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Manuscript for Submission

Causes and Drivers of Bushfires

by David Falvey[1]

Abstract

Historical analysis of Australian bushfire data spanning 170 years addresses whether the strength of recent fire events has been exacerbated by human-induced climate change. The question of "cause" looks at the characteristics of a wider range of natural hazards. Fire characteristics are compared with earthquake hazard characteristics: (1) energy – termed "magnitude"; (2) severity – termed "intensity"; and (3) resultant damage to people and structures – termed "impact".

Published global, Northern and Southern hemisphere temperature data are shown to vary consistently in phase over 170 years, but *vary in amplitude with statistical significance*. CO_2 levels north and south of the Equator have tracked quite consistently. Thus, Southern Hemisphere bushfire magnitude and intensity is compared with the Southern Hemisphere climate record, rather than a global data set.

28 major bushfires and associated droughts since 1850 show neither apparent drought extent, nor area burned, nor bushfire intensity, correlates with changes in Southern Hemisphere climate. Average rainfall from 1900 shows a wetter, rather than drier trend. Cyclone energy shows no significant trend with climate. Planet-wide "greening", through CO_2 fertilisation, is an insignificant contributor to bushfire magnitude. Combustion theory shows recorded "global warming" could have had no significant influence on bushfire magnitude or intensity. Any increase in Australian bushfire impact, as judged by lives lost, similarly, shows no correlation with bushfire magnitude, nor indeed, any observed Southern Hemisphere global warming.

Thus, bushfire magnitude seems much more likely driven by fuel load and any anomalous bushfire intensity is likely driven by anomalous ground level fuel load. The evidence suggests that any CO_2 emissions reduction will have no impact on future bushfire "severity.

Key words: Bushfires, Forest fires, Climate change, Natural hazard characterisation, Hazard magnitude, intensity, impact, History of fires and droughts, Fire magnitude and intensity *vs* global temperatures. Causes of bushfires.

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Introduction

Following the devastating Australian bushfire season over the Spring and Summer of 2019-2020, there has been much debate in both the media and scientific circles about whether anthropogenic climate change (ACC), or "global warming" (AGW) was the immediate cause of these events, or exacerbated their intensity.

This vexed question will be addressed, with a particular focus on the main burn area in Southeastern Australia, shown in Figure 1.

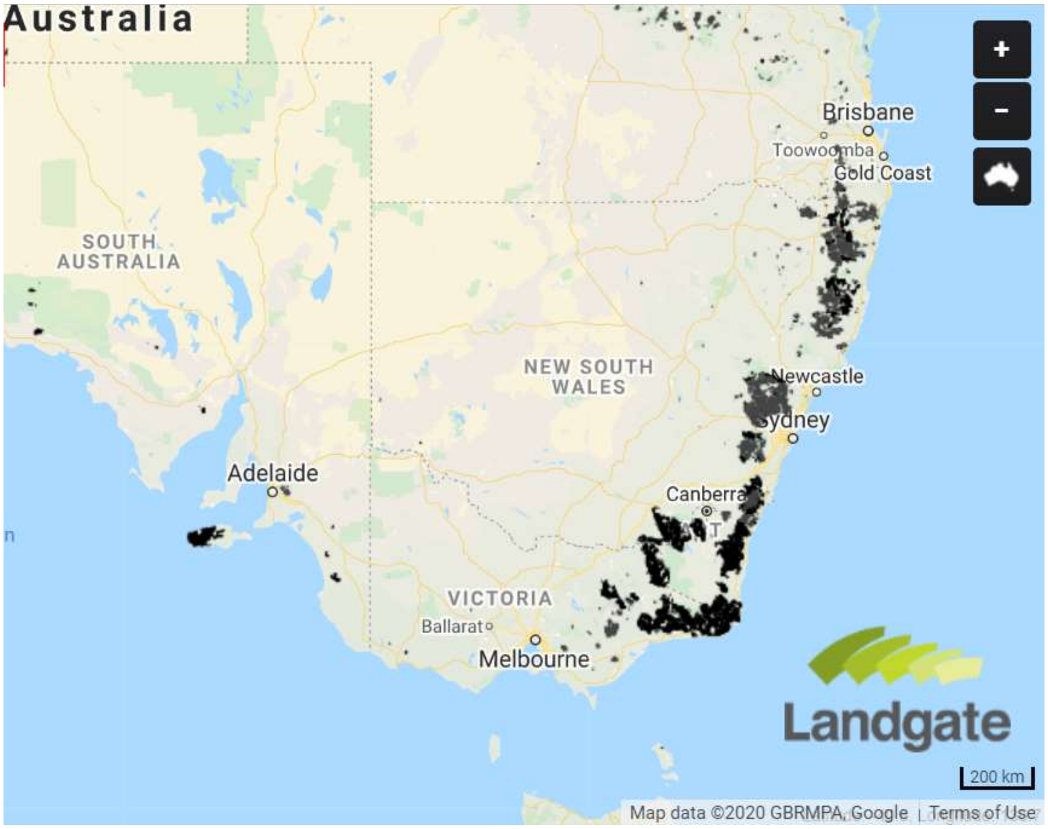

Figure 1: Landgate image of Southeast Australian bushfires in 2019 – 2020

Sources of Data

This paper has relied on cited papers and published data compiled exclusively from reputable official sources. These include a range of peer-reviewed publications and, most importantly, the internet sites of the Australian Bureau of Meteorology (BoM), CSIRO, the United States National Oceanographic and Atmospheric Administration (NOAA), the National Museum of Australia (NMA), various Australian State and Territory rural fire services, the Australian Broadcasting Corporation (ABC), Australian Geographic, the Australian Bureau of Statistics (ABS) and Geoscience Australia (GA). The analysis is solely the responsibility of the author.

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What Characterises a Bushfire Hazard?

Like any natural hazard, a bushfire or wildfire can be characterised by four essential features:

- Accumulation of potential chemical energy, in the form of wood cellulose[2], often in the living forest canopy and disproportionately deadwood at forest floor levels, in a geographic location – this is generally described as the fuel load;
- Ignition of that potential chemical energy (the TRIGGER event) and its generally partial conversion, across the burn area, into thermal energy through combustion – expressed as the hazard MAGNITUDE (a quantitative measure on a Log_{10} scale of the thermal energy released, in Joules);
- Potential intensification of the burn energy by "fire weather" and terrain – which can be expressed quantitatively as an increased combustion reaction rate, and semi-quantitatively as hazard INTENSITY (a relative measure of fire severity);
- Intersection of fire intensity with humans and their constructions, to produce destructive IMPACT (a human and financial measure of fire outcome)[3].

This protocol follows similar characterisations of earthquake and other natural hazards, linked to their "cause", of which these are three examples.

- The underlying "cause", or driving mechanism of an earthquake is the release of the strain energy accumulated in the upper lithosphere, often at a plate boundary. The component of energy that is suddenly released defines the event MAGNITUDE on the modified Richter Scale, and can also be measured in Joules. "Magnitude" was defined in seismology almost 100 years ago.
- The driving mechanism of a landslide hazard is conversion of the potential energy of a perched rock or mud mass into kinetic energy (MAGNITUDE); and
- The driving mechanism of a cyclone is the conversion of ocean-atmosphere thermal energy into the kinetic energy of a volume of rotating wind. This MAGNITUDE is known as accumulated cyclone energy (ACE). Cyclone "category", or wind velocity, defines its INTENSITY.

Thus, in looking for the cause of the recent Australian bushfires, it is important to start with the underlying energy (expressible on a Log_{10} scale as MAGNITUDE) of a bushfire, from the fuel which is its source, and how that fuel is converted into fire INTENSITY and IMPACT, and how that might be influenced by various weather, terrain and, possibly, climate and human factors.

Climate *vs* Weather

A review of the scientific literature suggests that "weather" may be viewed as the variability in temperature, winds and precipitation experienced seasonally and inter-annually. Thus, weather should also encompass the short-term, multi-year variability, embracing, for example, both the El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) ocean temperature cycles and their consequences.

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[2] Cellulose is made of very long unbranched fibrils composed almost exclusively of glucose, with hydrogen bonding. For combustion purposes, it is approximated by $C_6H_{12}O_6$.

[3] Geological and Nuclear Sciences New Zealand liken magnitude to the power output of a radio broadcast transmitter, while intensity refers to the strength of the received signal – effected by distance, pathway and atmospheric conditions.

The cyclical pattern of ENSO/IOD events is typically tens of years, with intervals between strong La Niña events lasting as long as 34 years (CSIRO).

This contrasts with "climate", a long-term pattern of weather changes that typically sees large land areas, for example, move from desert to savanna, or tundra to prairie, over hundreds, sometimes thousand, even millions of years. The changes wrought by the shift from the last Ice Age to the current Interglacial were, on a geological timescale, relatively rapid, taking some two thousand years from start to finish, although the period of most rapid change (warming) took just a few hundred years, with peak rates close to those seen over the most recent 50 years.

Therefore, for the purposes of the present analysis, "climate change" is defined as a variability, principally of temperature, on the order of a sixty to hundred-year timescale, or greater. This does not imply any particular cause, or mechanism.

The History of Australian Bushfires and Associated Droughts

The BoM believe that anthropogenic climate change is influencing the frequency and severity of dangerous bushfire conditions in Australia and other regions of the world. It should be noted that neither the *pre*-conditions, nor the concept of "severity" is scientifically defined on their website, or in other publications so far unearthed.

The assertion of the "anthropogenic cause" invites a closer examination of the recorded history of Australia's bushfires. Table 1 is a summary of bushfires events, or seasons of events that are reported to have burnt out more than 100,000 hectares, or 1,000 km^2. Probable bushfire events or groups of events, associated with the 1790/1793 drought and those subsequently "reported" up to 1850 occurred during colonial expansion are noted, but cannot be adequately verified. The alleged drought association is important. According to the National Museum of Australia, historical accounts and scientific analysis indicate that South-Eastern Australia experienced 27 drought years between 1788 and 1860, which cannot be adequately classified, and at least 10 *major* drought events from 1860 to 2000.

The 1895-1903 drought (the "Federation Drought") according to the National Museum of Australia was the worst to date. It affected almost the whole of Australia (https://www.nma.gov.au/definingmoments/resources/federation-drought). Stock and crop losses were the highest in Australian history. Nikolai Beilharz, for the ABC: "A reconstruction of the Federation drought has found that if it were to occur again today … (it would) cause an ecosystem collapse affecting more than a third of the country. The drought was one of the *world's worst recorded 'megadroughts*' … with 1902 the driest year on record." https://www.abc.net.au/news/rural/2019-07-16/federation-drought-analysis-finds-huge-ecosystem-losses/11312694

Table 1 was compiled, and confirmed, including area burned, from several accessible internet sources, including Wikipedia (with reliable authorship), the Australian Broadcasting Corporation, Australian Geographic, State/Territory rural fire services and Geoscience Australia. The colour code shows when significant droughts were associated with significant bushfires, as listed by the Australian Bureau of Statistics (https://www.abs.gov.au/), based on information provided by the BoM. Major droughts are shown in red; and lesser, but severe droughts, in orange. Since 1850, there have been 11 *major* bushfire events, or seasons, each resulting in more than 1 million hectares burnt, or one major event(s) every 15½ years.

Table 1: History of Australian Bushfires and Associated Droughts

Year	Principal Location	Death Toll	Hectares Burnt
1790/1793	NSW	?	?
1850/1851	Victoria	15	5 million
1862/1863	NSW	?	?
1897/1898 [4]	Victoria	12	0.26 m
1925/1926	Victoria	60	0.4 m
1938/1939 [5]	Victoria	71	2 million
1943/1944 [5]	Victoria	49	1 million
1951/1952	Victoria, NSW, ACT	13+	4.1 million
1955	South Australia	2	0.15 m
1961	Western Australia	0	1.8 million
1962	Victoria	32	>0.1 m
1965	NSW	5	0.53 m
1967	Tasmania	62	0.26 m
1974/1975	NSW, NT, Qld, SA & WA	6	117 million
1977	western Victoria	4	0.1 m
1980	NSW	5	1 million
1982/1983	Victoria & South Australia	75	0.42 m
1984/1985	NSW	4	3.4 million
1993/1994	NSW	4	0.80 m
2001/2002 [6]	NSW	0	0.75 m
2003 [6]	ACT & Victoria	7	1.3 million
2005 [6]	South Australia	16	0.15 m
2006/2007 [6]	Victoria; Sthn. NSW; ACT	5	1.4 million
2008/2009 [6]	Victoria	173	0.45 m
2013	NSW, Tasmania	3	0.15 m
2014	east Victoria	0	0.17 m
2015/2016	WA, NSW, SA Tasmania	9	0.32 m
2019/2020	Qld, NSW, Vic, ACT, SA	33	10.17 million[7]

The 1938-1943 "World War Two Drought" and the corresponding Victorian fire seasons are taken as a reference point for the baseline of the onset of *both* consistent and nation-wide recording of bushfires and the modern era of more rapidly changing climate (see Fig. 4). The frequency of *significant* Australian bushfires since 1938/39 is summarised in Figure 2, by the number of hectares burnt out per decadal period. Note that, even including the extraordinary 1974/1975 season and somewhat significant area burned out in the 2019/2020 season, there is

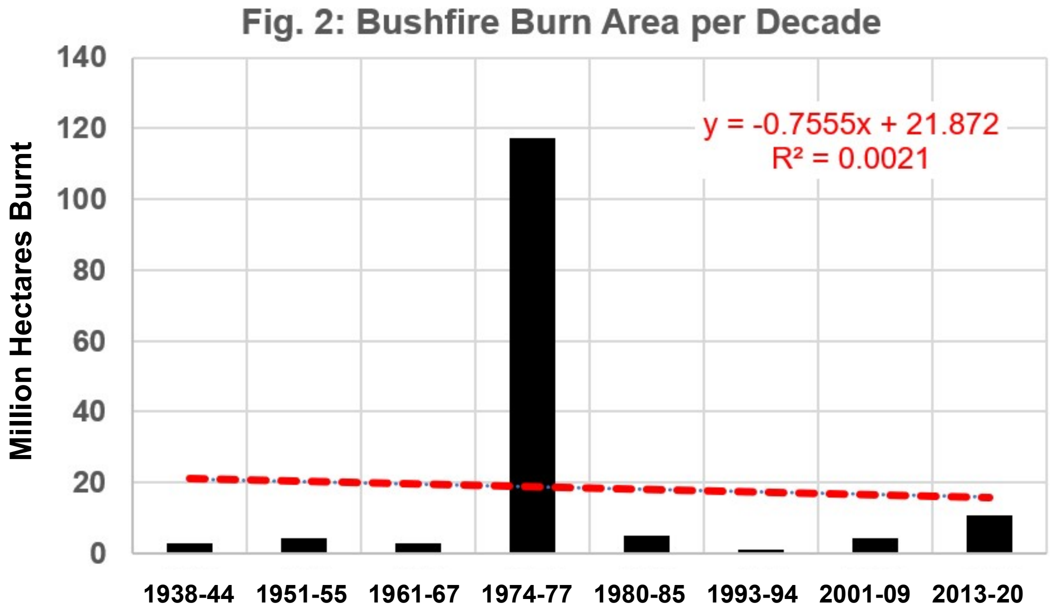
[4] The Federation Drought (1895-1903); acknowledged as Australia's worst on record. Interestingly, this drought is not associated with a significant bushfire season(s).

[5] The World War 2 Drought.

[6] The "Millennium Drought" (2001 – 2009), was possibly one of Australia's more prolonged droughts, comparable to the Federation Drought in length, but apparently not in "intensity".

[7] From: Morgan, et al (2020; Table 1); confirmed by CSIRO statement. Press reports vary.

an unconvincing negative correlation with time, more reasonably, no reliable correlation over 8 decades with observed climate change or AGW (R^2 = 0.0021).



Despite the difficulty of calibrating impact, a casual inspection of Table 1 also suggests no particular correlation between lives lost, as a fraction of the Australian population at the time (one of three possible measures of bushfire *impact*) and either bushfire magnitude, or changing climate over the same period.

Another critically important conclusion from this historical analysis is that *neither the drought, nor the bushfire season of 2019/2020 is the worst in Australia's history*. According to the National Museum, the "Federation Drought" (1895-1903) still ranks "worst" post 1788 drought; *and* the 1974-1975 fires were of unprecedented *magnitude*, burning ~15% of Australia's land mass, causing "extensive fire damage" (*impact*). It should rank as Australia's "worst" post-1788 bushfire season.

The frequency of bushfires does show an apparent increase from 1850 to 2020, but the convergence of major bushfire events with major droughts appears to have actually *decreased*; from 0.62 fire-and-drought events/decade before 1980, to 0.25 fire-and-drought events/decade since.

Indeed, in seeming contradiction to popular belief, the overall average rainfall across Australia since the Federation Drought, as shown by records since 1900, has statistically *increased* by about 0.63 mm per year (Figure 3; data from BoM). Note that 1900 is the earliest date that the BoM include in their rainfall records. BoM cite 2019 as the driest year on record, when just 278 mm of rain fell, but on 8 April, 2020, the BoM declared that: "… rainfall (is now) close to average nationally, with some inland areas, including NSW and Victoria, recording *above-average rainfall*." In the first 9 months of 2020, Australia's average rainfall has been 323 mm (average ~500 mm/yr). Weatherzone projects a wetter year in 2020. Kirchmeier-Young and Zhang (2020) note a similar increase in rainfall over a similar period in North America.

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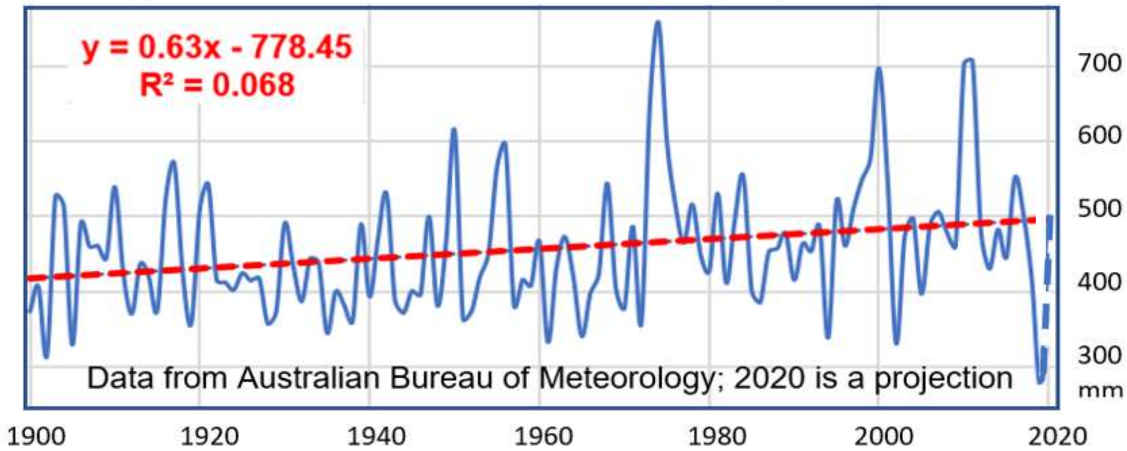
Fig. 3: Australia's mean annual rainfall (mm) - 1900 to 2020



Bushfire Thermal Energy and Event Magnitude

It is difficult to derive an exact number for bushfire thermal energy and event magnitude, even for the most recent bushfire events. As will be summarised below, it is possible to compute the thermal energy output from the combustion of common firewood, but it is only possible, at this point, to estimate the total combustion in a given fire event. The following equations describe the energy output of a bushfire, followed by its equivalent "magnitude", based on the methodology behind the Modified Richter Scale, as applied to earthquakes[8]:

Equation 1: $E_t = f \cdot C \cdot W \cdot (\text{area of burn})$

Equation 2: $M = ⅔ \cdot \text{Log}_{10}(E_t) - 3.2$; or, more simply, $M \propto \text{Log}_{10}(\text{area of burn})$

where E_t is the net thermal energy output of the bushfire event, or season; f is the fraction of the fuel load subject to total combustion; C is the unit energy released by total firewood combustion (typically 16×10^6 Joules/kilogram, but this is highly variable, and depends on the state of dryness of that fuel); W is the density of available fuel load (anywhere from 1,000 to 30,000 kilograms per hectare) and M is the bushfire event magnitude (an approximate numerical equivalent to, but not equal of the Richter Scale). E_t, and thus M, are both directly related to actual burn area, and to f•W. The primary variable in bushfire magnitude is thus fuel load converted to thermal energy and any consequent anomalous bushfire intensity most likely driven by anomalous dry fuel load, most likely at ground level, as developed below.

Interestingly, Accumulated Cyclone Energy (ACE) is calculated from the maximum estimated wind speed of a storm at 6-hour intervals over a cyclone's duration. Specifically, ACE can be calculated for any storm using the following formula (Collins; 2018):

$$ACE = 10^{-4} \cdot \sum v_{max}^2$$

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[8] Equation 2 is based on Richter's concept of magnitude, defined by event energy output: $\delta M \propto \delta E/E$; thus, $M \propto \text{Log}_{10}\, E$.

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where v_{max} is the estimated maximum sustained wind speed in knots at six-hour intervals and the sum of wind speeds squared is multiplied by 10^{-4} for convenience. This is similar to the original way earthquake magnitude was calculated from ground acceleration at a nominated distance from an epicentre. Cyclone Category is analogous to earthquake intensity, the Saffir-Simpson Hurricane Wind Scale being based on a sustained wind speed, categorised into a scale of 1 to 5, *eg*, speeds over 252 km/hr are Category 5. Category relates directly to potential property damage (*ie*, impact; https://www.nhc.noaa.gov/aboutsshws.php).

Thus, the quantity of energy released by any hazard event can be equated to its magnitude, analogous to that indicated for an earthquake by the Modified Richter Scale. For example, the Orroral Valley fire south of Canberra in February, 2020, burnt out 80,000 hectares (800 km^2) and released roughly 2×10^{15} Joules of thermal energy. This equates to a seismic event magnitude of 7 on the Richter Scale.

Instrumental History of Climate Change

The instrumental record of global surface temperatures is very patchy, even today. The Australian Bureau of Meteorology consider Australian temperature data reliable from 1910. These 110 year-long records are insufficient to extract a measure of “climate change” across the Australian continent, or separate a “climate signature”.

The BoM also publish global temperature data, and data for the northern and southern hemispheres, covering the period 1850 to present. These data are based on the Climatic Research Unit HadCRUT4 global gridded (5°x5°) temperature data set (Morice et al, 2012). NOAA also publish data from 1885. This time-consistent, 170-year set of records, covering broad swaths of the globe, is a much better basis for current climate change analysis, despite the undoubted sparsity of data in the 19th Century. Figure 4 shows a plot of temperatures extracted from the BoM website. The original data has been smoothed using a 17-point Gaussian filter.

Fig. 4: Global & Hemisphere Temperatures - Gaussian Filtered

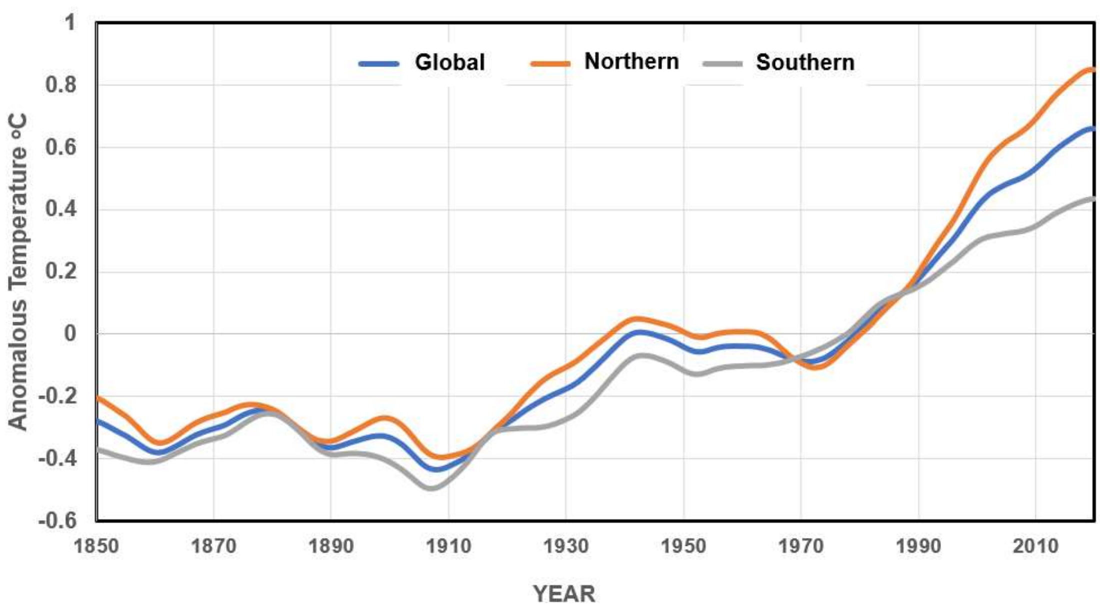

Figure 4. Climate averages of global temperatures, tabulated by BoM, from 1850 to 2018, extrapolated using NOAA data to May, 2020. The global data (blue) shows an approximate 30 to 60-year wavelength, which is taken here as a "best representation" of global climate over the short, 170-year period. The Gaussian filter was also applied to Southern Hemisphere (grey) and Northern Hemisphere (orange) data.

A commonly accepted driver of global climate change, at least since the late 20th Century, is Carbon Dioxide in the atmosphere. Figure 5 shows that, within the seasonal cycle of ±0.5 ppm, CO_2 levels in the Northern Hemisphere (at Mauna Loa) and the Southern Hemisphere (Cape Grim) have been virtually identical since the start of joint records in 1976.

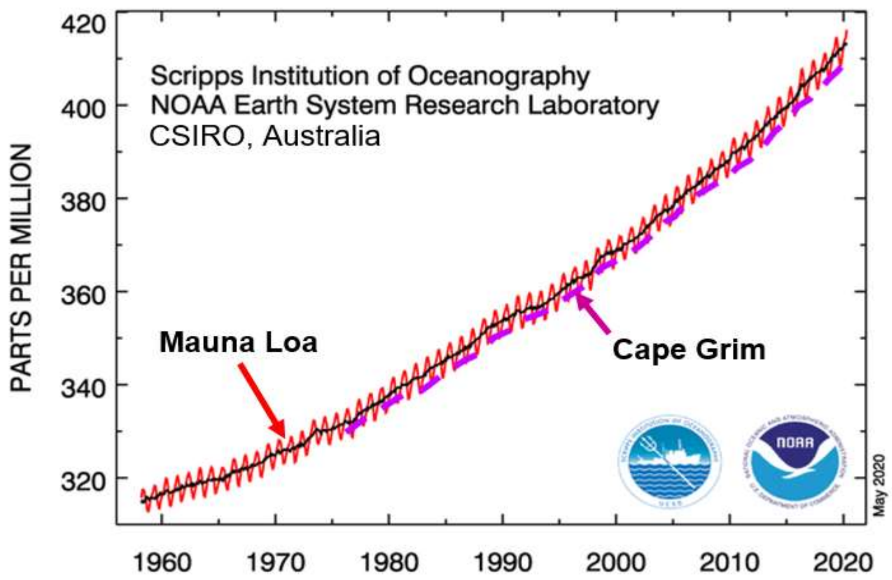

Figure 5. Measured atmospheric CO_2 data from (1) Mauna Loa Observatory, Hawaii (Scripps Institution of Oceanography and NOAA), shown as a black line, with annual variability (red line); and (2) Cape Grim Observatory, Tasmania (CSIRO), shown as a purple dashed line.

The observation, that CO_2 levels have tracked fairly consistently, north and south of the Equator, is not matched by the variability in the filtered temperature (presumed climate) anomalies between the Northern Hemisphere and Southern Hemisphere, shown on Figure 4. This could suggest a re-examination of the simplicity of a model that relates current global warming (largely or solely?) to the inexorable increase of CO_2 levels in the atmosphere. Whilst this may indicate a *prima facia* case for a more complex suite of global climate drivers than CO_2 alone, that is a separate matter to the issue of observed climate change and recent bushfire magnitude/intensity.

Australian bushfire magnitudes and Southern Hemisphere climate data can now be compared. The thermal energy released in historical Australian bushfires cannot be practically measured now, over a hundred years after many of these events, but it should be possible to make a reasonable estimate - to a first approximation - of historical bushfire *relative* magnitudes through the proxy of the recorded area burned. It will not be precise, because there are inadequate, or no records of the type, density and proportion of bushland burnt in past fires (the f•W values), but should be sufficient for a basic comparison.

Figure 6 plots this *proxy for seasonal bushfire magnitudes*, based on the Log_{10} of recorded seasonal burn area, as derived in Equations 1 and 2, against anomalous temperature for the Southern Hemisphere, as read off Figure 4. The use of the Log_{10} scale makes this a proxy for bushfire magnitude, comparable to, but *not* the numerically equal of the Modified Richter Scale used for earthquake magnitude.

Fig. 6: Bushfire Magnitude (proxy) *vs* Climate Anomaly: 1850 - 2020

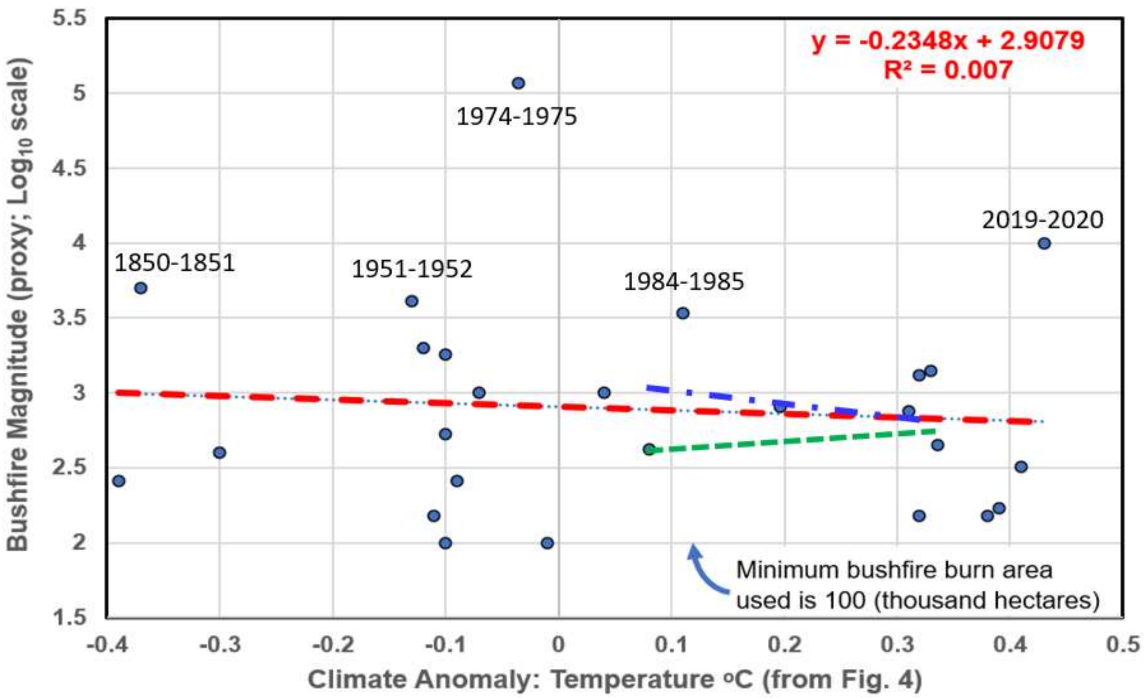

Fig. 6: Bushfire "proxy magnitude calculated from area burnt" *vs* Southern. Hemisphere (climate anomaly). Temperature, in °C; is from BoM website - Sthn. Hemisphere; for period 1850 - 2020; Gaussian filtered, as shown on Figure 4). The dashed red line shows a simple linear regression of all data. The dotted green line shows the observed effect of greening of the planet by CO_2 fertilisation, globally, from 1982 to 2010 (Fig. 8). The blue line shows the linear regression of observed bushfire events over that same period. The five highest magnitude seasons from 1850 – 2020 are also indicated and show a nearly even distribution *vs* climate anomaly over 170 years.

This plot clearly demonstrates an essentially random pattern; *ie*, no statistically significant correlation between bushfire proxy magnitude (burn area) and anomalous Southern Hemisphere climate between 1850/51 and 2019/20. Thus, empirical considerations lead to the conclusion that “global warming” over recent times has had no significant influence on bushfire magnitude, at least to a first approximation.

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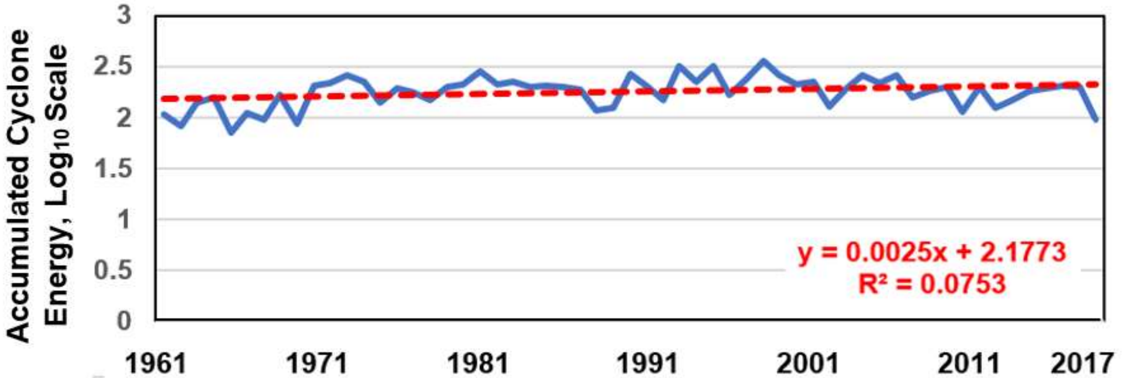
Another example of extreme weather data – specifically, accumulated cyclone energy (ACE) from the Southern Hemisphere (Fig. 7), also shows little variation with time (or with Fig. 4 temperatures) from 1961 to 2017 (data in Collins; 2018). ACE, expressed as relative magnitude (Log_{10} scale), increased slightly from 2.2 to 2.3 from 1961 to 2017, or 0.1%/year. This observation is consistent with Klotzbach and Landsea (2015), who also concluded essentially no statistically significant correlation between Southern Hemisphere ACE and climate from 1970 to 2014. CSIRO/BoM (2015) also noted that the number of "severe" tropical cyclones in the Australian region has decreased from 4.9/yr in the 1970s to about by 3.9/yr in the 2010s.

Fig. 7: Tropical Cyclone Energy (plotted as Magnitude) Southern Hemisphere



Carbon Dioxide and the Greening of the Planet

"Climate change", believed to be driven by CO_2 emissions, is also anecdotally associated with, not only more frequent extreme weather events, but with an increasing drought frequency, and thus soil dryness and poor plant growth. However, CSIRO, with ANU (CSIRO: *Deserts 'greening' from rising CO_2*; 2013), has found, based on satellite observations, that increased levels of CO_2 have helped increase green foliage on a global scale by an average of 11% from 1982-2010, through a process of CO_2 fertilisation, as shown in Figure 8.

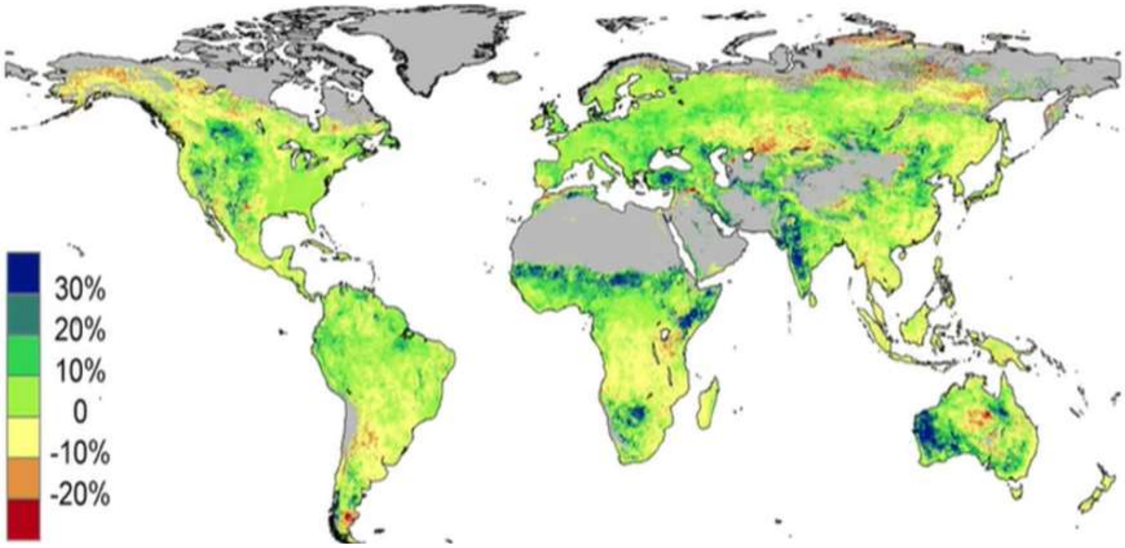


Figure 8: Greening of the planet by CO_2 fertilisation

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Thus, global aridity may be measurably decreasing, while greening is marginally adding to fuel load. Could this be the key to an increase in bushfire magnitude, with increasing global temperatures, despite Figure 6? To explore this possibility, consider the first derivative of Equation 1 with respect to W - the density of fuel load:

Equation 3: $dE_t/dW = E_t/W$ *or* $\delta E_t/E_t \propto \delta W/W$

Equation 4: $dM/dE_t = (⅔./\ln(10)) / E_t$ *or* $\delta M = 1.56 \cdot \delta E_t / E_t$

Thus, if foliage, or vegetation productivity has increased by an observed average of 11% from 1982-2010, then bushfire magnitudes should have increased by 0.17 magnitude units, over that period, or 2.5%. In the Orroral Valley example, magnitude should have increased, incrementally, from 7.0 to 7.2 over some 28 years – which is, arguably, insignificant.

Various CSIRO studies and analyses have delved further into the relationship between CO_2, temperature and vegetation productivity ("greening"). Wong, et al (1979) relate water use efficiency, W_p, to the ratio of the rates of water assimilation (A_l) to transpiration per unit of leaf area (E_l):

$$W_p = \frac{A_l}{E_l} = \frac{C_a}{1.6v}\left(1 - \frac{C_i}{C_a}\right),$$ from Wong, *et al* (1979)

where C_a and C_i are the atmospheric and intercellular CO_2, respectively, and υ is the leaf-to-air water vapor pressure difference.

$$\frac{dW_p}{W_p} = \frac{dC_a}{C_a} - \frac{1}{2}\frac{dv}{v}$$

This can be simplified to:

Equation 5: $\delta W/W = \delta C_a/C_a - ½\,\delta D/D$, from Donohue, et al (2013)

Where W is the green foliage density, or, as used herein, fuel load per unit area; C_a is the atmospheric CO_2 and D is the vapour pressure deficit, which is, in turn, related to change in temperature, and is estimated to increase by 7% per degree C (Roderick, 2020).

Looking at the period, 1982 to 2010, on a *global* scale, C_a increases from 340 ppm to 390 ppm (Fig. 5) and global δT increases from +0.1 °C to +0.6 °C (Fig. 4; blue line). Substituting in Equation 5, this gives:

$$\delta W/W = 14.7\% - ½ \cdot 1.75\% \approx 13\%$$

Which is satisfactorily close to the globally observed value of 11%.

Relating this to the Southern Hemisphere, an increase of 0.17 magnitude units, corresponding to a climate change of +0.05°C in 1982 to +0.38°C in 2010 (Fig. 4; grey line) is illustrated on Fig. 6 as a dotted green line. The trend is the reverse of the observed data, suggesting CO_2 "greening" has no significant effect on bushfire magnitudes.

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Bushfire Intensity

If it has been difficult to find a correlation between bushfire magnitude and climate change, it should be intuitively more likely to find that such a correlation exists with bushfire intensity. The concept of earthquake intensity was originally based on a measure of the damage caused by ground motion. The International Intensity Scale originates from that proposed by Giuseppe Mercalli, who devised an empirical scale, now ranging from 1 (not perceptible; instrumental detection only) to 12 (virtually complete destruction of all built structures).

Ground displacement is the underpinning quantification of "intensity". It is an empirical reckoning involving the magnitude of the seismic event, its depth (to the hypocentre) and distance from the epicentre, via a number of empirical equations developed over the years. The original concept was introduced in 1935 by Richter (1958) and remains the most common parametrisation. The standard, or simplified surface-wave formula is:

Equation 6: $M_S = \log_{10}(A/T) + 1.66 \log_{10}(\Delta) + 3.3$

In more simplified form: Intensity $\propto$ *function* (M_S, Δ)

Where A is maximum amplitude of ground surface displacement in micrometres; T is the period of the seismic wave – usually about 20 seconds; and Δ is distance to the epicentre. A more complex formulation includes factors for focal depth in kilometres; a seismic station correction; and a regional, or "geological" correction.

In the case of the *potential* bushfire hazard, Leonard et al. (2014), calculated (*bush)fire line intensity* (FLI), based on three spatial inputs: W, the potential, or total available fuel load (as used in Equation 1; here, in tonnes/ha); θ, maximum landscape slope (in degrees); and fire weather severity (Forest Fire Danger Index; FFDI, abbreviated here to "F"). This is expressed in Equation 7 (after Leonard, et al, 2014):

Equation 7: $FLI = 0.62 \cdot W^2 \cdot F \cdot e^{0.069\,\theta}$

McArthur (1973) Forest Fire Danger Index (F) is the most widely used "fire weather" index in Australia. It was developed in the 1960s by A. G. McArthur to measure and warn of the danger posed by fire in Australian forests. In qualitative description it ranges from "low to moderate" (0 – 11) up to "catastrophic" (>100). It could be seen as analogous to the Mercalli Scale, except the FFDI is a measure of potential intensity, whereas the Mercalli Scale is actual observed intensity. The potential FFDI involves temperature, T (°C); wind speed, ε; relative humidity, φ; and a drought factor, DF, which is a temporally accumulated soil moisture deficit (Dowdy, 2018):

Equation 8: $F = e^{(0.0338T - 0.0345\varphi + 0.0234\varepsilon + 0.243147)} \times DF^{-0.987}$

Essentially, a simplified Equation 7, based on the most significant factors, becomes:

Equation 9: $FLI \propto W^2 \cdot F$

Noting that this is *potential* fire line intensity, an estimate is needed of actual FLI. This will require inclusion of f – the fraction of the fuel load subject to total combustion, from Equation 1. Looking at the derivation of Equation 9 in Leonard et al (2014), it might therefore be concluded that an actual FLI should be given by:

Equation 10: $\mathrm{FLI} \propto (f \cdot W)^2 \cdot F$

However, as important as it would seem, f•W is not a parameter set that is readily accessible for past bushfires in Table 1. In order to explore the climate effect on actual fire line intensity further, this study will resort to using F (or FFDI) as a proxy, being the only accessible parameter. Figure 9 shows a data set of spatially averaged observed Summer FFDI values, from 1951 – 2016, throughout southern Australia (south of 30°S), as detailed in Dowdy (2018).

The trendline in Fig. 9 shows underlying FFDI increased from 19.4 in 1951 to 22.7 in 2016, or 0.25%/year, with a relatively weak correlation (R^2). Observationally, there is also a poor correlation between fire season mean FFDI and climate change illustrated in Fig. 4, ranging from -0.1˚C to +0.4˚C for that period. The four major bushfire seasons between 1951 and 2016 also show,effectively, no relationship between FFDI with time or climate change. It is regretable that published FFDI estimates are not available over a wider range of years.

Fig. 9: Averaged Observed Summer FFDI: 1951 – 2016

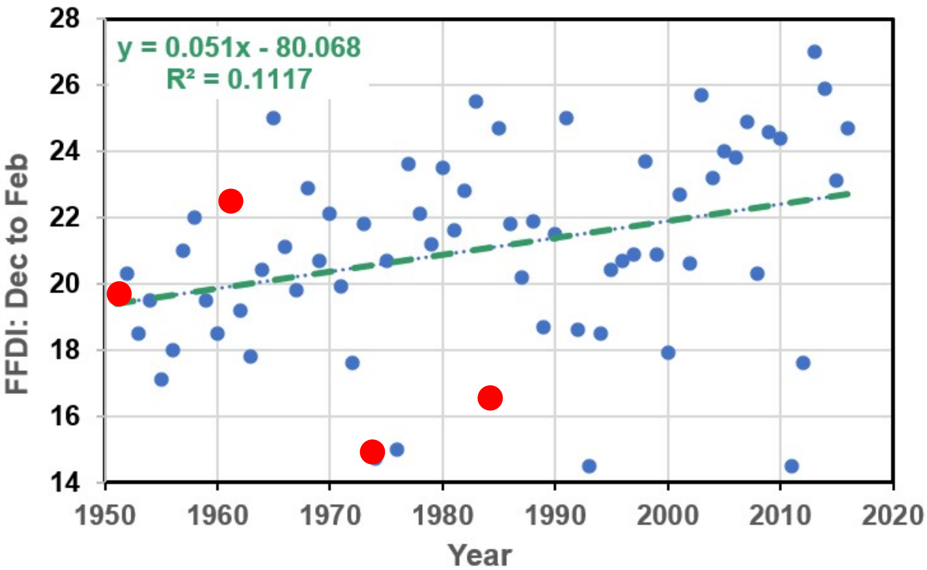

Fig. 9: Forest Fire Danger Index (1951 – 2016); mean observed values of FFDI for December through February; from Dowdy (2018). The four major bushfires between 1951 and 2016 are shown here by red dots for magnitudes >3.2 (from Table 1 and Fig.6) also show a relatively poor relationship with FFDI. The regression line and the four dots lie within the FFDI classification of “high” (12 to 24).

As noted, and numerically expressed in Equation 10, bushfire line intensity (FLI) is more sensitive to the square of the burnt fuel load per unit area ($(f \cdot W)^2$) than it is to FFDI. An estimate of f•W for even the significant bushfires in Table 1, from 1951

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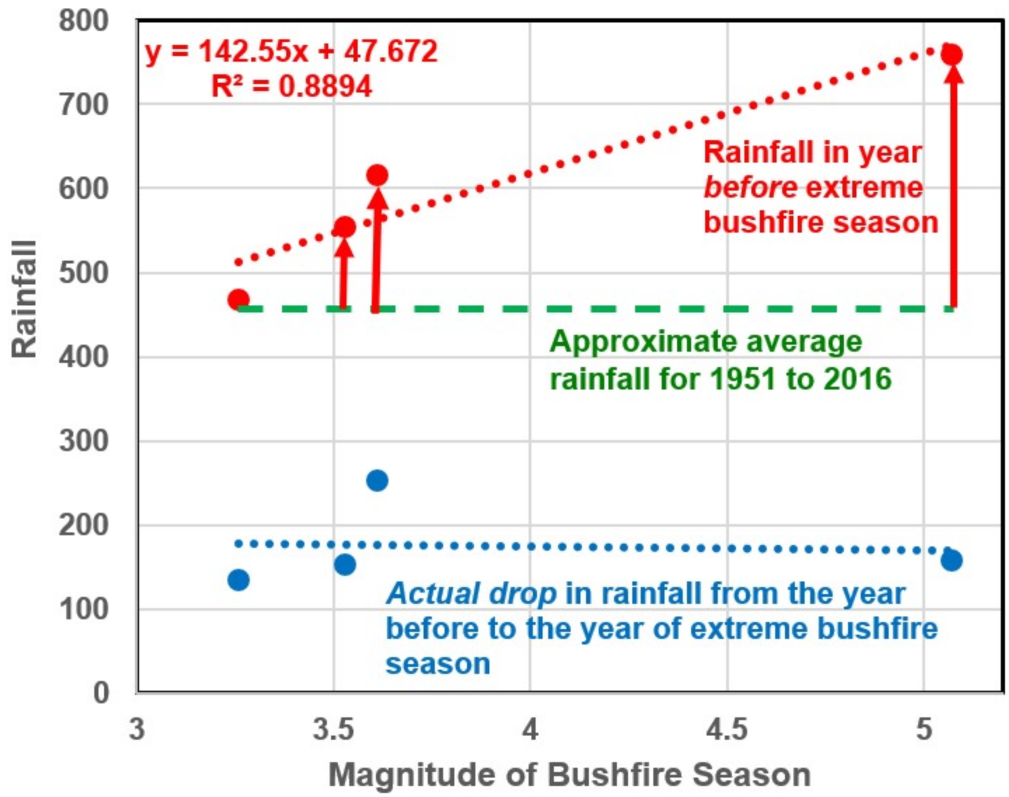
through 2016, is not available in the published (readily discoverable?) literature, but to assume it is constant for bushfires that range in area burnt by four orders of magnitude, would seem an oversimplification.

Thus, in order to move to the next level of approximation, in respect of a proxy for bushfire line intensity (FLI), a relative level of f•W for higher magnitude bushfires would seem indicated. Fig. 3 provides a clue. Fig. 10 shows a plot of rainfall statistics against the four bushfires of magnitude greater than 3.2, corresponding to a burn area of greater than 1.5 million hectares (from Table 1 and Fig. 4), that fall within the 1951 to 2016 data window of Dowdy: namely, 1950/51; 1961; 1974/75 and 1984/85. Whilst there are admittedly few data points, two conclusions are possible:

1. Higher magnitude bushfires occur in relative drought years, that closely follow higher than normal rainfall years; *ie* it may be concluded that at least one year of excess vegetation growth leads to an excess fuel load one or two years later. This observation agrees with that of Roderick (2020); *and*
2. The relative depths of the drought that hosts the four higher magnitude bushfire seasons, as marked by the drop in rainfall, has no correlation with that magnitude; *ie* drought factor, DF, is not a significant influence on Forest Fire Danger Index, or on bushfire intensity, despite that assertion in Equation 8.

Fig. 10: Bushfire Magnitude (Major fires: 1951 – 2016) *vs* Rainfall



Thus, just as there is a connection between earthquake magnitude and intensity, a similar connection is apparent between bushfire magnitude (at least its proxy, area of burnt) and actual intensity $((f \bullet W)^2 \bullet F)$. Thus, to attempt a better estimate of intensity,

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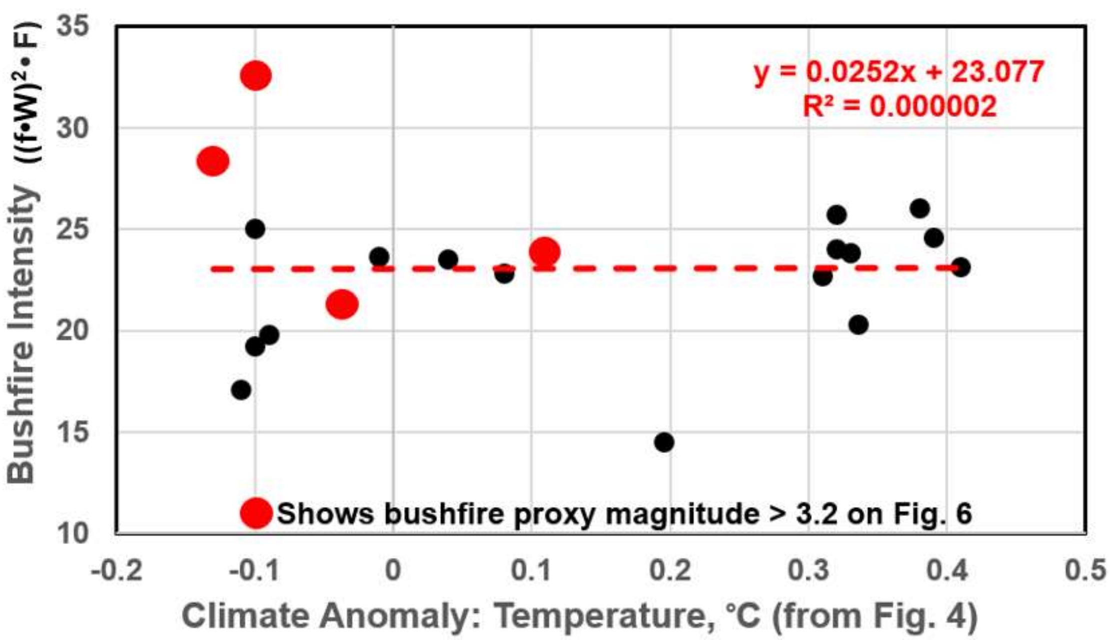
the four major bushfires have been (arbitrarily) assigned a burnt fuel load per unit area (f•W) that is 20% higher than other bushfire seasons in the 1951 to 2016 window. These are thus assigned a relative $(f•W)^2$ of 1.44; the remainder, a relative $(f•W)^2$ of 1.0.

The resultant plot of relative bushfire line intensity ($(f•W)^2$ • F) against climate temperature anomaly is shown in Figure 11. The four events/seasons with arbitrarily adjusted values for f•W are shown with larger red dots. Interestingly, three of these events occur in the first 33-year half of the study window, when anomalous temperatures were about -0.02°C ±0.08°C; the fourth occurs in the last 33-year window, when anomalous temperatures were about +0.23°C ±0.17°C.

Fig. 11: Bushfire Intensity *vs* Climate Anomaly (1951 – 2016)



Given the necessary assumptions made, bushfire intensity shows no definitive correlation with climate change temperature anomaly, at least in the window from 1951 – 2016. However, it must be acknowledged that the actual burnt fuel load density (f•W) remains the biggest unknown in historical (bush)fire line intensity estimates. This was emphasised by the Howitt Society (2020) submission to the Australian Royal Commission into Natural Disasters: "Reducing (ignitable) fuel loads is a key to improved outcomes with wildfire. Whilst a large-scale fuel reduction burning (FRB) program will not stop fires, it will create a mosaic of burnt and unburnt country of varying ages which will reduce fire intensity..."[9]

Chemistry of Wood Combustion

This conclusion raises the question as to whether any link between bushfire magnitude and climate change could be justified from consideration of the process of

[9] Succinctly: "*if you want to stop these landscape fires just take away the stuff that burns*"!

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wood combustion and its theoretical underpinning. To a first approximation, conversion of cellulose to burn products is summarised by:

$2C_6H_{12}O_6$ + 2(*metal ion*$^{++}$) + 13 $O_2 \rightarrow$ 2(*metal carbonate*) +10 CO_2 +12 H_2O + *Energy*

The metal ions are likely to be derived from soil fractions of any of the more common metallic elements in the surface of the Earth's crust: aluminium 8.3%, iron 5.6%, calcium 4.2%, sodium 2.5%, magnesium 2.4%, and potassium 2.0%. The metal carbonate product is ash. The energy released is typically 16,000 kilojoules/kilogram of common firewood, dependent on water content (*Source*: The Engineering Toolbox).

Energy, as used in this context, is the release of heat caused by oxidation of cellulose and other organic compounds in wood. The chemical bonds of the atoms in wood, once broken, release more energy than are needed to form their combustion products, and this excess energy is released as heat. It would seem logical that the reaction rate should be relatable to bushfire intensity.

Activation energy, in Joules/mol, is the minimum amount of energy required to initiate a reaction, and is a constant within the small ambient temperature ranges considered here. It is the height of the potential energy barrier between the potential energy minima of the reactants and products. The Arrhenius equation relates the rate at which a chemical reaction proceeds to activation energy and temperature:

Equation 10: $k = A \cdot e^{(-E_a/RT)}$

where k is the reaction rate coefficient, A is the frequency factor for the reaction, E_a is the activation energy, R is the universal gas constant (8.3145 Joules/°K·mol), and T is the absolute temperature (degrees Kelvin), and e is the exponential constant.

From the Arrhenius equation, it can be seen that the rate of reaction changes according to temperature. Normally, this means a chemical reaction proceeds more quickly at a higher temperature.

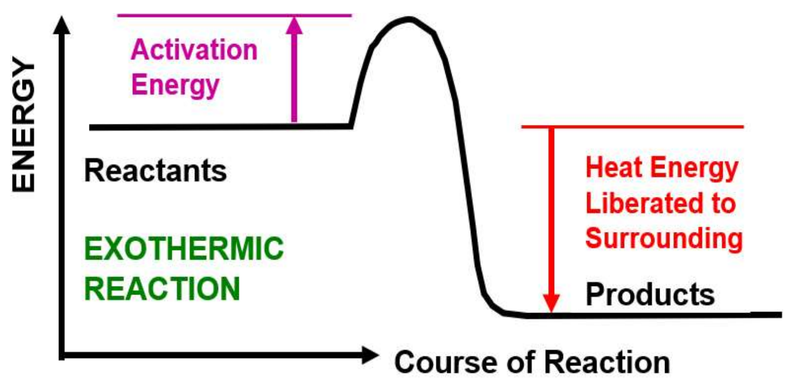

Figure 12. The relationship between activation energy and heat energy liberated during the course of a combustion reaction.

For the purposes of this analysis, the question is: by how much does the wood combustion reaction rate increase with an increase in temperature due to global warming, say, from 295.0°K in SE Australia in 1930 to 295.8°K today (Figure 4).

The first derivative of Equation 10 is:

Equation 11: $dk/dT = A{\cdot}E_a{\cdot}e^{(-E_a/RT)}/R{\cdot}T^2$ and

Equation 12: $dk/k = A{\cdot}dT/R{\cdot}T^2$ *or* $\delta k/k \propto \delta T/T^2$

In other words, an increase in temperature will cause a disproportionately small increase in reaction rate. Thus, assuming that A/R is constant, an increase of 0.8°K at 295°K (0.3% increase) will produce an increase of 0.001% in reaction rate. Thus, from theoretical considerations, it is concluded that "global warming" over the last 90 years has had no statistically significant influence on either bushfire magnitude or intensity.

Conclusions

This historical review and analysis of Australian bushfires over the last 170 years has focussed on instrumentally observed temperature changes and related climate indicators. It has consciously *not* considered other human-related factors that probably *do* bear on fire magnitude, intensity and impact, but cannot be adequately quantified, or related, in either way to fire "severity", and thus have not been part of this analysis, namely:

- Possible increases in the incidence of arson, or other trigger events;
- Increasing population density and impact on forest use;
- Claimed reductions in fuel load clearing; *or*
- Improvements in firefighting – preparedness, methods and equipment.

Specifically, the focus here is on whether the strength (better defined as intensity) of recent bushfires in Australia has been exacerbated to any significant degree by human-induced climate change. This debate has provoked discussion as to how any such perceived trend might be reversed. The vexed question of "cause" (not an event "trigger") was addressed by looking at the general characteristics of other natural hazards. Earthquakes, the best studied of these, are characterised by: (1) released strain energy – magnitude; (2) consequential ground displacement – intensity; and (3) resultant damage to people and structures – impact. The same characteristics can be ascribed to the bushfire hazard: released *thermal* energy through burning wood fuel - magnitude; consequential, weather and terrain-driven *fire spread* – intensity; and resultant damage to people and structures – impact.

The Southern Hemisphere instrumentally recorded climate, defined here as a variability on the order of a sixty to hundred-year timescale, or greater, has changed over the last 170 years. This is evidenced by the Gaussian-filtered *global* temperatures, an approximation for climate, varying from -0.28°C in 1850, through a relative low of -0.43°C in 1908, to +0.66°C today. Differences between the Northern and Southern Hemisphere temperatures and the shorter amplitude variations superimposed on this 170-year oscillatory increase, suggests that the drivers are manifold – seemingly including rising CO_2 levels, solar effects, orbital harmonics, and a probable "heat island" effect, at least in the Northern Hemisphere, with an oceanic "heat sink" in the Southern Hemisphere. This accords with the observations and models of Scafetta (2016).

Australian bushfires, commonly associated droughts, recorded since European settlement, show that the continent has been effected by both for *at least* 232 years, but that both the 2019/2020 drought and bushfire seasons are far from the worst in Australia's recorded history. Neither the qualitative "severity" or "impact" of drought, nor area burned in bushfire seasons (the Log_{10} of which is proposed as a proxy for bushfire magnitude), nor a model of intensity, correlates convincingly with the record of Southern Hemisphere climate variations. Indeed, a proxy for bushfire magnitude shows no correlation with climate change. Average rainfall history from 1900 shows high variability, but a wetter, rather than drier trend. Southern Hemisphere cyclone energy shows no significant trend with anomalous temperature, while the cyclone numbers in and around Australia seem to be decreasing. Planet-wide "greening", through a process of CO_2 fertilisation, is shown to be insignificant to the enhancement of bushfire magnitude. From a model of bushfire intensity and an examination of combustion theory, it can be shown that burnt fuel load has the dominant influence on bushfire intensity, and that "global warming" over the last 70 to 90 years makes no significant contribution.

A qualitative assessment suggests that any increase in bushfire impact over the last 232 years since European settlement, as judged by lives lost, proportionate to population, similarly, shows little correlation with bushfire magnitude, or with presumed anthropogenic climate change or global warming.

It is therefore concluded that (1) climate change drivers are several – including rising CO_2 levels, solar variations, orbital harmonics, *and* probable "heat island" and "heat sink" effects; (2) neither bushfire magnitude nor intensity can be attributed to "climate change", and certainly not that particular component likely due to rising CO_2 levels; and (3) if not climate change, bushfire magnitude seems likely driven by fuel load quantity and combustion energy related to the state of dryness of that fuel. Any anomalous bushfire intensity is likely driven by anomalous ground-level fuel load and dryness (see, Howitt Society, 2020). This indicates that any strategy of CO_2 emissions reduction that aims to specifically tackle a perceived increase in bushfire impact would be futile.

It is clear that bushfire impact can only be mitigated, practically, by reducing, controlling and managing anomalous fuel load, by any means, and to the greatest extent possible.

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