In the arid zone, FFDI values are high year round, but fire activity is limited by the lack of continuous fuels due to previous fires or slow vegetation growth. Vegetation grows slowly unless there has been heavy antecedent rainfall, typically associated with infrequent continental penetration of the summer monsoon (Russell-Smith *et al* 2007, Murphy *et al* 2013). In temperate southern Australia, fuel loads are seldom a major constraint on fire activity, but fire weather and fuel moisture are (Bradstock 2010, Boer and Bowman 2016). Fire is concentrated in the summer months (November–March). Mean values of FFDI are moderate but daily values are highly variable because of infrequent days of extreme fire danger associated with high temperatures and strong, dry winds from the arid interior. These weather events when coupled with ignitions are responsible for much of the area burnt in southern Australia (Hanstrum *et al* 1990, Fox-Hughes 2008, Attiwill and Adams 2013).

Frequent lightning is an annual feature of the end of the fire season in northern Australia, but it is not responsible for the fires earlier in the fire season. Rather, humans deliberately ignite fires early in the dry season, when they are easier to control and self-extinguish at night (Bowman *et al* 2011, Huffman 2013, Russell-Smith *et al* 2013). The importance of humans in driving fire occurrence in Australia is evident in that land management and fire ignition practices of indigenous people in Northern and central Australia have a measurable impact on fire size (Bird *et al* 2012). Differences in fire occurrence are also detectable across administrative boundaries, for example between the Northern Territory and Queensland, due to different human land management and pastoral practices (Russell-Smith *et al* 2003). Lightning is less frequent in southern Australia, and is responsible for only a minority of fires there, although these burn a disproportionately large area (Attiwill and Adams 2013), while humans are responsible for the majority of fire ignitions in this area of the continent (Collins *et al* 2015). Overall, the limited temporal association of lightning and fire activity suggests that the continent's fire seasons are shaped, at least in part, by human-derived ignitions (figure 1). This temporal disconnect between the climatically expected fire season and fire observations has been established globally by Le Page *et al* (2010), who found a delayed fire season throughout most of Australia relative to the lightning season.

Projections of FFDI values for regions across Australia under plausible future climate scenarios suggest that the fire weather regimes of northern Australia are unlikely to change substantially (Hennessy *et al* 2005, Clarke *et al* 2011). In the arid zone, fire activity is likely to decrease as drier conditions reduce plant growth and hence reduce fuel loads and contiguity, the limiting factors for fire activity in this zone (Bradstock *et al* 2014, Boer and Bowman 2016), but increased water use efficiency due to elevated atmospheric CO_2 concentration may at least partly offset this (Bradstock 2010). Conversely, periods of high FFDI in the temperate zone are thought likely to increase, leading to increases in fire activity and the length of the fire season in this economically important region where most Australians live (Bradstock *et al* 2014). However, our results suggest that unambiguously attributing increases in fire activity to climate change will be difficult in Australia given its characteristically high inter-annual variability in FFDI. Future changes to fire seasons will be determined by relatively small changes in median FFDI values because they proportionally increase the frequency of extreme fire weather conditions. The primary drivers of the current patterns are large-scale inter-annual climate modes that influence drought cycles over the continent. For example, we found a correlation between the number of days with FFDI above the median value when MODIS hotspots are detected and negative SOI values during the spring and summer months in the arid and temperate climate zones. This is consistent with findings by Verdon *et al* (2004), that there are more days of high fire danger during El Niño episodes (large negative values of SOI). An association between negative SOI values and area burnt has also been reported (Nicholls and Lucas 2007), as we found (figure 5). The IOD has also been shown to influence fire weather in Southern Australia by creating drought conditions (Saji *et al* 1999, Cullen and Grierson 2009, Cai *et al* 2013). Our findings support this by revealing correlation between the IODMI and number of days above $FFDI_{50}$ for the temperate zone (figure 6). Therefore, reliable projections of the frequency and magnitude of future fire seasons, particularly in temperate regions, will depend on accurate predictions of how ENSO and IOD respond to changing climate.

Objectively defining seasonal patterns in fire activity is essential for detecting future trends, and attributing these trends to global climate change. It is more straightforward to meteorologically define 'fire weather season' than to quantify the start and duration of actual fire activity each year. Thus it is extremely difficult to pinpoint the effect of climate change on apparently 'anomalous' fire events. The combination of high resolution fire records, meteorological data and climate reconstructions using palaeoclimate proxies can identify trends in fire activity. For example, an analysis of fire records and meteorological data has shown an increase in fire activity in Spain since 1968, associated with worsening fire weather (Piñol *et al* 1998), and in the Western US, fire records, meteorological data and palaeoecological reconstructions of fire activity and drought signal a recent trend in worsening fire seasons (Westerling *et al* 2006) with both the number of large fires and the area burnt increasing in recent decades (Dennison *et al* 2014). However, these integrative historical reconstructions are only possible where there are abundant high resolution fire records and climate data and reconstructions. Unfortunately, in Australia, such records are patchy, reflecting the limited period of fire records over much of the continent, and a general paucity of trees suitable for reconstructing fire and drought activity using dendrochronological methods (Brookhouse 2006, Heinrich and Allen 2013). Hence, our approach using satellite fire detections combined with climate data provides an important baseline from which to detect shifts in the temporal and geographical patterns of fire activity in a region where a historical frame is largely lacking.

Conclusion

Australia's mid latitude position creates climates highly conducive to landscape fire. Fire seasons vary across a latitudinal gradient, from spring in the monsoon tropics to late summer and autumn in the temperate zone. Lightning shows strong seasonal patterns but is not well aligned with the observed fire seasons, suggesting a predominant role of human ignitions. Analysis of a 12 year satellite record shows high inter-annual variability in fire activity in spring and summer in the temperate zone. A 111 year meteorological time series also shows high inter-annual variability in fire weather, linked to ENSO and IOD climate modes. Such high variability presents a challenge to predicting seasonal patterns of fire activity and possible long-term lengthening of fire seasons as a result of climate change. We demonstrate that short scale variation in fire weather (including diurnal cycles) strongly shape landscape fire activity, and these effects are modulated by geographic gradients in climate and inter-annual climate cycles. We provide evidence that some of these patterns are affected by availability of fuel and ignition sources that are likely to be strongly influenced by the interaction of humans (land management, fire suppression and ignitions) and climate. Therefore, our findings are broadly consistent with Bradstock's (2010) 'four-switch model', in which the relative constraints on fire activity vary at the continental to regional scales. Our approach allowed us to consistently and objectively describe and compare the onset, duration and inter-annual variability in fire seasons in contrasting climate zones. Although temporal trends are currently difficult to demonstrate given the current shallow time depth of the MODIS fire activity record, this approach provides a template for future analyses of long-term trends in fire activity that has potential application in other fire prone landscapes globally.

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