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Modulating influence of drought on the synergy between heatwaves and dead fine fuel moisture content of bushfire fuels in the Southeast Australian region

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ABSTRACT

During the 2019-20 summer season, Australia experienced frequent heatwave events with scorching temperatures and massive bushfires with dense smoke. These catastrophic heatwaves and bushfires resulted in huge socio-economic and ecological losses. The frequency and intensity of both heatwaves and bushfires are projected to increase in the future warming world. While considerable effort has been directed at understanding the physical mechanisms of these individual extreme events, an investigation of their interaction is lacking. We focus on the relationship between heatwaves and bushfire fuels by considering dead fine fuel moisture content, a critical factor that regulates the intensity, spread rate and the likelihood of profuse spotting of fires. We investigate the relationship by exploring the statistical correlations between various heatwave characteristics (frequency, duration, magnitude, and amplitude) and mean dead fine fuel moisture content over southeast Australia in the peak heat and fire season. This relationship varies among different heatwave characteristics as well as with regions. The prolonged duration of a heatwave is well associated with dead fine fuel dryness around the southeastern parts of the Southeast Australian region, whereas the hotter heatwave season favours the lower dead fine fuel moisture content over the Northeast parts of the Southeast Australia and central Victorian region. Results also suggest that dead fine fuel moisture content is significantly decreased on heatwave days compared to non-heatwave days. Lastly, we explored the effects of rainfall deficit on the relationship between heatwave and mean dead fine fuel moisture content by splitting the seasons based on the Standard Precipitation Index (SPI). Results show that the correlation strength is both seasonally and regionally dependent.

1. Introduction

1.1. Background to heatwaves and fires in the Australian context

Heatwaves are a well-known feature of the Australian climate. Australian heatwaves can have devastating consequences causing problems to human health and leading to deaths (Coates et al., 2014). For example, the 2009 heatwave antecedent to the Black Saturday bushfires killed 374 people (Australian Bureau of Statistics, 2010) and resulted in economic losses of approximately 1.3 Billion USD (Munich Re, 2009). Frequent and prolonged heatwaves have additional impacts on the productivity of crops and livestock (Asseng et al., 2011; Wheeler et al., 2000).

Heatwaves are also a critical factor in the development of extreme bushfires (Clarke et al., 2013). Bushfires result in a wide range of adverse societal effects like socio-economic losses, ecological damage, hazardous public health effects, and agriculture productivity impacts (Borchers Arriagada et al., 2020; Ulubaşoğlu et al., 2019; Zammit et al., 2019). The estimated annual cost of bushfires in Australia is approximately 400 million USD (Ashe et al., 2009). However, extreme bushfire events can exact a much higher cost. The 2009 Black Saturday bushfires alone resulted in an economic loss of ~4.4 Billion USD (Teague et al.,

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2010), while the unprecedented bushfires in 2019–20 destroyed 2448 homes with a burnt area measuring about 5.5 million ha in New South Wales alone (NSW Rural Fire Service, March 31, 2020).

Bushfires require an ignition agent, adequate fuel load, favourable fire weather, and low fuel moisture content (FMC) (Bradstock, 2010). However, initial surface spread and intensity of fires are regulated mainly by FMC (Sullivan, 2009). FMC represents the water quantity in the fuel, which indirectly determines the amount of heat released during the burning of the fuel (Viney, 1991). Bushfire fuels are broadly classified into two types: live fuels and dead fuels. Live fuels are comprised of the living foliage and branches of trees, shrubs and grasses, and their moisture content is determined directly from soil moisture stores through the vascular supply (Yebra et al., 2013). Dead fuels are comprised of dead grass, leaves, twigs, bark, and branches that accumulate at the surface or are suspended amongst living vegetation. The moisture content of dead fuels is determined as an equilibrium between the fuels and the surrounding environment (Simard, 1968; Viney, 1991).

Dead fuels can be further classified based on their environmental response times, into dead fine fuels with a 1–10 h response time, and dead coarse fuels with a 100–1000 h response time (Bradshaw et al., 1983; Deeming et al., 1977). The response time represents the time required for the FMC of respective fuel particles to equilibrate in response to changes in environmental conditions. The response time of fuel is a function of fuel size and density (Anderson, 1990). The 1, 10, 100, and 1000-h fuels correspond to sizes of less than 6.35, 6.35 to 25.4, 25.4 to 76.2, and greater than 76.2 mm in diameter, respectively. Dead fine fuels are specifically considered in fire management due to their importance in governing the ignition and the early spread rate of fires (Rothermel, 1983). The FMC of dead fine fuels is also an important indicator of lightning-induced fire ignition (Dowdy and Mills, 2012).

The FMC of dead fuel particles is mainly dependent on the size of the fuel, rainfall, and surrounding atmospheric conditions (Matthews, 2014). Dead FMC varies with physical processes like vapour exchange, precipitation, and latent heat (Viney, 1991). On non-rainy days, dead fuel moisture content responds to the local weather conditions via water vapour exchange processes (Nolan et al., 2016a), which are mainly governed by the vapour pressure deficit of surrounding air (Resco de Dios et al., 2015). The vapour pressure deficit of air represents the atmospheric aridity and is linked with land-atmosphere feedback (Zhou et al., 2019). Positive land-atmosphere feedback, which is correlated with atmospheric aridity, also strongly influences heatwave conditions (Hirsch et al., 2019).

Heatwaves are commonly defined as periods of consecutive days with high daytime and/or night-time temperatures exceeding a threshold (Perkins and Alexander, 2013). According to the Clausius-Clapeyron relationship, the increased air temperature enhances the saturation vapour pressure (Bohren and Albrecht, 2000). The rise in the saturation vapour pressure of air in a constant moisture environment will increase vapour pressure deficit, which would result in a decrease in dead fine fuel moisture content (Nolan et al., 2016a). The persistent blocking highs over or adjacent to the affected region during a heatwave period hinders precipitation events (Vautard et al., 2013), which also favours (live and dead) fuel dryness. Land-atmosphere feedback, global warming, and high-pressure synoptic systems are just some of the common drivers of both fuel dryness and heatwave conditions. Given the commonalities between their driving mechanisms, it is reasonable to suspect that there might be a link between heatwave characteristics and dead fine fuel moisture content. Sullivan and Matthews (2013) studied the response of modelled FMC of 1 h (fine) dead fuels (<6.35 mm in diameter) to heatwave conditions in the week prior to the Black Saturday bushfires. They found that the FMC of dead fine fuels during heatwave conditions are significantly reduced compared to non-heatwave conditions. Ruffault et al. (2018) also found that the fast-responding dead fuels (nothing but dead fine fuels) over the northern Mediterranean region reacted more to combined hot and dry weather compared to only dry weather conditions during large wildfires. However, previous studies did not systematically investigate the link between heatwave characteristics and dead fine fuel moisture content.

1.2. Aims of this study

There are many remaining knowledge gaps around the interaction between heatwaves and fuel moisture in Australia, and trends of observed maximum temperatures over South-East Australia (SEA) are increasing (Alexander and Arblaster, 2017). Increasing global mean temperatures have contributed to the increase in the probability of occurrence of extreme heat events across the globe, and this increase is expected to continue during the 21st Century (Cowan et al., 2014; IPCC, 2013; Meehl and Tebaldi, 2004; Russo et al., 2014). The frequent occurrence of higher temperatures may increase the risk of both combined and independent increases in heatwave conditions and fuel dryness. Hence, it is important to explore the relationship between heatwaves and dead fine fuel moisture content.

Our study investigates the relationship between heatwave characteristics and dead fine fuel moisture content over SEA. The relationship between heatwaves and dead fine fuel moisture content provides an insight into heat-related compound extreme events like heatwaves and bushfires. Heatwave conditions, dead fine fuel availability, and its mean moisture content are also linked to the amount of precipitation that falls over a region. Hence, we analyse the effect of rainfall deficit on the relationship between heatwave characteristics and dead fine fuel moisture content.

2. Methods

2.1. Study area

The study area comprises parts of South-East Australia (SEA), where severe bushfires readily occur (Clarke and Evans, 2019; Williams et al., 2012). The study area is segregated into three regions based on their temperature and rainfall characteristics (Table 1). The classified regions are the North-East corner of SEA (NE-SEA), the South-East corner of SEA (SE-SEA), and Central Victoria (Cen-VIC). The map of the study area with our study regions is shown in Fig. 1. The three different regions are selected where the interannual variations of respective peak heat and fire season precipitation vary substantially between regions (see in Fig. 2). Here the peak heat and fire season refer to the period where most of the intense heatwaves and devastating bushfires have occurred in the

Table 1
Description of regions used in this study.

Region name	Latitude boundaries (°S)	Longitude boundaries (°E)	Description
North-East corner of South-East Australia (NE-SEA)	26.5–32.5	151–153.75	Northeast parts of New South Wales (NSW) and south-east parts of Queensland (QLD); mostly sub-tropical climate; warm and sub-humid
South-East corner of South-East Australia (SE-SEA)	32.5–39	146.75–152.25	Southeast parts of NSW, Australian Capital Territory (ACT), and eastern VIC; mostly temperate climate with most of the plant growth in spring; warm and dry summers
Central Victoria (Cen-VIC)	35.75–39	143–146.75	The central part of VIC; temperate climate with most of the plant growth in spring; warm and dry summers

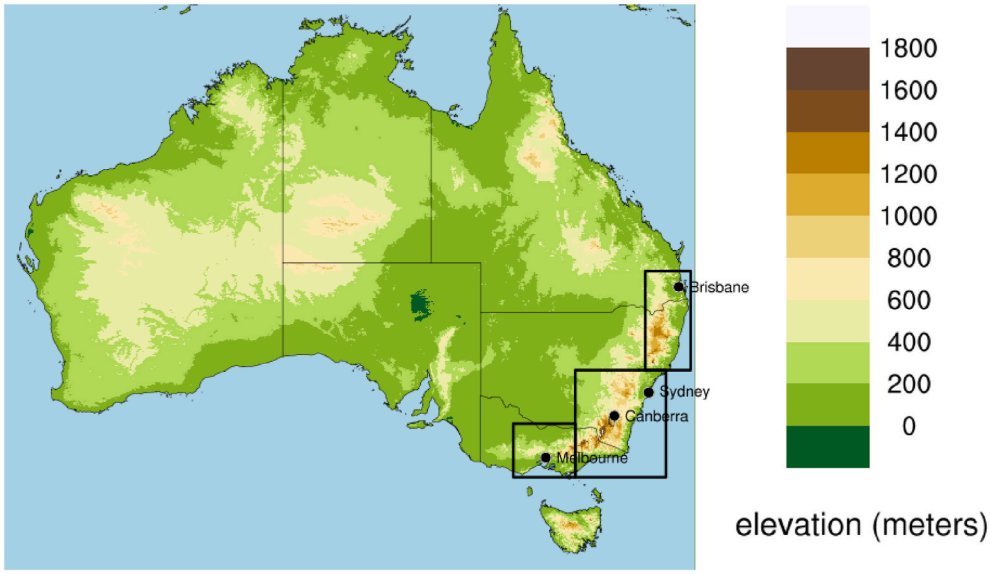

Fig. 1. Topographical map of locations of the regions used in this study. The top box is the North-East corner of SEA (NE-SEA), the bottom right one is the South-East corner of SEA (SE-SEA), and the bottom left one is Central Victoria (Cen-VIC).

past. For the purpose of this study, the duration of peak heat and fire season for the NE-SEA region is taken to be from October to January, for the SE-SEA region from November to February, and for the Cen-VIC region from December to March. In the warm and sub-humid NE-SEA region, interannual daily mean temperature variations of peak heat and fire season differ significantly with the other two regions. The average peak heat and fire season precipitation in the NE-SEA, SE-SEA, and Cen-VIC regions is about 101.7, 68.8, and 44.2 mm, respectively. The average daily mean temperature is about 20.6, 19.7, and 19.5 °C over the NE-SEA, SE-SEA, and Cen-VIC regions, respectively. The average vapour pressure deficit values are approximately 2.1, 2.3, and 2.4 kPa across the NE-SEA, SE-SEA, and Cen-VIC regions, respectively. The vegetation type observed in all three study regions is mostly eucalypt forest and woodland (Keith and Pellow, 2015; Prober et al., 2017).

2.2. Data

In this study, we used the observational gridded data of daily maximum temperature, minimum temperature, rainfall, and vapour pressure at 3 p.m. local time at 0.05 ° × 0.05 ° horizontal resolution provided by the Australian water availability project (AWAP) dataset (Jones et al., 2009). Due to the lack of vapour pressure data availability, we limit our analysis to the period of 1971–2020. The AWAP observational dataset is constructed with the available high-quality station data across Australia by employing the hybrid gridded algorithm technique (Jones et al., 2009). Many previous studies have used the AWAP dataset to study Australian heatwaves and have noted its suitability for climatological analysis (Herold et al., 2016; Perkins et al., 2015; Perkins and Alexander, 2013). Several factors may affect the quality of the AWAP dataset such as the methods used in the gridding procedure, temporal variability of the station density and the lack of data homogenisation. However, the AWAP dataset is supported by a dense station network in the SEA region, and so is well-suited to the present study.

2.3. Heatwave definitions

Australian heatwaves are typically defined as a period of three or more consecutive hot days, with temperature exceeding the relative thresholds (Cowan et al., 2014; Perkins et al., 2015; Perkins and Alexander, 2013). Nairn and Fawcett (2013) developed the Excess Heat Factor (*EHF*) index, which considers a three-day period temperature relative to the earlier average monthly temperature and relative climatological temperature of a certain base period. Perkins and Alexander (2013) found that an *EHF*-based heatwave definition is well-suited to investigate climatological heatwave characteristics in the Australian context. The *EHF* index can be applied to most of the impact-based studies, due to its consideration of both long-term and short-term climatology of mean temperature in its formulation. *EHF* is calculated according to Perkins et al. (2015) and is formulated as follows

$$T = \frac{(T_{max} + T_{min})}{2} \tag{1}$$

$$EHI_{sig} = \frac{(T_i + T_{i-1} + T_{i-2})}{3} - T_{90} \tag{2}$$

$$EHI_{acc} = \frac{(T_i + T_{i-1} + T_{i-2})}{3} - \frac{(T_{i-3} + \ldots + T_{i-32})}{30} \tag{3}$$

$$EHF = EHI_{sig} \times max(EHI_{acc}, 1) \tag{4}$$

where T_{max}, T_{min} and T are the daily maximum, minimum, and mean air temperatures, respectively, and the subscript i denotes daily values. T_{90} is the 90th percentile of 15-day window daily T_i for the climate reference period 1961–90.

The reference period is selected because it is standardised and used by the Australian Bureau of Meteorology (Perkins et al., 2015). EHI_{sig} and EHI_{acc} are the significance and acclimatisation excess heat indices based on the long term and previous month climatology of mean temperature (for further reading, please refer to Nairn and Fawcett, 2013; Perkins et al., 2015). In this study, a heatwave is defined as a period of three consecutive days with positive *EHF* values. Furthermore, heatwave characteristics are computed according to Perkins and Alexander (2013) and are defined as follows.

HWF (Heatwave frequency): number of days that contribute towards a heatwave in a season,
HWD (Heatwave duration): length of the most prolonged heatwave in a season,
HWM (Heatwave magnitude): mean magnitude of EHF in all heatwave days in a season, and HWA (Heatwave amplitude): peak daily EHF value of the warmest heatwave in a season.

All the heatwave characteristics in this study are calculated for the

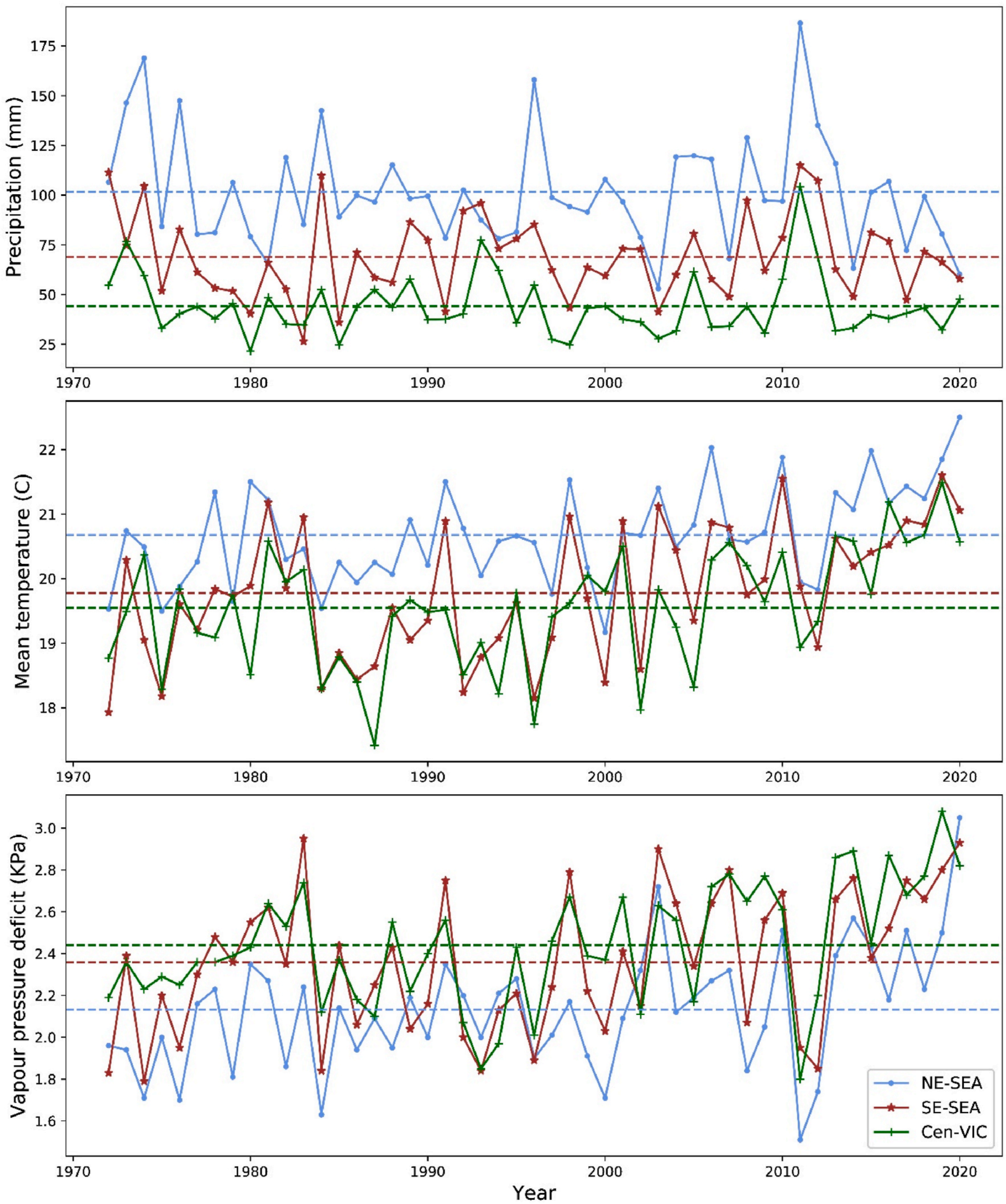

Fig. 2. Interannual variations of area-averaged (land only) precipitation (top panel), mean daily temperature (middle panel), and vapour pressure deficit (bottom panel) of peak heat and fire season in the respective study regions. Dotted lines represent respective regional mean conditions over 49 (1971–72 to 2019–20) peak heat and fire seasons.

peak heat and fire season of the respective regions (ref. Sec 2.1).

2.4. Dead fuel moisture

In our study, the semi-mechanistic model of Resco de Dios et al. (2015) is used to estimate the fuel moisture content of dead fine fuels (≤25 mm diameter). This model is built on the inverse relation between vapour pressure deficit (VPD) and dead fine fuel moisture content (hereafter as DFMC) and is as follows

$$DFMC = a + b\exp(-c \times VPD) \quad (5)$$

where VPD is the vapour pressure deficit expressed in kPa, the parameter a represents the minimum DFMC, b is the difference between the maximum and minimum DFMC, and c represents the rate of decline in DFMC with VPD. VPD is computed as the difference between saturation and actual vapour pressure values. The saturation vapour pressure (e_s) is calculated using the daily maximum air temperature (Monteith and Unsworth, 1990), according to Nolan et al. (2016a), and the vapour pressure at 3 p.m. local time is considered as the actual vapour pressure. The a, b and c values are approximated using non-linear least squares curve fitting analysis by Nolan et al. (2016a); their values are 6.79, 27.43, and 1.05, respectively. The DFMC model (Eq. (5)) with suggested parameter values (a, b, and c by Nolan et al. (2016a)) has been well-validated with observations over the SE-SEA and Cen-VIC regions in various vegetation types (Nolan et al., 2016a). Nolan et al. (2016a) also indicated that the DFMC model could be applied elsewhere without any site-specific standardisation. Hence, in the present study, we use Eq. (5) with the parameter values recommended by Nolan et al. (2016a) to approximate the daily minimum DFMC values in all three study regions.

2.5. Standardised Precipitation Index

In this study, the Standardised Precipitation Index (SPI) (Mckee et al., 1993) is used to characterise dry or wet conditions in the regions in terms of rainfall deficit. SPI is calculated by fitting the gamma distribution of standardised monthly precipitation anomalies and for specified preceding months compared to the corresponding months in the climatological base period. In many parts of the SEA region, the plant (fuel) growth and mean moisture content are dependent on the spring and summer season rainfall amount (Hutchinson et al., 2005). The vapour pressure deficit, which is the critical variable in DFMC calculation, likely varies with the regional concurrent and antecedent precipitation amount (see in fig. s1). Many previous studies (e.g., Herold et al., 2016; Perkins et al., 2015) have shown that antecedent rainfall deficit is associated with heatwave characteristics over much of the SEA region. Heatwave characteristics and the mean moisture content and availability of fuels[1] are independently coupled with antecedent and concurrent seasonal rainfall variations. Hence, in this study, the 6-month SPI (SPI-6) of January, February, and March are used to incorporate peak heat and fire seasonal rainfall variations over the NE-SEA, SE-SEA, and Cen-VIC regions, respectively. SPI-6 represents the comparison of precipitation accumulations over the previous six months (like August to January for SPI-6 of January) with the same six-month accumulations over the full period (1971–72 to 2019–20). To accommodate all the changes in the relationship between heatwaves and DFMC during various seasons, we considered the season as dry if SPI-6 ≤ -0.5; normal to near normal if $-0.5 <$ SPI-6 < 0.5; wet if SPI-6 ≥ 0.5. Mckee et al. (1993) categorised the drought using the SPI thresholds as follows: 0 to −0.99 - mild drought; −1 to −1.49 - moderate drought; −1.5 to −1.99 - severe drought; and −2 or less - extreme drought. However, here we considered area-averaged SPI-6 to classify the seasons broadly and hence have chosen the thresholds as mentioned above to accommodate mean regional rainfall variations. The interannual variations of SPI-6 in different regions are shown in Fig. 3.

2.6. Approach

Heatwaves are measured using various characteristics (see Section 2.3), which are calculated seasonally (Perkins, 2015). Hence, we explore the relationship between peak heat and fire seasonal heatwave characteristics (HWF, HWD, HWM, and HWA), and the mean dead fine fuel moisture content (DFMC) of the respective season for the three study regions. The seasonal mean of DFMC is computed as the average of DFMC values in the heatwave days of the corresponding season. The consideration of all days in the season would average out the inter-seasonal variability and could lead to inconsistent statistical relationships. The whole season average of DFMC could even remove the influence of the presence of low DFMC values, which are of critical importance in the context of fire management. The DFMC of heatwave days is expected to be lower compared to normal days. Hence, we focus on the DFMC values on heatwave days rather than considering all days in the season. Therefore, our results are constrained to DFMC on heatwave days over the 49 peak heat and fire seasons of the respective regions. Furthermore, we try to identify the influence of antecedent and concurrent seasonal rainfall deficit on the relationship between heatwave characteristics and mean DFMC. To facilitate this, we first classified the 49 seasons into three categories, namely dry, near-normal, and wet, based on SPI-6 values (refer to Sec. 2.5) of the respective study regions. After that, we investigated any changes in the heatwave and mean DFMC relationship as before but in various seasons over different study regions.

3. Results

3.1. Correlation between heatwave characteristics and dead fine fuel moisture content

To describe the statistical relationship between heatwave characteristics and mean dead fine fuel moisture content (DFMC), we calculated their correlations over 49 (1971–72 to 2019–20) peak heat and fire seasons of the respective regions (Fig. 4). In this study, correlations were calculated using the non-parametric Spearman rank correlation method. The heatwave characteristics data does not follow the normal distribution (Perkins and Alexander, 2013); hence the non-parametric method is appropriate to analyse the correlations. The non-parametric methods are also less sensitive to the outliers and non-normal distribution data (Caesar et al., 2006; Perkins and Alexander, 2013). Previous studies have also used the Spearman rank correlation method to analyse the relationship between antecedent rainfall and heatwave characteristics over the Australian region (Herold et al., 2016; Perkins et al., 2015). However, the parametric Pearson correlation method produced patterns of correlation between heatwave characteristics and mean DFMC that were mostly similar to that of the Spearman rank method in all the considered study regions (fig. s2).

The correlations are mostly similar among those longevity-related heatwave characteristics (HWF and HWD) and those of intensity related heatwave characteristics (HWM and HWA). Amongst longevity-related heatwave characteristics, HWD has the strongest anti-correlation with mean DFMC over the parts of the SE-SEA and Cen-VIC region. This suggests that prolonged heatwave events are strongly associated with lower mean DFMC values over the parts of the SE-SEA and Cen-VIC region. Of the intensity related heatwave characteristics, HWM has strong negative correlations with mean DFMC compared to HWA in all the three study regions. It suggests that a substantially hotter heatwave season is associated with lower mean DFMC over large tracts of NE-SEA and Cen-VIC regions. The intensity related heatwave characteristics (HWM and HWA) have considerably strong anti-correlations with mean DFMC, mainly in the NE-SEA and Cen-VIC regions. In contrast, less area of the NE-SEA region has a significant negative correlation between longevity-related heatwave characteristics (HWF and HWD) and mean dead fine fuel moisture content.

The climatology of the mean dead fine fuel moisture content of heatwave days and all days in the non-heatwave peak heat and fire season of the respective region are shown in Fig. 5(a) and (b) respectively. The minimum climatological mean DFMC values are observed in heatwave days, particularly in inland arid regions, which are mainly plains dominated by grasslands. The mean difference between DFMC of respective heatwave days and all days of non-heat wave seasons is shown in Fig. 5(c). All differences are statistically significant at a 95% confidence level; significance is tested with Welch modified *t*-test (Welch, 1947). The statistically significant composite difference between mean DFMC of respective heatwave days and all days of the non-heatwave season is largest in the SE-SEA and Cen-VIC regions (see in Fig. 5(c)). The largest differences are observed in the regions of elevated topography. There is a significant reduction in mean DFMC of about 4% during heatwave days compared to non-heatwave season days over much of the study regions. In addition, the mean DFMC is lower in the seasons of prolonged heatwaves and in the seasons of higher average heatwave intensity compared to non-heatwave seasons, particularly in the regions of the existing relationship between heatwave and mean DFMC (see in fig. s3). Hence, these results suggest that there is an

[1] Here fuel availability only really applies to dead fuels, where it is defined as the proportion of the total fuel load that has a moisture content below the moisture content of extinction.

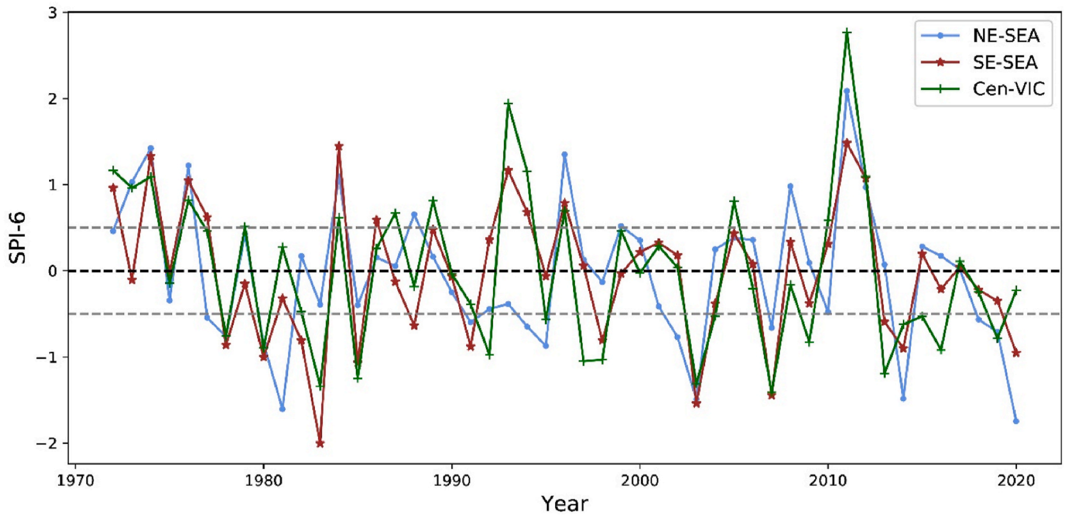

Fig. 3. Area averaged (land only) 6-month time scale SPI (of January for NE-SEA, of February for SE-SEA, and of March for Cen-VIC) in the three study regions. The SPI-6 values between top and bottom dotted lines ($-0.5 < \text{SPI-6} < 0.5$) represent normal to near normal conditions of dryness, above top dotted line ($\text{SPI-6} \geq 0.5$) represent wet years, and below the bottom dotted line ($\text{SPI-6} \leq -0.5$) represent dry years.

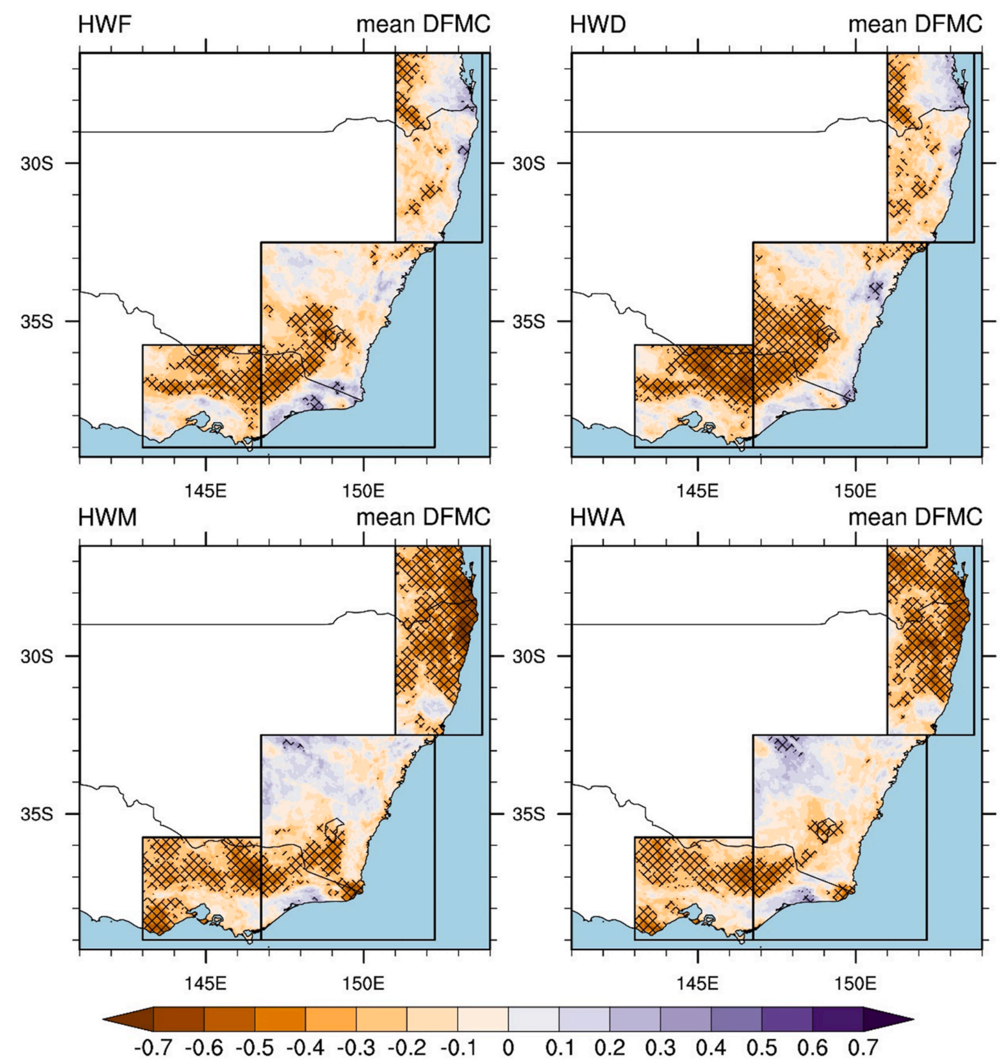

Fig. 4. Spearman rank correlations between heatwave characteristics and mean dead fine fuel moisture content (DFMC) over 49 (1971–72 to 2019–20) peak heat and fire seasons of the respective regions. Hatched regions indicate significant correlations at the 95% confidence level.

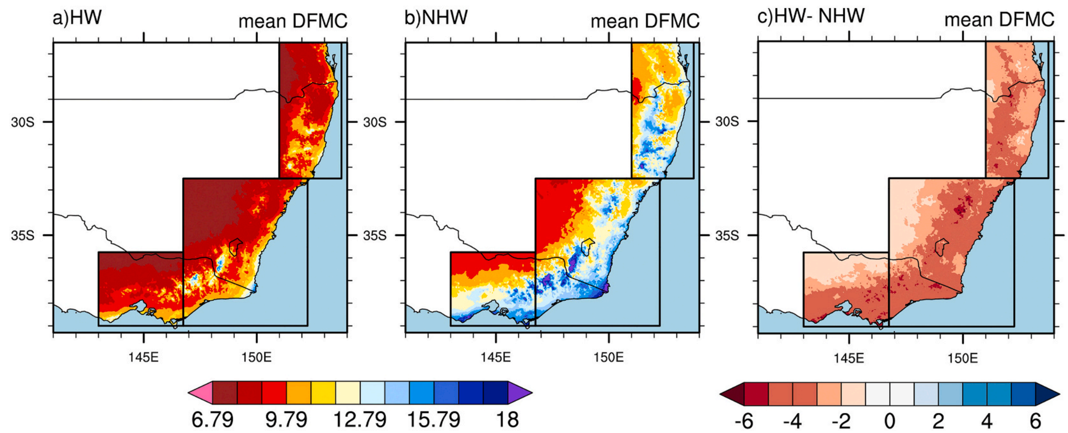

Fig. 5. Climatology of dead fine fuel moisture content (DFMC) a) only in heatwave (HW) days, b) all days in non-heat wave (NHW) seasons over 49 (1971–72 to 2019–20) peak heat and fire seasons in the respective regions. c) The composite mean difference between the dead fine fuel moisture content of respective heatwave days and all days of non-heat wave seasons. All the mean difference values are statistically significant at the 95% confidence level.

identifiable relationship between heatwave characteristics and lower mean dead fine fuel moisture content over some parts of the study regions and that heatwaves may have a significant effect on dead fine fuel dryness.

3.2. *Effect of rainfall deficit on the heatwave-dead fine fuel moisture content relationship*

Here, we further investigate the influence of antecedent and concurrent rainfall variations on the statistical relationship between heatwave characteristics and mean dead fine fuel moisture content. Fig. 6 displays the correlation of HWD with mean DFMC (top panel) and HWM with DFMC (bottom panel) for all 49 peak heat and fire seasons (first column), for only dry seasons (second column), for only near-normal seasons (third column) and only wet seasons (fourth column). The results of this investigation are mostly similar between longevity-related heatwave characteristics (HWF and HWD) and those of intensity related heatwave characteristics (HWM and HWA). Hence, the results of HWD and HWM are shown, which have significantly stronger correlations. A summary of area-averaged (only statistically significant cells) correlations of heatwave characteristics (HWD and HWM) with mean DFMC for each season among different regions are provided in Fig. 7. The portion of land area with statistically significant correlations are shown as percentage values for the corresponding region in a respective season in Fig. 7.

Results show that stronger anti-correlations are observed between HWM and mean DFMC in most parts of the NE-SEA region for all seasons considered (see in Figs. 6 and 7). In contrast, HWD has weaker negative correlations against mean DFMC in the NE-SEA region for dry and near-normal seasons. Only in wet seasons, the correlations between HWD and mean DFMC are strong and positive, and these significant correlations span around one-fourth of the NE-SEA region. In the far south of the SE-

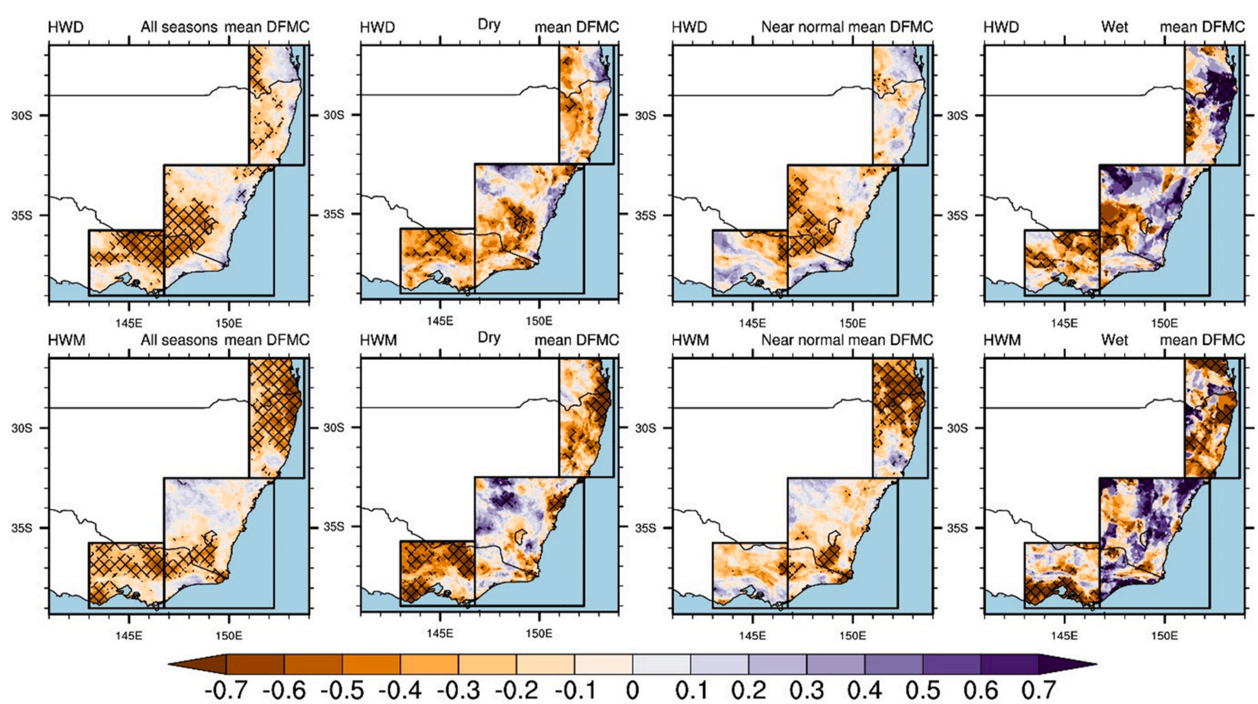

Fig. 6. Spearman rank correlations between heatwave characteristics (HWD (top panel) and HWM (bottom panel)) and mean dead fine fuel moisture content (DFMC) over the period 1971–72 to 2019–20 in all seasons (first column), in only dry years (second column), near-normal years (third column) and wet years (fourth column). Hatched regions indicate significant correlations at the 95% confidence level.

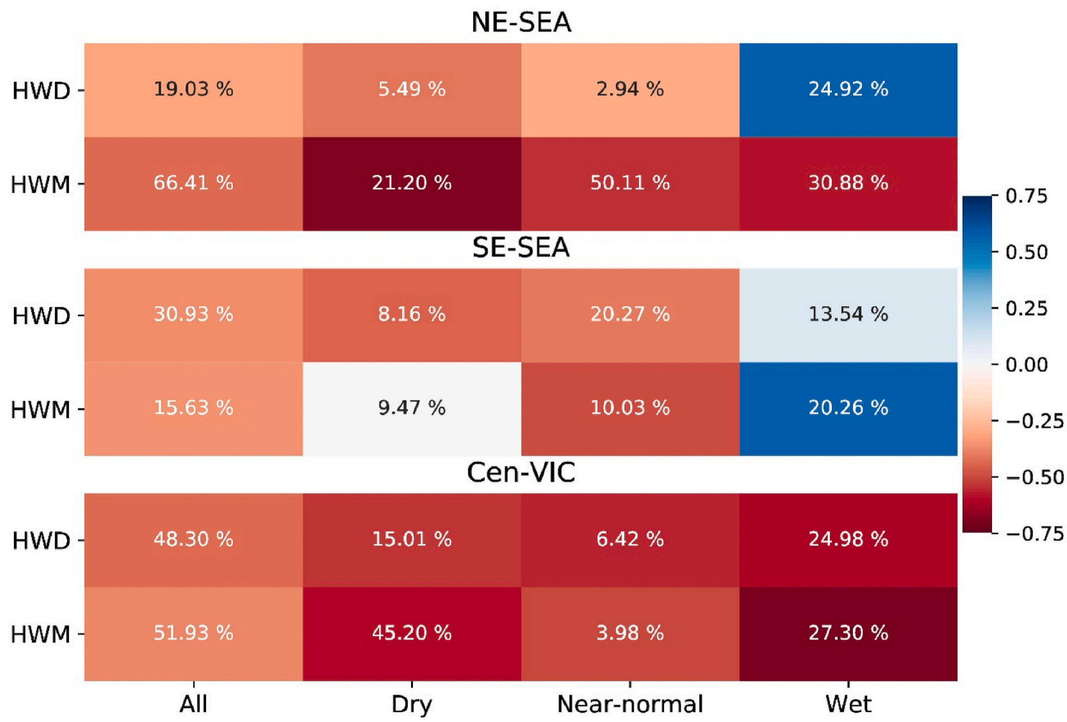

Fig. 7. Correlation matrices represent area-averaged (only statistically significant cells) correlations of heatwave characteristics (HWD and HWM) with mean DFMC in different seasons for the respective regions (shown in the colour bar; red indicates negative correlations while blue indicate positive). The percentage values represent the percent of land area with a statistically significant correlation in a corresponding region of the respective season. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

SEA region, HWD is strongly anti-correlated with mean DFMC in dry and near-normal seasons compared to wet seasons. However, only the near-normal season correlations are statistically significant over the broad area of the SE-SEA region compared to the dry season. A less significant association exists between HWM and mean DFMC in the SE-SEA region in dry and near-normal seasons. While in wet seasons, HWM has a strong positive correlation with mean DFMC in some parts of the SE-SEA region. Conversely, in most parts of the Cen-VIC region, both HWM and HWD are strongly anti-correlated with mean DFMC, particularly in the dry and wet seasons. However, HWM and mean DFMC correlations are significant over a wide area of the Cen-VIC region, particularly in the dry season compared to HWM and mean DFMC. This indicates that rainfall variations modulate the relationship between heatwave characteristics and mean DFMC, particularly the association between mean DFMC and HWD in the NE-SEA and HWM in the SE-SEA region.

Furthermore, we calculated the peak heat and fire season distribution of daily dead fine fuel moisture content in the different regions with varying seasons to investigate the spread in DFMC values among the regions. The seasonal distributional variations of daily DFMC values in different seasons are shown in Fig. 8. In each of the three study regions, the drier seasons are associated with high frequent occurrence of low DFMC values (for example, DFMC $<$ 10%) compared to other seasons. The NE-SEA region has experienced less frequent extremely low DFMC values (DFMC $<$ 7%) compared to the other two study regions. This suggests that the NE-SEA region has a minimal number of days, a smaller extent of the area with extremely low DFMC values or both, compared to the other two regions.

4. Discussion

This study is the first to systematically investigate the relationship between heatwaves and dead fine fuel moisture content using a high resolution observational gridded dataset over southeast Australia. This was facilitated by exploring the correlations between four heatwave characteristics (frequency, duration, magnitude, and amplitude) and mean DFMC; the composite difference of DFMC for heatwave days and all days of the non-heatwave season. In addition to this, the effect of rainfall deficit on the heatwave-DFMC relation was investigated via

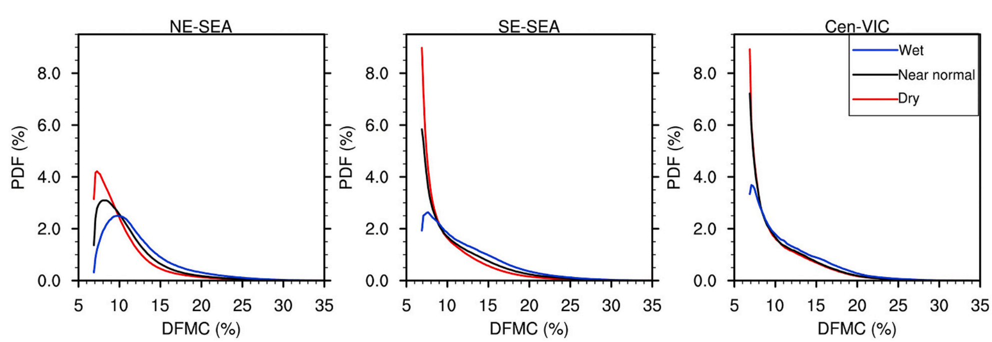

Fig. 8. Probability distribution function (PDF) of dead fine fuel moisture content (DFMC) values of the selected regions in respective seasons (from 1971–72 to 2019–20).

studying the correlations between heatwave characteristics and mean DFMC in different seasons with varying rainfall amount.

Results show that the relationship between heatwaves and dead fine fuel moisture content varies between regions in their respective peak heat and fire season. Heatwave duration (HWD) is the most important heatwave characteristic associated with mean DFMC over the south of the SE-SEA region (Fig. 4). Substantially stronger anti-correlations exist between HWD and mean DFMC than other characteristics for the south of the SE-SEA region, implying that prolonged heatwaves are associated with lower mean DFMC values over these regions. The results confirm the expectation that a continuous period of hot and dry air in the surrounding atmosphere during prolonged heatwaves favours very dry fuels. These long-lasting consecutive periods of intense hot conditions can significantly lower the dead fine fuel moisture content by not allowing them to recover. Although the strength of the statistically significant correlations between heatwave frequency (HWF), average heatwave intensity (HWM), and heatwave amplitude (HWA) with mean DFMC is lower, a negative correlation still exists over the south of the SE-SEA region, which suggests that these heatwave characteristics may also favours the lower mean DFMC values (Fig. 4). Further research is required to determine whether these heatwave characteristics interact to reduce mean DFMC over SE-SEA.

Average heatwave intensity (HWM) is the most dominant heatwave characteristic related to mean DFMC across most of the NE-SEA region, as determined by significant negative correlations with mean DFMC over much of the region. This means that a greater increase in mean heatwave intensity over a season could result in a greater decrease in mean DFMC. However, only a few parts of the NE-SEA region have a significant relationship between longevity-related heatwave characteristics (HWF and HWD) and the mean DFMC. This emphasises the importance of each heatwave characteristic on the mean DFMC in different regions. Parts of the Cen-VIC region have a similar correlation pattern among the longevity-related heatwave characteristics and intensity-related heatwave characteristics with mean DFMC, respectively. However, both the longevity-related heatwave characteristics (HWF and HWD) operate on different timeframes; for example, HWF is the total count of heatwave days, and HWD is the length of the most prolonged heatwave in a season. Similarly, intensity-related heatwave characteristics measure different things: HWA is the hottest day of the hottest event, while HWM is the average intensity across all events.

The regional variations observed in the relationship between mean DFMC and the different heatwave characteristics may be due to the spatially varying influence of various large scale climate variability modes (like El Nino Southern Oscillation (ENSO) and South Annular Mode (SAM)) on heatwaves over SEA (Perkins et al., 2015). ENSO influences both the seasonal precipitation and temperature in the SEA region, and SAM mainly affects temperature extremes over the South Australian region (includes Cen-VIC) (Perkins et al., 2015). Both heatwaves and DFMC are directly affected by temperature and implicitly influenced by precipitation. Further investigation is needed to identify the influence of large scale climate modes on the relationship between heatwaves and DFMC.

The quantitative change in mean DFMC between heatwave days and all days of the non-heatwave season is shown in Fig. 5 and suggests that the mean DFMC values are significantly lower in heatwave days compared to regular days. These results are consistent with interactions of heatwaves and DFMC over Portugal (Boer et al., 2017), and is similar to modelled fuel moisture of fine (1 h) dead fuels (Sullivan and Matthews, 2013). The reduction in mean DFMC values in heatwave days is higher in elevated landscapes (see in Fig. 5(c)), indicating that heatwave affected areas can be expected to have drier dead fine fuels. These dry fuels increase the flammability, spread rate, and spotting potential of bushfires, which allows the fires to rapidly escalate to extreme levels (Sharples et al., 2016). The connected patches of dry fuels favour the formation of large bushfires that burn vast areas, like in the 2019-20 Australian mega-fires (Nolan et al., 2020).

The seasonal variability in the correlation coefficients of both heatwave duration (HWD) and average intensity (HWM) with mean DFMC is seen in all the three study regions (see in Fig. 6). This is consistent with findings of studies in the northern Mediterranean region, where it has been shown that combined hot and dry weather has a considerable effect on the fast-responding dead fuels (nothing but dead fine fuels) compared to only dry conditions during large wildfires (Ruffault et al., 2018). However, both heatwave duration and average intensity are anti-correlated with mean DFMC even in the wet seasons over the parts of the Cen-VIC. These wet season anti-correlations are seen mainly in the coastal area of the Cen-VIC region. This coastal region is mostly a non-forested land with major urban centres like Melbourne and experiences less rainfall than other parts of the region. In contrast, positive correlations are observed between mean DFMC, particularly with HWD in wet seasons over the parts of NE-SEA and SE-SEA regions. These positive correlations in wet seasons are observed in regions (NE-SEA and SE-SEA) where higher average precipitation is recorded during the peak heat and fire seasons compared to the Cen-VIC region. More precipitation is associated with higher relative humidity, which may increase the mean DFMC. Seasonal precipitation varies greatly across Southeast Australia due to the spatially varying influence of the large scale climate variability modes (like ENSO, Indian Ocean Dipole (IOD)) (Cai et al., 2009; Risbey et al., 2009). Hence, the results of this study highlight the importance of both seasonal and regional variations in the relationship between heatwave characteristics and mean DFMC. Future work is needed to elucidate the reasons for both the spatial variation and seasonal variation in the strength of the relationship between mean DFMC and heatwave characteristics.

To better understand the changes in the heatwave and mean DFMC relationship over different regions and seasons, the distributional variations in daily DFMC values were also analysed (see in Fig. 8). The drier seasons were densely distributed with low DFMC values (means DFMC $<10\%$) compared to wet seasons, over all the three study regions. This suggests that drier seasons could be accompanied by a larger area and/or a greater number of days with lower DFMC values. These changes are consistent with the findings of Nolan et al. (2016b), who observed that the median values of daily dead fine fuel moisture content values over SEA in the dry season were lower compared to the wet season. High temperatures during dry seasons are expected and are due to the increase in sensible heat release to the atmosphere by lower latent heat flux (Alexander, 2011). The extreme temperatures result in heatwaves and a rise in vapour pressure deficit values. However, the respective peak heat and fire seasonal mean vapour pressure deficit values of the NE-SEA region are lower compared to the other study regions even though the respective regional daily mean temperature values are comparatively higher (see in Fig. 2). This is likely due to the sub-humid climate of the NE-SEA region, which favours the increase in actual vapour pressure values. The increased actual vapour pressure values support a reduction in vapour pressure deficit. As expected, the vapour pressure deficit values are higher in the dry regions like Cen-VIC and SE-SEA, and the increase in vapour pressure deficit values leads to a reduction in DFMC. The distribution curve of the NE-SEA region is slightly shifted towards the right compared to other study regions, which suggests the decrease in the frequency of low DFMC values. This frequency decrease of low DFMC values could be due to the lower vapour pressure deficit.

The regional and seasonal dependence of the heatwave and dead fine fuel moisture content relationship could have some implications to fuel dryness mapping and in the planning of prescribed burning activities. The results presented in this study are relevant to improving better approximations of dead fine fuel moisture content, which further helps operational fire management planning and policy development. In addition, these results could help in improving the estimation of fire danger over Southeast Australia, for example, as part of the new Australian Fire Danger Rating System (Matthews et al., 2019).

5. Conclusions

A significant anti-correlation between heatwave characteristics and mean dead fine fuel moisture content has been demonstrated over many parts of southeast Australia. The relationship varies between heatwave frequency, duration, magnitude, and amplitude, along with the region. The areas surrounding the south of the SE-SEA region have substantially strong negative correlations between prolonged heatwave duration and mean DFMC. In the northeast parts of southeast Australia, intensity related heatwave characteristics (HWM and HWA) have significant anti-correlation with mean DFMC, whereas a weaker correlation exists between longevity-related heatwave characteristics (like HWF and HWD) and mean DFMC. This emphasises the importance of each heatwave characteristic in this relationship in different regions. Results show a significant reduction in mean DFMC values in heatwaves days compared to normal days. The strength of the relationship between heatwave characteristics and mean DFMC varies seasonally as well as across regions. However, the anti-correlation strength is substantially stronger in drier seasons compared to other seasons in the regions with an existing relation. This implies that heatwave conditions, particularly in dry seasons, seem to be important but are not compulsory for the existence of low dead fine fuel moisture content in the regions with an existing relationship. The frequent occurrence of extreme minimum DFMC is observed in Central Victoria and Southeast parts of South-East Australia regions, especially in respective dry seasons. Further, in the future, one can study the relationship between heatwaves and coarser dead fuels (100 and 1000 h), which could provide a more comprehensive understanding of the link between dead fuel dryness and extreme heat.

CRediT author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wace.2020.100300.

References

Australian Bureau of Statistics, 2010. Year Book Australia, 2009–10. https://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/1301.0Chapter1042009%E2%80%9310.

Alexander, L., 2011. Extreme heat rooted in dry soils. Nat. Geosci. https://doi.org/10.1038/ngeo1045.

Alexander, L.V., Arblaster, J.M., 2017. Historical and projected trends in temperature and precipitation extremes in Australia in observations and CMIP5. Weather Clim. Extrem. https://doi.org/10.1016/j.wace.2017.02.001.

Anderson, H.E., 1990. Moisture diffusivity and response time in fine forest fuels. Can. J. For. Res. https://doi.org/10.1139/x90-046.

Ashe, B., McAneney, K.J., Pitman, A.J., 2009. Total cost of fire in Australia. J. Risk Res. https://doi.org/10.1080/13669870802648528.

Asseng, S., Foster, I., Turner, N.C., 2011. The impact of temperature variability on wheat yields. Global Change Biol. https://doi.org/10.1111/j.1365-2486.2010.02262.x.

Boer, M.M., Nolan, R.H., Dios, V.R. De, Clarke, H., Owen, F., Bradstock, R.A., 2017. Changing weather extremes call for early warning of potential for catastrophic fire. Earth's Futur. https://doi.org/10.1002/2017EF000657.

Bohren, C.F., Albrecht, B.A., 2000. Atmospheric Thermodynamics.

Borchers Arriagada, N., Palmer, A.J., Bowman, D.M.J.S., Morgan, G.G., Jalaludin, B.B., Johnston, F.H., 2020. Unprecedented smoke-related health burden associated with the 2019–20 bushfires in eastern Australia. Med. J. Aust. https://doi.org/10.5694/mja2.50545.

Bradshaw, L.S., Deeming, J.E., Burgan, R.E., Cohen, J.D., 1983. The 1978 National Fire-Danger Rating System: Technical Documentation. USDA For. Serv. Gen. Tech. Rep. INT-169.

Bradstock, R.A., 2010. A biogeographic model of fire regimes in Australia: current and future implications. Global Ecol. Biogeogr. https://doi.org/10.1111/j.1466-8238.2009.00512.x.

Caesar, J., Alexander, L., Vose, R., 2006. Large-scale changes in observed daily maximum and minimum temperatures: creation and analysis of a new gridded data set. J. Geophys. Res. Atmos. 111.

Cai, W., Cowan, T., Raupach, M., 2009. Positive Indian Ocean dipole events precondition southeast Australia bushfires. Geophys. Res. Lett. 36.

Clarke, H., Evans, J.P., 2019. Exploring the future change space for fire weather in southeast Australia. Theor. Appl. Climatol. 136, 513–527. https://doi.org/10.1007/s00704-018-2507-4.

Clarke, H., Lucas, C., Smith, P., 2013. Changes in Australian fire weather between 1973 and 2010. Int. J. Climatol. https://doi.org/10.1002/joc.3480.

Coates, L., Haynes, K., O'Brien, J., McAneney, J., De Oliveira, F.D., 2014. Exploring 167 years of vulnerability: an examination of extreme heat events in Australia 1844-2010. Environ. Sci. Pol. https://doi.org/10.1016/j.envsci.2014.05.003.

Cowan, T., Purich, A., Perkins, S., Pezza, A., Boschat, G., Sadler, K., 2014. More frequent, longer, and hotter heat waves for Australia in the Twenty-First Century. J. Clim. https://doi.org/10.1175/JCLI-D-14-00092.1.

Deeming, J.E., Burgan, R.E., Cohen, J.D., 1977. The National Fire-Danger Rating System–1978. Intermountain Forest and Range Experiment Station, Forest Service, US.

Dowdy, A.J., Mills, G.A., 2012. Atmospheric and fuel moisture characteristics associated with lightning-attributed fires. J. Appl. Meteorol. Climatol. https://doi.org/10.1175/JAMC-D-11-0219.1.

Herold, N., Kala, J., Alexander, L.V., 2016. The influence of soil moisture deficits on Australian heatwaves. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/11/6/064003.

Hirsch, A.L., Evans, J.P., Di Virgilio, G., Perkins-Kirkpatrick, S.E., Argüeso, D., Pitman, A.J., Carouge, C.C., Kala, J., Andrys, J., Petrelli, P., Rockel, B., 2019. Amplification of Australian heatwaves via local land-atmosphere coupling. J. Geophys. Res. Atmos. https://doi.org/10.1029/2019JD030665.

Hutchinson, M.F., Mcintyre, S., Hobbs, R.J., Stein, J.L., Garnett, S., Kinloch, J., 2005. Integrating a global agro-climatic classification with bioregional boundaries in Australia. Global Ecol. Biogeogr. https://doi.org/10.1111/j.1466-822X.2005.00154.x.

IPCC, 2013. Climate change 2013: the physical science basis, contribution of working group I. Fifth Assess. Rep. Intergov. Panel Clim. Chang.

Jones, D.A., Wang, W., Fawcett, R., 2009. High-quality spatial climate data-sets for Australia. Aust. Meteorol. Oceanogr. J. https://doi.org/10.22499/2.5804.003.

Keith, D.A., Pellow, B.J., 2015. Review of Australia's Major Vegetation Classification and Descriptions. Cent. Ecosyst. Sci. UNSW, Sydney.

Matthews, S., 2014. Dead fuel moisture research: 1991-2012. Int. J. Wildland Fire. https://doi.org/10.1071/WF13005.

Matthews, S., Sauvage, S., Grootemaat, S., Hollis, J., Kenny, B., Fox-Hughes, P., 2019. Implementation of Models and the Forecast System for the Australian Fire Danger Rating System.

Mckee, T.B.T., Doesken, N.J.N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. In: Eighth Conference on Applied Climatology. American Meteorological Society, Boston. Eighth Conf. Appl. Climatol. https://climate.colostate.edu/pdfs/relationshipofdroughtfrequency.pdf.

Meehl, G.A., Tebaldi, C., 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305, 994–997.

Monteith, J.L., Unsworth, M.H., 1990. Principles of Environmental Physics, second ed. Edward Arnold, London, p. 291pp.

Munich Re, 2009. Heavy losses due to severe weather in the first six months of 2009, press release, 27 July 2009. www.munichre.com/en/press/press_releases/2009/2009_07_27_press_release.aspx.

Nairn, J., Fawcett, R., 2013. Defining heatwaves: heatwave defined as a heat-impact event servicing all communiy and business sectors in Australia. CAWCR technical report No. 060. https://www.cawcr.gov.au/technical-reports/CTR_060.pdf.

Nolan, R.H., Boer, M.M., Collins, L., Resco de Dios, V., Clarke, H., Jenkins, M., Kenny, B., Bradstock, R.A., 2020. Causes and consequences of eastern Australia's 2019–20 season of mega-fires. Global Change Biol. https://doi.org/10.1111/gcb.14987.

Nolan, R.H., Boer, M.M., Resco De Dios, V., Caccamo, G., Bradstock, R.A., 2016b. Large-scale, dynamic transformations in fuel moisture drive wildfire activity across southeastern Australia. Geophys. Res. Lett. 43, 4229–4238. https://doi.org/10.1002/2016GL068614.

Nolan, R.H., Resco de Dios, V., Boer, M.M., Caccamo, G., Goulden, M.L., Bradstock, R.A., 2016a. Predicting dead fine fuel moisture at regional scales using vapour pressure deficit from MODIS and gridded weather data. Remote Sens. Environ. 174, 100–108. https://doi.org/10.1016/j.rse.2015.12.010.

Perkins, S.E., 2015. A review on the scientific understanding of heatwaves-Their measurement, driving mechanisms, and changes at the global scale. Atmos. Res. https://doi.org/10.1016/j.atmosres.2015.05.014.

Perkins, S.E., Alexander, L.V., 2013. On the measurement of heat waves. J. Clim. 26, 4500–4517. https://doi.org/10.1175/JCLI-D-12-00383.1.

Perkins, S.E., Argüeso, D., White, C.J., 2015. Relationships between climate variability, soil moisture, and Australian heatwaves. J. Geophys. Res. https://doi.org/10.1002/2015JD023592.

Prober, S.M., Gosper, C.R., Gilfedder, L., Thiele, K.R., Williams, K.J., Yates, C.J., 2017. Temperate eucalypt woodlands. Aust. Veg. 3, 410–437.

Resco de Dios, V., Fellows, A.W., Nolan, R.H., Boer, M.M., Bradstock, R.A., Domingo, F., Goulden, M.L., 2015. A semi-mechanistic model for predicting the moisture content of fine litter. Agric. For. Meteorol. https://doi.org/10.1016/j.agrformet.2015.01.002.

Risbey, J.S., Pook, M.J., McIntosh, P.C., Wheeler, M.C., Hendon, H.H., 2009. On the remote drivers of rainfall variability in Australia. Mon. Weather Rev. 137, 3233–3253.

Rothermel, R.C., 1983. How to predict the spread and intensity of forest and range fires. US Dep. Agric. For. Serv. Gen. Tech. Rep. https://doi.org/10.2737/INT-GTR-143.

Ruffault, J., Curt, T., Martin-Stpaul, N.K., Moron, V., Trigo, R.M., 2018. Extreme wildfire events are linked to global-change-type droughts in the northern Mediterranean. Nat. Hazards Earth Syst. Sci. https://doi.org/10.5194/nhess-18-847-2018.

Russo, S., Dosio, A., Graversen, R.G., Sillmann, J., Carrao, H., Dunbar, M.B., Singleton, A., Montagna, P., Barbola, P., Vogt, J.V., 2014. Magnitude of extreme heat waves in present climate and their projection in a warming world. J. Geophys. Res. Atmos. 119, 12–500.

Sharples, J.J., Cary, G.J., Fox-Hughes, P., Mooney, S., Evans, J.P., Fletcher, M.S., Fromm, M., Grierson, P.F., McRae, R., Baker, P., 2016. Natural hazards in Australia: extreme bushfire. Climatic Change 139, 85–99. https://doi.org/10.1007/s10584-016-1811-1.

Simard, A.J., 1968. The Moisture Content of Forest Fuels.

Sullivan, A.L., 2009. Wildland surface fire spread modelling, 1990 - 2007. 2: empirical and quasi-empirical models. Int. J. Wildland Fire. https://doi.org/10.1071/wf06142.

Sullivan, A.L., Matthews, S., 2013. Determining landscape fine fuel moisture content of the Kilmore East "Black Saturday" wildfire using spatially-extended point-based models. Environ. Model. Software 40, 98–108. https://doi.org/10.1016/j.envsoft.2012.08.008.

Teague, B., McLeod, R., Pascoe, S., 2010. 2009 Victorian Bushfires Royal Commission Final Report. Parliam, Victoria Melb.

Ulubaşoğlu, M.A., Rahman, M.H., Önder, Y.K., Chen, Y., Rajabifard, A., 2019. Floods, bushfires and sectoral economic output in Australia, 1978–2014. Econ. Rec. https://doi.org/10.1111/1475-4932.12446.

Vautard, R., Gobiet, A., Jacob, D., Belda, M., Colette, A., Déqué, M., Fernández, J., García-Díez, M., Goergen, K., Güttler, I., Halenka, T., Karacostas, T., Katragkou, E., Keuler, K., Kotlarski, S., Mayer, S., van Meijgaard, E., Nikulin, G., Patarčić, M., Scinocca, J., Sobolowski, S., Suklitsch, M., Teichmann, C., Warrach-Sagi, K., Wulfmeyer, V., Yiou, P., 2013. The simulation of European heat waves from an ensemble of regional climate models within the EURO-CORDEX project. Clim. Dynam. https://doi.org/10.1007/s00382-013-1714-z.

Viney, N.R., 1991. A review of fine fuel moisture modelling. Int. J. Wildland Fire. https://doi.org/10.1071/WF9910215.

Welch, B.L., 1947. The generalization ofstudent's' problem when several different population variances are involved. Biometrika 34, 28–35.

Wheeler, T.R., Craufurd, P.Q., Ellis, R.H., Porter, J.R., Prasad, P.V.V., 2000. Temperature variability and the yield of annual crops. Agric. Ecosyst. Environ. 82, 159–167.

Williams, R.J., Gill, A.M., Bradstock, R.A., 2012. Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World. CSIRO publishing.

Yebra, M., Dennison, P.E., Chuvieco, E., Riaño, D., Zylstra, P., Hunt, E.R., Danson, F.M., Qi, Y., Jurdao, S., 2013. A global review of remote sensing of live fuel moisture content for fire danger assessment: moving towards operational products. Remote Sens. Environ. 136, 455–468. https://doi.org/10.1016/j.rse.2013.05.029.

Zammit, K., Howden, M., Martin, P., 2019. Agricultural overview. Agric. Commod. 9, 5.

Zhou, S., Park Williams, A., Berg, A.M., Cook, B.I., Zhang, Y., Hagemann, S., Lorenz, R., Seneviratne, S.I., Gentine, P., 2019. Land–atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity. Proc. Natl. Acad. Sci. U.S.A. https://doi.org/10.1073/pnas.1904955116.