BLACK SUMMER 2019–20 RESEARCH
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SOIL AND FUEL MOISTURE PRECURSORS OF FIRE ACTIVITY DURING THE 2019-20 FIRE SEASON, IN COMPARISON TO PREVIOUS SEASONS

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We also acknowledge the communities affected by the 2019-20 fires.

EXECUTIVE SUMMARY

Australia experienced unprecedented bushfires during the 2019-20 fire season. Millions of hectares were burned, almost 3,000 homes were destroyed, there were 26 fatalities, and communities were exposed to smoke for extended periods. Low soil and vegetation moisture content due to antecedent dry conditions were a key driver of fire activity.

This report extends the work in two Bushfire and Natural Hazards CRC projects to examine the 2019-20 fire season:

- *Mitigating the effects of severe fires, floods and heatwaves through the improvements of land dryness measures and forecasts*: this project was conducted by the Bureau of Meteorology and examined soil moisture using a system called JASMIN. The research team produced soil moisture datasets at a range of depth levels that are consistent with Australia's weather and climate prediction system.
- *Mapping bushfire hazards and impacts:* this project was conducted by Australian National University and examined vegetation moisture using the Australian Flammability Monitoring System (AFMS). The project has produced live fuel moisture mapping from satellite data.

The national spatial datasets produced by these projects are consistent and regularly updated, separately examining soil and vegetation moisture variability, as both quantities influence fuel availability and therefore fire behaviour.

This project explores the overlaps between these data sets, as well as comparing other available data (including the Australian Landscape Water Balance) to identify atmospheric, soil and fuel moisture characteristics that contributed to fire risk during Black Summer.

Spatially coherent historical and regularly updated soil and fuel moisture datasets are critically important to fire managers so that an accurate, quantifiable assessment of potential fire activity in the landscape can be made, and this can be benchmarked against historical conditions. This information is crucial to making accurate assessments of risk and identifying situations that fall outside of historical records. One of the valuable aspects of JASMIN is that it can also be used in a predictive way and is therefore useful in anticipating soil moisture and therefore fire risk into the future in a quantitative manner on weather (short-term) and seasonal timescales. Research work in the 'Land Dryness' project also demonstrated the capacity of soil moisture to predict future vegetation moisture content and thus more directly anticipate fire potential.

This project examines the interaction of atmospheric parameters with soil and fuel moisture content over scales of days, weeks to months, and years. Such an integration has not been undertaken previously. Consideration of each of these timeframes is important when making accurate assessments of fire risk. The interaction between them is also critical, as a compounding of the individual processes at the different scales occurs and this was seen in the cumulative effects of antecedent dry years, low winter rainfall and heatwaves during the Black Summer.

This project examined six fire events that were nominated for investigation by the relevant jurisdictions. The fires are:

- Badja Forest Rd, Courtegany- New South Wales
- Stanthorpe – Queensland
- Corryong – Victoria
- Kangaroo Island – South Australia
- Yanchep – Western Australia
- Orroral Valley – Australian Capital Territory

The scope of the project included examining the following:

- multi-annual to annual variation of rainfall distributions
- multi-week influence of soil moisture on live fuel moisture content
- the multi-day influence of heatwaves on vegetation moisture
- soil and fuel moisture properties that distinguished 2019-20 from the previous two seasons.

Key findings of the project include:

- Antecedent rainfall over most firegrounds was exceptionally low on timescales from months to years.
- High seasonal temperatures set a broad scene for shorter timescale heatwaves.
- Hot conditions were also characterised by anomalously low atmospheric moisture close to the time of several fires (Stanthorpe, Corryong and Orroral Valley).
- Heatwaves (measured by 'Excess Heat Factor') were associated in most fire locations with a perceptible decrease in live fuel moisture content immediately prior to fire occurrence.
- Strong correlation is seen between the two soil moisture metrics AWRA-L and JASMIN over the domains in which fires occurred (although the metrics have different underpinning physical basis), confirming similar findings during the 'Land Dryness' project.
- Spatial monitoring of soil and fuel moisture presents an accurate mechanism for quantifying potential fire risk.
- Drought Factor has limited representation of moisture deficit in dry conditions.
- Rapid falls in live fuel moisture can occur with the onset of warmer weather in dry conditions.
- The magnitude of simulated soil moisture content is highly land surface model dependent, so further refinement of numerical weather prediction model land surface schemes will benefit fire management.

- The 2018-19 and 2017-18 seasons were dry and hot, but not as extreme as 2019-20.
- The dominant drivers are not the same at all fires. For example, rainfall deficits were historically low at Stanthorpe, but not at Kangaroo Island, indicating that conditions could have been worse in the latter event.

The findings confirm impressions of fire practitioners regarding the extremity of conditions antecedent to the 2019-20 fire season. Importantly, the datasets used in the project present a measurable and spatially coherent approach to estimating fire risk from observed and modelled soil and fuel moisture. Operational application of the datasets and approaches used here will assist in producing accurate soil and vegetation moisture forecasts for prediction of fire risk in the future.

Some immediate benefits for fire managers of this work include:

- AWRA-L provides comparably valuable root-zone soil moisture information to JASMIN. AWRA-L is currently available on a daily basis (e.g. at http://www.bom.gov.au/water/landscape/#/sm/Actual/day/-28.4/130.4/3/Point////2021/6/14/). In particular, relative values of AWRA-L soil moisture provide an historical context for values on several timescales, allowing a qualitative assessment of fire risk in the environment.
- On an annual and area-integrated basis, mean levels of fuel moisture content can change substantially, especially in forested areas of eastern Australia. By implication, successive years of dry conditions can lead to dramatic downward changes in fuel moisture content, and thus heightened fire risk.
- Related to these points, and as noted in the Key Findings above: if soils are very dry in the cool season, even if fuel moisture content is close to normal at that time, the fuel moisture can rapidly decrease coinciding with the onset of much warmer conditions. This observation can act as a useful warning indicator for fire managers of potential rapid onset of increased fire risk.

Each of the meteorological and moisture variables investigated in this study contributed useful information to an understanding of increased fire risk at each site during the 2019-20 Australian summer. Fuel moisture content provided perhaps the most immediate indicator of present fire risk. Soil moisture content permitted an assessment of future changes in fuel moisture content. Both of these integrated changes in meteorological parameters. As such, the meteorological parameters (temperature, precipitation, atmospheric moisture represented by vapour pressure) contributed an understanding of why soil and fuel moisture changed in the ways that they did and offered information on how they would change in the future. Monitoring these quantities can help fire and land managers understand how and why fire risk changes across a landscape.

FUTURE WORK

This project was conducted over a short time period with one objective being to establish a pathway for future research and operational application.

The following opportunities for future research with likely operational benefits have been identified:

- The project results indicate that most of the studied variables interact over a range of timescales. Further investigation to understand the nature and quantity of these interactions will be of benefit to better estimate fire risk.
- The project focused on spatial data of live fuel moisture. An analogous spatial approach to assess dead fuel moisture in very dry conditions is required to develop a complete assessment of fuel availability.
- Detailed examination of the fire intensity against spatial heterogeneity of soil and fuel moisture variability within each fireground would be valuable, to better predict likely fire intensity resulting from soil and fuel moisture variations.
- The project briefly explored the connection between heatwaves and live fuel moisture. Appropriate datasets were not readily available, however further investigation of the links between heatwaves and fire risk resulting from changes in fuel moisture content is critical to understanding, for example, overnight fire activity in a changing climate.
- The soil moisture model parameterisations in land surface schemes can be further developed to improve soil moisture estimation. Developments will have positive flow-on effects to a range of weather forecasting applications, including seasonal fire risk predictions, and thus providing fire managers with enhanced predictive capability for a range of important activities.
- Inclusion of ground water may improve the soil moisture models and benefit seasonal predictions.
- Unexpected interactions and connections that emerged between the strands of this project should be further explored to improve future services. For example, it seems likely that live fuel moisture content can constrain the range of possible values of sub-surface water content.

In summary, better understanding and spatial mapping of the influence of atmospheric, soil and fuel moisture will assist fire and land managers predict fire risk, which is critical for strategic and tactical planning. Many of the recommendations could be inclusions to the Australian Fire Danger Rating System (AFDRS), and therefore of immediate benefit to fire and land managers following the introduction of the AFDRS to operational use over the next two fire seasons.

END-USER PROJECT IMPACT STATEMENT

Dr Lachie McCaw, *Department of Biodiversity, Conservation and Attractions, WA*

This report provides a comprehensive and insightful examination of soil and fuel moisture precursors of fire activity during the 2019/20 fire season. The report employs a case study approach to provide broader context to the numerous fires that affected large parts of eastern and southern Australia over a period of five months in the spring and summer of 2019/20. Drawing together different but related data sets and decision support products this project builds upon previous work undertaken through the Bushfire and Natural Hazards CRC and highlights what can be achieved through effective collaboration between scientific disciplines. Importantly, the report places the seasonal conditions of the 2019/20 fire season in a longer-term context and highlights not only the similarities in the southern Australian fire environment during this period but also important differences that affected the behaviour and impacts of individual fires. Fire managers benefit from a nuanced understanding of the role of regional and local conditions, as these influence what actions may be most effective in mitigating the threat of future fires to the community and the environment. I congratulate the research team on their achievement in delivering an informative and well-integrated report in a tight timeframe.

David Field, *Supervisor – Bush Fire Analyst, Community Resilience – Planning & Predictive Services, Rural Fire Service, NSW*

The 2019 - 2020 bush fire season was the worst season NSW has ever experienced. Severe, prolonged drought and repeated intense heatwaves were significant drivers low fuel moisture and extreme fire behaviour throughout the season. This report highlights both the severity of the 2019 – 20 season and that the existing metrics of fuel availability and soil dryness can continue to be improved upon. It is essential that our understanding of fuel availability and dryness continues to be improved and refined through research such as this.

Adam Leavesley, *Bushfire Research Utilisation Manager, Parks and Conservation Service, Environment, Planning and Sustainable Development Directorate, ACT*

This report presents a detailed investigation of the soil and fuel moisture conditions at locations subject to high intensity bushfires in the 2019-2020 season. The work assesses the outputs from two excellent new landscape-scale systems developed using Bushfire and Natural Hazards CRC funding – *Improving land dryness measures and forecasts* and *Mapping bushfire hazards and impacts* – alongside an historical Bureau of Meteorology system the Australian Landscape Water Balance (AWRA-L). The locations range from southern Queensland south to Victoria and west to southern WA. The timescales investigated range from days to years. The work showcases the new datasets, details fuel moisture dynamics at different timescales and in different places and is a most welcome contribution to understanding the role of fuel moisture in bushfire behaviour.

But from an operational perspective, the report begs a whole lot of questions. Which of these datasets is best for what operational purposes? How can these data best be turned into operational intelligence? How much would operationalisation cost and how long would it take? Operational fuel moisture intelligence is a critical gap in the operational functionality of Australian bushfire managers. Of course, it is the job of scientists to identify the next research priorities and it was not in the project brief to address operationalisation. But nonetheless, I believe it is incumbent upon me to point out that landing this functionality and capturing the benefits for operators is urgent and must be higher on the agenda than initiating more research.

INTRODUCTION

This project investigated the impact of soil and live fuel moisture content on six fires that occurred during the "Black Summer" 2019-20, in a range of jurisdictions and in a variety of landscapes.

The Bushfire and Natural Hazards CRC *Improving land dryness measures and forecasts* and *Mapping bushfire hazards and impacts* (including the Australian Flammability Monitoring System, AFMS) projects delivered research findings that, individually and combined, have the potential to improve the preparedness of fire agencies and the broader community in the face of bushfires. This extension project applies those findings to identify differences in soil and fuel moisture and their associated weather parameters between the 2019-20 Australian fire season and the immediately preceding seasons. Those seasons were also dry, and fire was perceived as a threat during the warmer months, but fire extent and impact was substantially less than in 2019-20.

In addition, this project examined interactions in the temporal scale of various atmospheric and land surface processes. The three timescales include: the annual to multi-annual climate scale on which drought conditions developed in many regions of Australia; the multiweek period over which soil moisture influences fuel moisture state; and the daily-weekly timescale on which synoptic weather influenced soil and especially fuel state. In particular, the degree to which heatwave conditions influenced diurnal recovery of fuel moisture was examined.

Some research has been published to date on the 2019-20 fires, most focused on southeastern Australia, given the extremity of the fire events that occurred there. One research strand has focused on statistical analysis of likely causes of the fires, identifying antecedent drought and soil moisture deficits together with, live and dead fuel availability, high temperatures, low relative humidity, and elevated wind speed as contributing factors[1]. Given these factors, other research has examined the extent to which high severity fire occurred in the landscape affected by the 2019-20 fire events[2]. This work indicated that while the 2019-20 fires were extremely widespread, the proportion of high-severity fire was similar to some other recorded severe fire events. The extent of the fires in comparison to other forest biomes was addressed in other work[3,23], confirming that the fires were globally significant, burning an unprecedented 21% of the Australian continental forest biome. Analysis of satellite data related to the extent of forest burned, set in the context of historical fire records showed that nothing similar has been seen since at least the mid-nineteenth century[23]. The fire extent, severity, and occurrence of the most intense collection of pyroconvection yet observed prompted consideration of the extent to which climate change could be attributed as a cause of the fires[4]. This work demonstrated a combination of modes of climate variability in fire-promoting phases together with long-term climate trends contributed to the extremity of the fire events. The authors also noted that climate projections from a decade or more ago suggesting that Australia would emerge from the range of historical variability by 2020 have proven unfortunately accurate and that it will be important for the community to pursue mitigation and adaptation strategies as a matter of high priority. Finally, some work focused on the interaction of heatwaves and dead fuel moisture in preconditioning the landscape to a high level of fire activity[5].

Concurrently with this project, a Bureau of Meteorology research team has examined coupled fire-atmosphere interactions of each fire (apart from the Orroral Valley fire). Brief descriptions of each of these fires were written for that project and adapted here to avoid duplication of effort.

BACKGROUND

This project examined six fires:

- Stanthorpe (QLD)

The Stanthorpe fire was first reported during the afternoon of 06 September 2019 after an accidental ignition on the edge of the Broadwater State Forest outside Stanthorpe. The fire burned through drought-affected mixed forest and farmland in strong northwesterly winds ahead of a strong southwesterly change during the evening of 06 September (see the synoptic summary corresponding to the time of the fire). Four houses were lost in the fire which burnt approximately 2000 ha before being controlled on 07 September.

- Yanchep (WA)

A fire was reported in the Yanchep National Park on the afternoon of 11 December 2019. The fire burnt through mostly Banksia and Tuart woodland on the coastal plain north of Perth, but also ran through some melaleuca and pine forest. A petrol station and house were destroyed on the evening of 11 December as a result of ember attack. The fire took four days to extinguish, burnt a total of approximately 11,000 ha and threatened the coastal townships of Yanchep and nearby Two Rocks on several occasions, including during overnight periods when fire management staff were expecting the fire to be more quiescent.

- Corryong (VIC)

A fire was most likely ignited by lighting in forest near Talmalmo, NSW on 29 December 2019. The fire was named the Green Valley, Talmalmo fire in NSW. On the afternoon of 30 December, the fire crossed the Murray River into Victoria, becoming known as the Corryong fire in that state. Between early afternoon of 30 December and early morning on 01 January, the fire burnt nearly 110,00 ha of forest and farmland. The fire was active overnight on 30 December, with some spotting documented up to 2 km ahead of the main fire front. The fire continued to burn until widespread rainfall in late January 2020.

- Badja Forest Rd, Countegany (NSW)

A fire was ignited most likely by lightning on the afternoon of 27 December 2019 in the Badja State Forest. The fire burnt southeast to Cobargo, coalescing with four other fires, and eventually reaching a size in excess of 315,000 ha. The Badja fire exhibited a number of extreme fire behaviours including rapid overnight spread on 30 December and very substantial pyroconvection. Peaks of fire activity occurred in prefrontal hot, dry northwesterly airstreams on 30-31 December 2019 and 04 January 2020 (see synoptic description for more detail). Kangaroo Island (SA)

Several fires occurred on Kangaroo Island from 20 December 2019 through to 06 February 2020 burning 211,000 ha in total, nearly half the island. The Ravine fire was one of the largest and most destructive, having been ignited by lightning on 30 December in the Flinders Chase National Park. The fire broke containment lines on the morning of 03 January, fanned by hot, northerly winds (see the discussion on the synoptic situation at that time), with a further peak in fire activity occurring on 08-09 January 2020. The fire burned through mallee/woodland forest and grassland in the west of Kangaroo Island.

- Orroral Valley (ACT)

Accidental ignition by an Australian Defence Force helicopter on 27 January 2020 caused the Orroral Valley fire, which burnt through into February 2020*. The fire burnt through 80% of the Namagdi National Park, parts of the Tidbinbilla Nature Reserve and several thousand ha of rural land on 27 January, burning almost 87,000 ha in total before being downgraded to patrol status on 17 February.

Fire locations are indicated in the map below:

FIGURE 1: LOCATIONS OF THE FIRES STUDIED IN THIS REPORT.

Given the geographic diversity in fire events investigated, each fires' results are presented as a separate section, bookending the results with a general overview and concluding with a summary of key findings for each individual event and those applicable across the set of fires.

* (summary available at: https://www.environment.act.gov.au/__data/assets/pdf_file/0004/1495237/orroral-valley-fire-rapid-risk-assessment-namadgi-national-park-overview.pdf, with further background information available at: https://www.nasa.gov/feature/goddard/2020/australias-orroral-valley-fire-consumes-over-155000-acres-in-a-week)

ORIGINAL BUSHFIRE AND NATURAL HAZARDS CRC PROJECT DESCRIPTIONS

We briefly document the Bushfire and Natural Hazards CRC projects that were extended to form this current project.

Improving land dryness measures and forecasts

This Bushfire and Natural Hazards CRC project, formally titled *Mitigating the effects of severe fires, floods and heatwaves through the improvements of land dryness measures and forecasts*, (also colloquially known as the JASMIN project, after the modelling framework developed within the project) was a partnership with the Bureau of Meteorology, and addressed a fundamental limitation in our current ability to estimate and predict landscape dryness for fire prediction and fire management applications. The current operational fire management practices in Australia use two models of cumulative soil water deficit, namely Keetch–Byram Drought Index (KBDI)[14] and Mount's Soil Dryness Index (SDI)[15], for fuel availability and fire danger rating calculations. KBDI and SDI are simple water balance models where processes like evapotranspiration, run-off and canopy interception are parameterised with crude empirical formulations, which can lead to large errors in the estimated soil moisture state. Further, both KBDI and SDI assume that a single number can be used to describe both the dryness of the surface and root-zone soil layers. However, the dependency of fire potential to moisture in a layer of soil at a particular depth may change with season[16]. A good soil moisture estimation system should therefore work throughout the seasons and should not depend upon a fixed depth of soil horizon (like KBDI and SDI) to indicate fire risk. A system employing a multi-layer soil model is suggested to be the best solution.

To address this, the project developed a standalone prototype land surface modelling system, called Joint UK Land Environment Simulator based Australian Soil Moisture Information (JASMIN) to produce daily soil moisture analyses. The new soil moisture analyses system is based on the Joint United Kingdom Land Environment Simulator (JULES) land surface model[17]. The JASMIN system covers the whole of Australia at a spatial resolution of 5 km. The system is run with an hourly time step and output is stored at 00 UTC daily. The soil column in JASMIN is 3 m deep and is divided into four layers of 0.1, 0.35, 0.65 and 2 m depth from the surface. JASMIN is a modern, state of the art land surface modelling system and calculates the soil moisture state with greater sophistication than the current operational models and accounts for details such as soil texture, solar insolation, root depth, vegetation type and stomatal resistance. The soil moisture estimate from JASMIN is found to provide a robust alternative to the methods currently used in fire prediction. This is evident from the verification performed against in-situ measurements from soil moisture probes. KBDI and SDI show large errors over regions where they are used operationally. KBDI, for example, has a large wet bias over southern regions that could underestimate fire risk[18]. The JASMIN system can produce reliable soil moisture information over a wide range of land-use types, which potentially extends its utility to other applications as well. Also, JASMIN is shown to have good skill for both surface and deep soil horizons[19].

In addition to the development of the JASMIN system, the project also focused on the calibration of JASMIN soil moisture, downscaling of JASMIN soil moisture and the prediction of Live Fuel Moisture Content using JASMIN soil moisture information. The calibration methods developed offer a simple but effective solution for a faster adoption of JASMIN in current operational practices by transforming the native JASMIN outputs in units of moisture excess to moisture deficit values that range from 0–200, as required by McArthur's Forest Fire Danger Index (FFDI)[13]. The motivation for the downscaling research was the recognition that applications such as fire danger mapping may require soil moisture information at higher spatial resolution due to the large spatial variability of soil moisture in the landscape. The final objective of the project was thus to explore the relationship between soil moisture and live fuel moisture content (LFMC) using the datasets from JASMIN and Australian Flammability Monitoring System (AFMS), respectively. The analysis carried out indicates that soil moisture is a leading indicator of LFMC. This project developed a simple yet skilful model to predict live fuel moisture content for the whole of Australia[20].

To summarise, the project developed several outputs, a list of which is given below.

a. High-resolution KBDI and SDI datasets – 1970 onwards, updated in near real time (NRT) and available via an internal web server.

b. JASMIN volumetric soil moisture – 2010 onwards, updated NRT, available via BoM THREDDS and AFMS.

c. Calibrated JASMIN soil dryness – total 8 products with varying characteristics, designed to accommodate specific user need and application: 2010 onwards, updated NRT, available via BoM THREDDS server

d. Downscaled JASMIN surface volumetric water content at 1 km spatial resolution.

e. An LFMC product developed using a simple predictive model based on soil moisture.

Mapping bushfire hazards and impacts

The project "Mapping Bushfire Impacts and Hazards' used cutting-edge technology and imagery to produce spatial information on fire hazard and impacts. Fuel Moisture Content (FMC) is one of the primary drivers affecting fuel flammability that leads to fires. Therefore, the Project used satellite observations well-grounded with field data over the highly climatologically and ecologically diverse Australian region to estimate FMC and flammability for the first time at a continental-scale. The methodology includes a physics-based retrieval model to estimate FMC from MODIS (Moderate Resolution Imaging Spectrometer) reflectance data at 500m every 4 days using radiative transfer model inversion[21]. The algorithm was evaluated using 360 observations at 32 locations around Australia with mean accuracy for the studied land cover classes (grassland, shrubland, and forest) close to those obtained elsewhere (r^2=0.58, RMSE=40%) but without site-specific calibration.

The project also evaluated the feasibility and relative benefits of using alternative remote sensing imagery to compute FMC at finer spatial or temporal resolutions. The evaluated data sources include the geostationary Japanese Himawari-8 satellite (10min, 2km), the European Sentinel-2 (5 days, 20 m), the Landsat (16 days, 30m) and VIIRS (daily, 750 m) satellites. VIIRS obtained the highest accuracy retrieval (r^2=0.8, RMSE=19%, n=6178) followed by Sentinel-2 (r^2=0.8, RMSE=23, n=6178), Landsat-8 (r^2=0.8, RMSE=24, n=6178) and Himawari-8 (r^2=0.7, RMSE=24, n=6178). VIIRS, therefore, is likely the best candidate to ensure the continuity of data provision. Sentinel-2 and Himawari-8 were the best second and third candidates that obtain similar accuracies while increasing the spatial (Sentinel-2, 20m) and temporal (Himawari-8, 10 minutes) resolutions of the products displayed in the AFMS. More details are available in (21).

Given the importance of high-resolution FMC maps, the Project adapted Yebra et al (2018) for computing the FMC maps to Sentinel 2 data at a resolution of 20 meters. This higher resolution allows the identification of local FMC gradients in the landscape that are currently not identifiable using the 500 m pixel resolution of the MODIS product currently underpinning the Australian Flammability Monitoring System (AFMS).

RESEARCH APPROACH

As noted, each fire has been examined individually, but the same approach has been used for all fires. A number of comparison plots are provided initially for context, together with a national overview of weather and climate conditions during the southern Australian 2019-20 fire season.

There are three tiers of timing studied: multi-annual, multi-week and multi-day. On a multi-annual timescale, the gradual increase in intensity in the severity of drought in the study regions is investigated. On a timescale of weeks to months, key atmospheric parameters are tracked. Changes in soil moisture content in the weeks leading to the fires affected fuel moisture content. Finally, the role of heatwaves in the days leading to fire ignition and spread is teased out to assess the impact on preconditioning fuels to burn.

Soil moisture content is assessed using two complementary models: the four-soil level JASMIN soil moisture modelling system investigated in the Bushfire and Natural Hazards CRC Land dryness project, for which approximately a decade of data is available, and which is based on the JULES Land Surface model in the Bureau of Meteorology's numerical weather prediction system, as described above. The other soil moisture system used in this report is the Australian Landscape Water Balance model (AWRA-L), a three soil-level model developed for hydrological purposes and implemented by the Bureau. AWRA-L data is available for a longer period than JASMIN, for the purposes in this report back to 1990, affording a deeper historical perspective on the state of soil moisture in the regions of the fires investigated in this report. The Land Dryness project demonstrated comparable performance between the two models, a result replicated below.

Finally, two additional studies were conducted as the opportunity arose during the project. An investigation of the Land Surface Model characteristics and their impacts on soil moisture is documented in the Kangaroo Island analysis. Additionally, comparisons between high resolution maps of fire severity and FMC were carried out to assess if spatial patterns in fuel dryness were a key determinant of fire severity. These analyses are presented in Supplement 1.

FINDINGS

COMPARISON BETWEEN FIRE HAZARDS

Background on the large-scale climate conditions

The Black Summer fires of 2019/2020 occurred in unprecedented climatic conditions, including 2019 being Australia's hottest as well as driest year on record[7]. The extreme fire weather conditions that occurred were associated with the combined influence of various factors including the Indian Ocean Dipole mode of variability[4], multi-year drought[7], a sudden stratospheric warming event (as the key driver of the strongly positive phase of the Southern Annual Mode at that time)[8] and human-caused climate change[9,10,11].

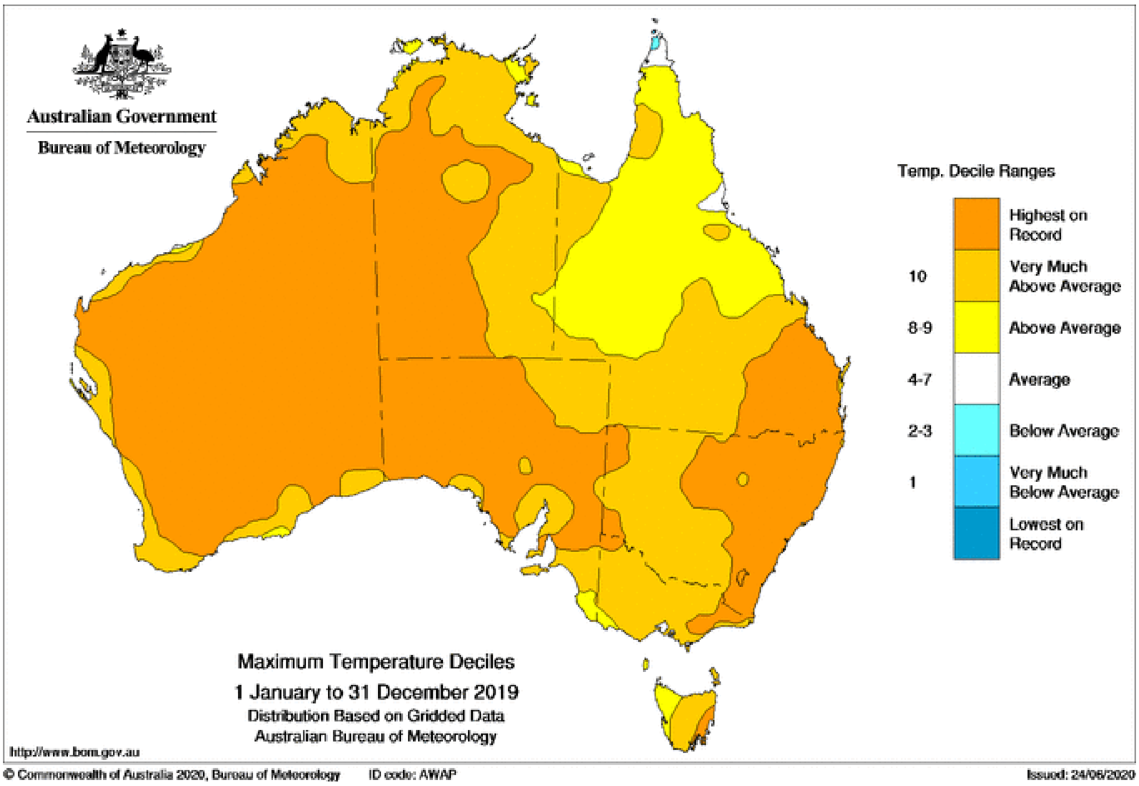


FIGURE 2: MAXIMUM TEMPERATURE DECILES BASED ON ANNUAL AVERAGE VALUES, PRESENTED FOR 2019 AS COMPARED TO OTHER YEARS ON RECORD.

In addition to 2019 being highly anomalous as a year, strong anomalies also occurred for individual months. Examples of this are shown in Figure 3 which shows temperature and rainfall anomalies for December 2019 as compared to the climatological average for that month. This is also presented for the preceding years of 2017 and 2018 to further highlight the exceptional nature of the conditions that occurred around the start of the 2019/20 summer. This shows that virtually all of Australia apart from Tasmania was around 1-5 degrees hotter than normal during December 2019. The entire eastern seaboard had rainfall deficits, with magnitudes of around 50 mm to 200 mm. South Australia also had deficits throughout the state, including the Kangaroo Island region of focus examined in subsequent sections of this report. The only regions with average or above average rainfall were western Tasmania as well as a few small and remote regions of Western Australia.

In contrast to 2019, the previous Decembers of 2018 and 2017 had conditions that were much less extreme for temperature and rainfall (Figure 3). Those summers only resulted in relatively small regions of below average temperatures with most locations being above the long-term average, as has now become more common than not due to human-caused climate change[6,12]. The magnitude of the temperature and rainfall anomalies, however, was much less than in December 2019. Drought conditions were persistent over several years in some regions leading into the 2019/20 summer (Figure 4), including in parts of eastern Australia[7]. However, the 2017 and 2018 rainfall deficits were not as extreme as 2019 including as shown in Figure 3 for December in those years.

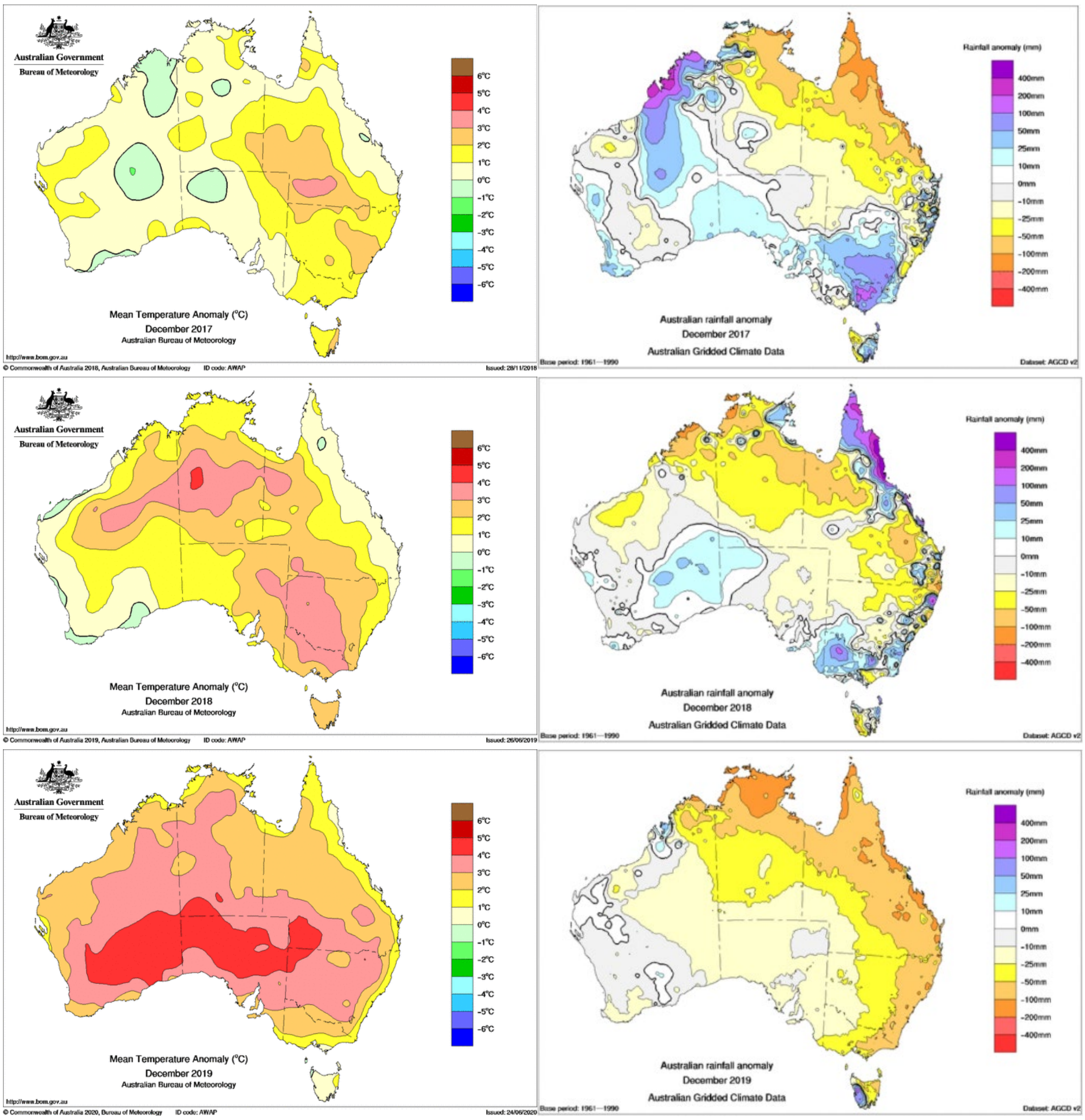


FIGURE 3: MEAN TEMPERATURE (LEFT COLUMN) AND RAINFALL (RIGHT COLUMN) DURING DECEMBER FOR 2017 (UPPER ROW), 2018 (MIDDLE ROW) AND 2019 (LOWER ROW). THIS IS SHOWN AS THE ANOMALY AS COMPARED TO THE LONG-TERM CLIMATOLOGICAL AVERAGE FOR DECEMBER.

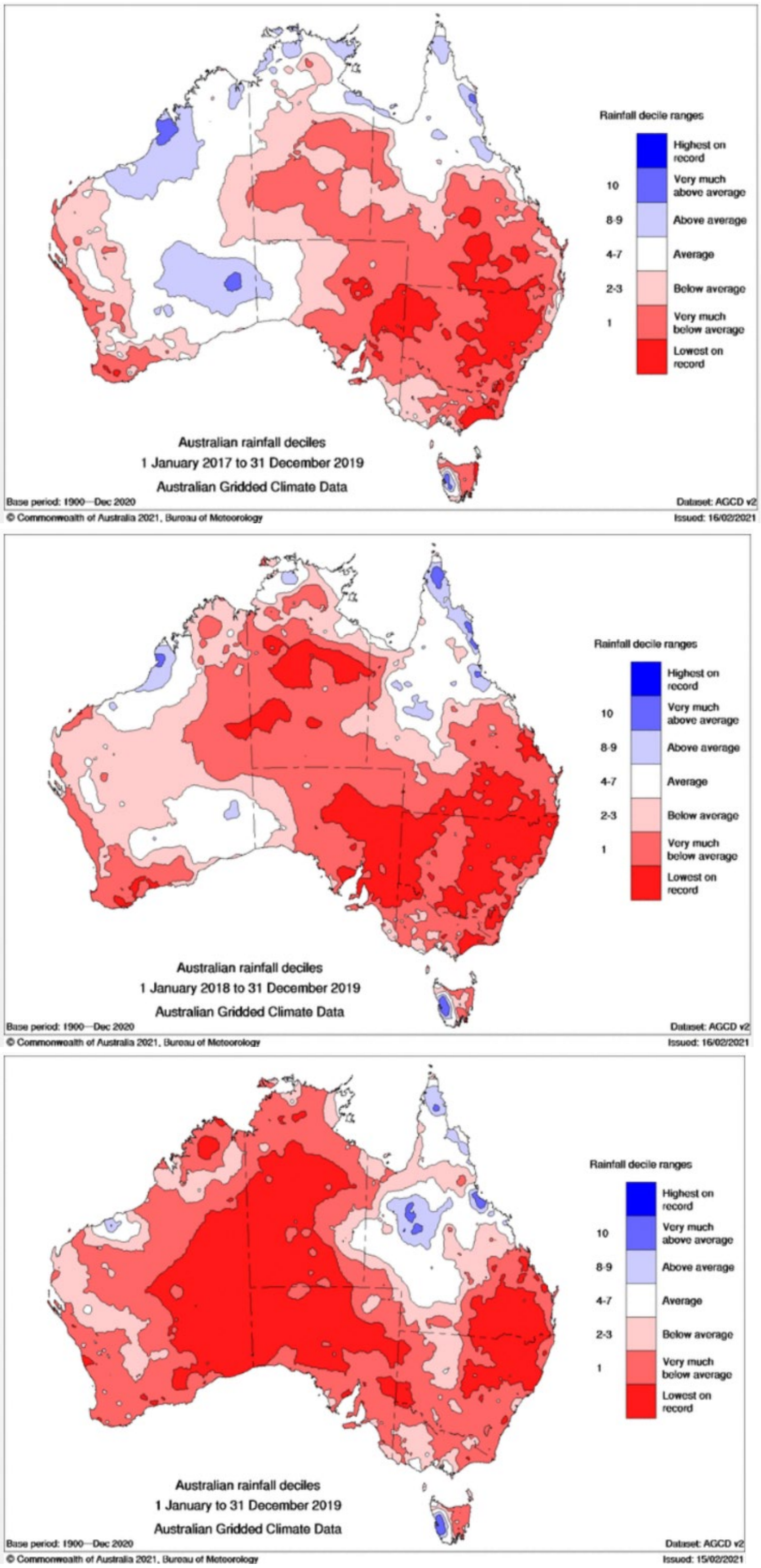


FIGURE 4: LONG-TERM RAINFALL DEFICITS THROUGH AUSTRALIA OVER THE 3-YEAR (UPPER PANEL), 2-YEAR (MIDDLE PANEL) AND 1-YEAR (LOWER PANEL) PERIODS LEADING UP TO THE 2019/2020 SUMMER. THESE ARE SHOWN AS DECILES IN COMPARISON TO ALL OTHER PERIODS OF RECORD.

Longer-term variability of conditions

Figure 4 provides a sense of the spatial distribution of rainfall deficits over several time periods. In this section in contrast, we examine more closely the variations with time of rainfall over the firegrounds themselves. In this way, differences between the conditions leading into the 2019-20 season and the immediately previous season (and earlier ones) become clearer.

Figure 5 shows a long-term timeseries of six-month averaged monthly rainfall for each fire, including both a central point of the fire area and the average across each fire, based on gridded Australian Water Availability Project (AWAP) data. The vertical axis is scaled in mm of rainfall and is compressed to provide a sense of the overall changes in rainfall over an extended period, rather than detail for any particular short interval.

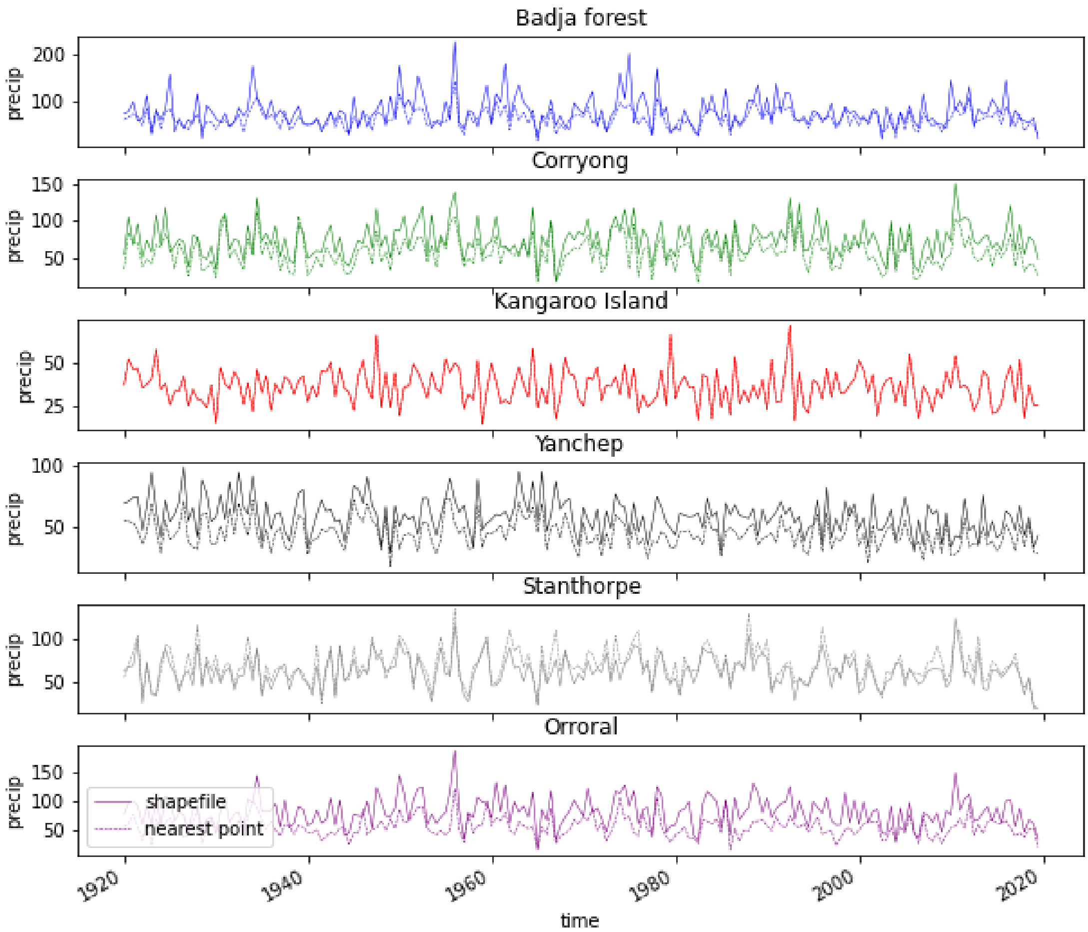


FIGURE 5: SIX-MONTH RUNNING MEAN OF MONTHLY RAINFALL FOR EACH FIRE FROM AWAP GRIDDED DATASET. SOLID LINES REPRESENT FINAL FIRE BOUNDARY-AVERAGED VALUES. DOTTED LINES REPRESENT VALUE AT A SINGLE GRID CELL.

Differences between single plotted locations (as an approximately central representative point - dotted) and fire area averaged rainfall (solid) give an indication of the variability of rainfall across the firegrounds. To some extent, this is a function of fire size – the largest fires were more than 100 times the size of the smallest – but it is not the sole influencing factor. Quite substantial spatial variation in rainfall over time is evident for Yanchep, for example, as the second smallest fire in area. Much less variation is evident in the case of Badja, a very much larger fire.

A uniform decline of average rainfall is evident into the 2019-20 summer. The decline is least evident on Kangaroo Island and Yanchep, but quite clear over a period of several years from 2016 at each of the east coast fire sites (Badja, Orroral Valley, Stanthorpe and Corryong).

Focusing on the most recent decade highlights the precipitation decline into the period in which fires were ignited. In Figure 6, the last 5 years of precipitation between 2015-2020 is highlighted. Fire final boundary-averaged precipitation is again presented, this time as percentiles of the period 1920-2019. Three rolling means are shown for each fire: two year (yellow lines), 6-monthly (blue lines) and 3-monthly (red lines).

All plots decline towards the end of 2019 as noted above, but the rate varies depending on the broad region of the specific fires. Thus, Kangaroo Island and Yanchep display short-term variability during or leading into 2019 but with a steady decline of two-year averaged precipitation from a high in 2018. Stanthorpe, on the other hand, displays lowest percentile precipitation across all three averaging periods for most of 2019. Badja, Orroral and Corryong show three-monthly running mean rainfall above the 50th percentile at the start of 2019 but decline at varying rates during the year. In each of the latter three cases, the underlying two-year running mean rainfall remained below the 25th percentile, pointing to a longer-term rainfall deficit.

Before examining variability of soil moisture over time for each of the fires, the two soil moisture systems used in this report, JASMIN, and AWRA-L, are compared to assess the degree to which they are consistent, noting the different approaches used in each case to generate soil moisture estimates. As noted, both systems are examined because they have different advantages: AWRA-L extends for a longer period than JASMIN, but JASMIN has greater vertical resolution through the top three meters of the soil profile. In addition, research work on JASMIN within the Bushfire and Natural Hazards CRC has demonstrated its applicability to fire management in Australia.

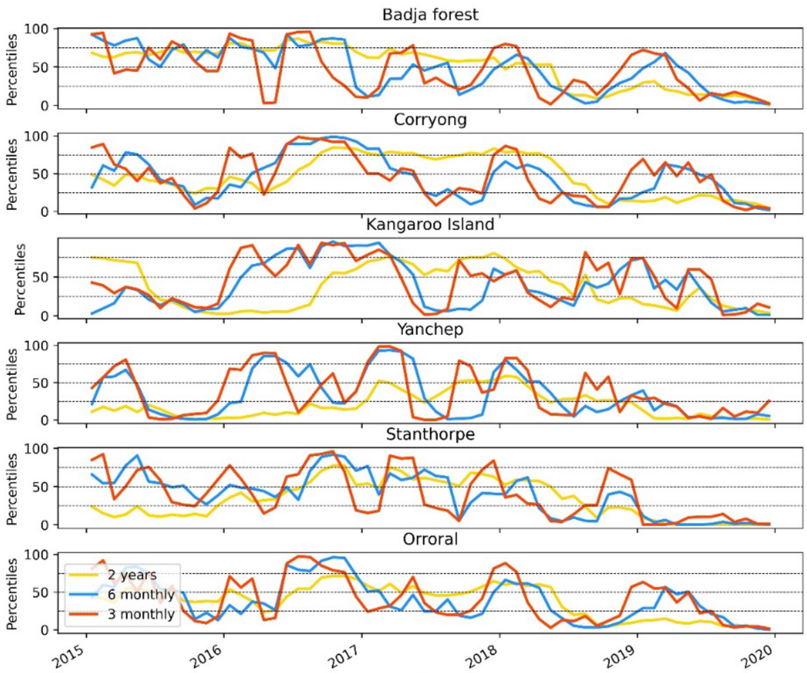
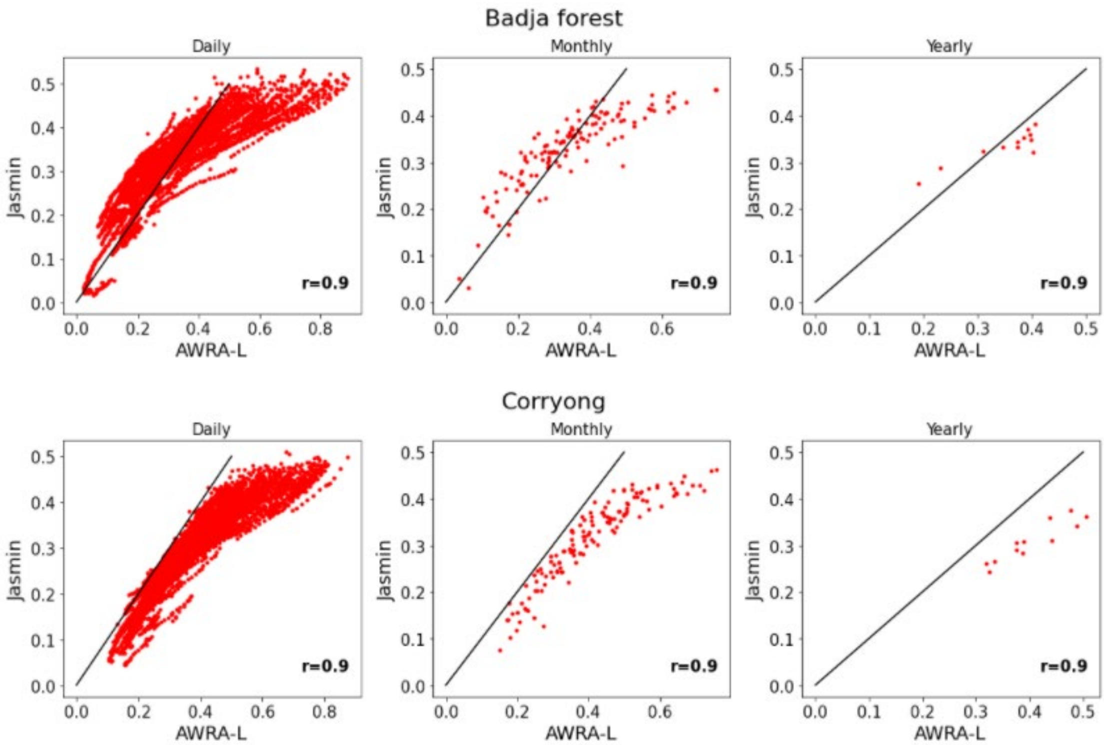


FIGURE 6: RANKINGS OF AWAP PRECIPITATION AVERAGED ACROSS THE FINAL FIRE BOUNDARY FOR EACH FIRE. AVERAGING PERIODS ARE: TWO YEAR (YELLOW), SIX-MONTHLY (BLUE) AND THREE-MONTHLY (RED).

The comparison is made within the final fire boundary for each fire event. Correlations are calculated for daily values of root-zone (0-1 m) soil depth, and for monthly and yearly average values. The quantities compared are volumetric soil moisture content, measured as m^3/m^3 i.e., cubic meters of water per cubic meter of dry soil. Root-zone values are used because both JASMIN and AWRA-L (cumulatively) calculate soil moisture content for that soil depth.

Correlations between JASMIN and AWRA-L are generally high, and consistent across daily, monthly, and yearly comparisons (noting that there are only ten years of average data available for JASMIN, so that the yearly plots show only that number of points of comparison). The highest correlation occurs for Kangaroo Island where the correlation value is 1.0 for daily and monthly timescales, dropping to 0.9 for the yearly plot. The lowest was a still reasonable 0.7 for each timescale at Yanchep. The difference at Yanchep likely results from a different representation of the soil profile in this region: the input data in each case is identical gridded weather (including precipitation) data.



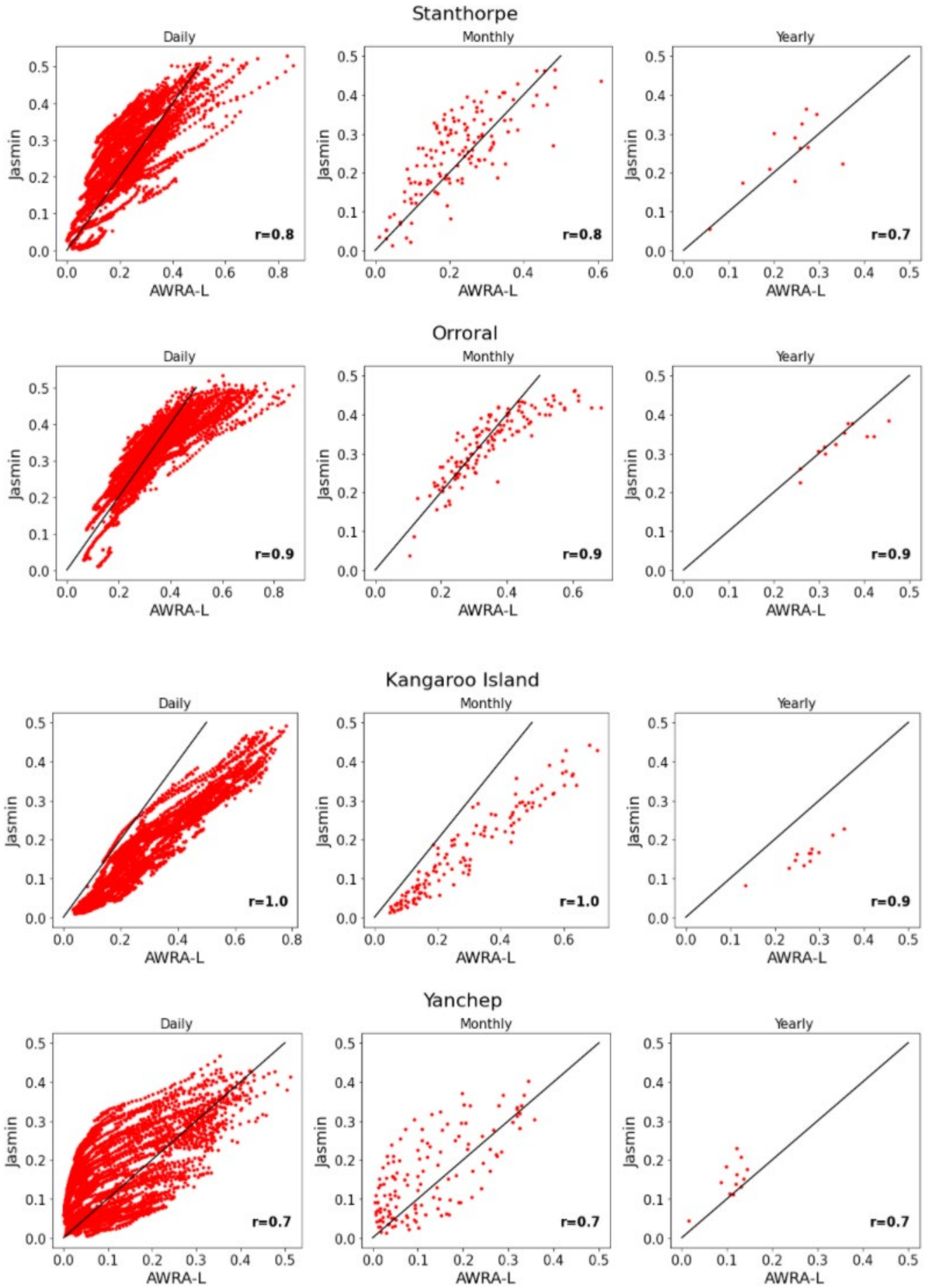


FIGURE 7: COMPARISON OF JASMIN AND AWRA-L SOIL MOISTURE ACROSS EACH FIRE SITE.

We examined daily soil moisture anomaly percentiles for the period June 2019 through January 2020 (Figure 8), for both AWRA-L and JASMIN. Thus, for each day the plot shows the extent to which soil moisture values deviate from average on that day. For compactness, the legend indicates the JASMIN 0-0.1 m layer as "0.1 m", 0.1-0.35 m layer as "0.25m", 0.35-1.0 m layer as "0.65m" and 1.0-3.0m layer as "2m". For the eastern Australian fires (Stanthorpe, Orroral Valley, Badja and

Corryong) and Kangaroo Island, most soil layers for both AWRA-L and JASMIN experienced soil moisture anomalies below 20%, certainly from October 2019 onward. The Great Dividing Range sites, Badja and Corryong, had higher relative moisture levels in upper soil layers in the months prior to October, but these rapidly declined as the warm season progressed. Only the JASMIN 0-0.1 m layer varied above 50% as it responded rapidly to precipitation events. However, this layer also dried rapidly in the wake of such events. Deeper soil layers and the AWRA-L root-zone (0-1 m) layer provided a better indicator of the true degree of landscape dryness. This is not to say that the top, shallow, layer moisture content value is not useful. It is simply not particularly helpful as an indicator of the true degree of landscape dryness.

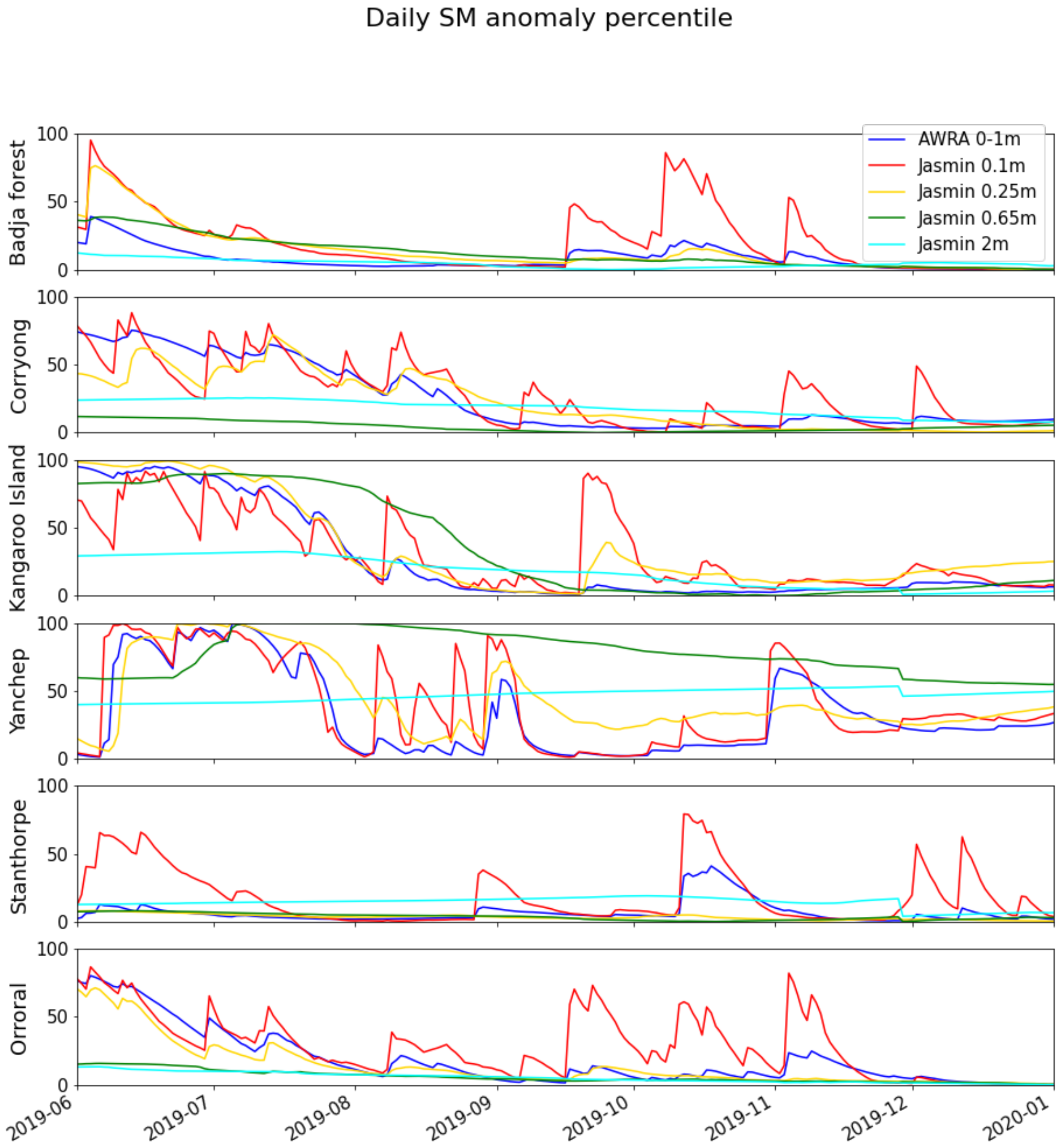


FIGURE 8: SM DAILY PERCENTILE ANOMALY RANK JUNE '19 TO JAN '20.

Yanchep, on the other hand, did not experience as extreme soil moisture conditions, with percentile anomalies grouped around 50% for both JASMIN and

AWRA-L into December 2019, suggesting that this fire was not as strongly driven by soil moisture deficits as others. This is potentially a function of Yanchep being in a different physical and vegetation environment than, say, the east coast fires. It demonstrates that there is value in exploring the interrelationship between the soil and fuel representations across the landscape to better understand what these quantities are indicating about the potential for fire ignition and spread, and to assist in operational decision-making.

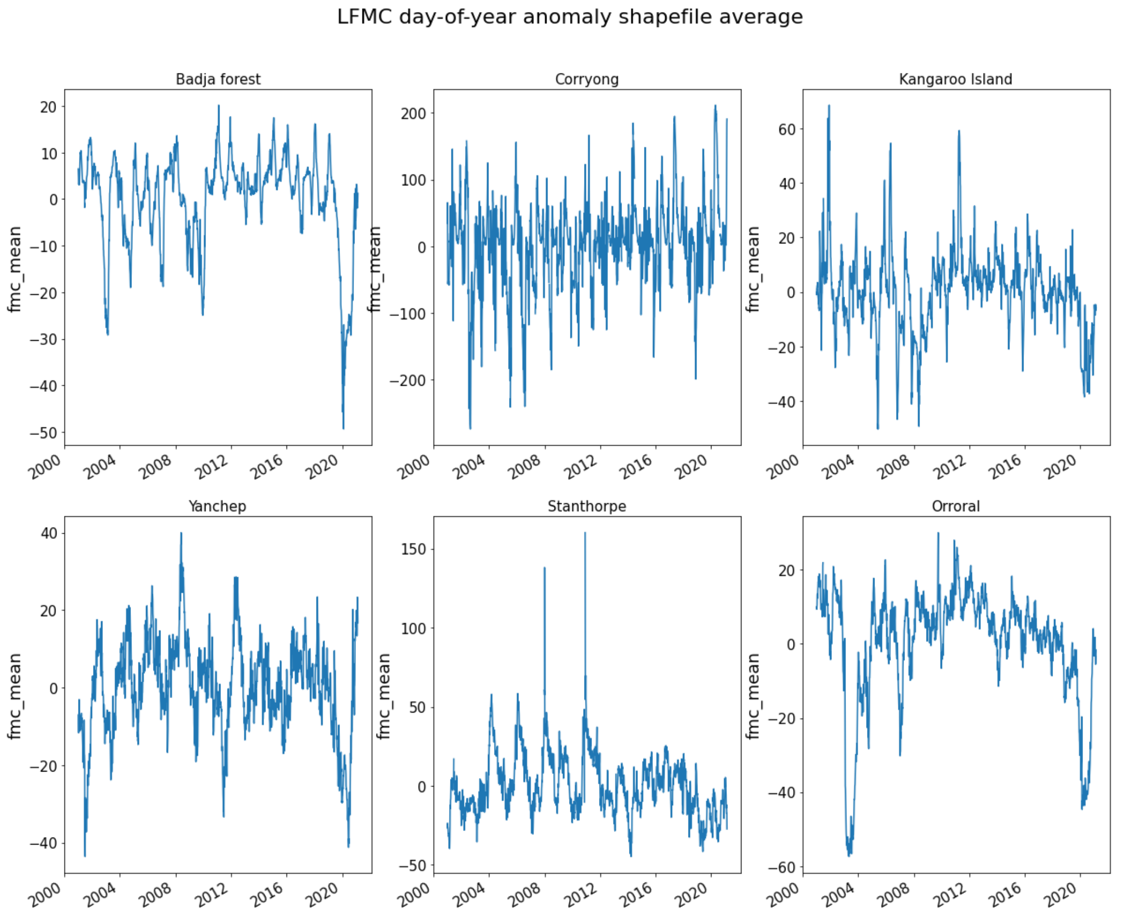


FIGURE 9: LIVE FUEL MOISTURE CONTENT ANOMALY OVER THE LAST TWO DECADES FROM MODIS DATA FOR EACH FIRE, AVERAGED ACROSS FIRE AREAS.

In light of soil moisture variation touched on above, it is interesting to examine fuel moisture content (Figure 9). FMC data displayed here was derived from MODIS and is available from 2001 onward. Most sites displayed substantial short-term FMC variability through the available record, with some sites (Badja, Kangaroo Island, Yanchep and Orroral Valley) showing a steep decline towards the end of 2019. These patterns don't always align closely with the soil moisture patterns (e.g., Yanchep), indicating a number of factors at work to influence the fuel state of vegetation within the firegrounds.

On the other hand, it is clear from plots of daily FMC anomaly percentiles (Figure 10) that all sites experienced low or declining levels of FMC leading into the period of fire ignition: Badja had fire boundary averaged FMC anomaly percentile near 50% in June 2019 which declined uniformly to lowest recorded values by the end of December 2019; Stanthorpe hovered near lowest values until the fire in early September then rose. The rise here is very likely to have been strongly contaminated by the presence of burnt vegetation within the fire boundary.

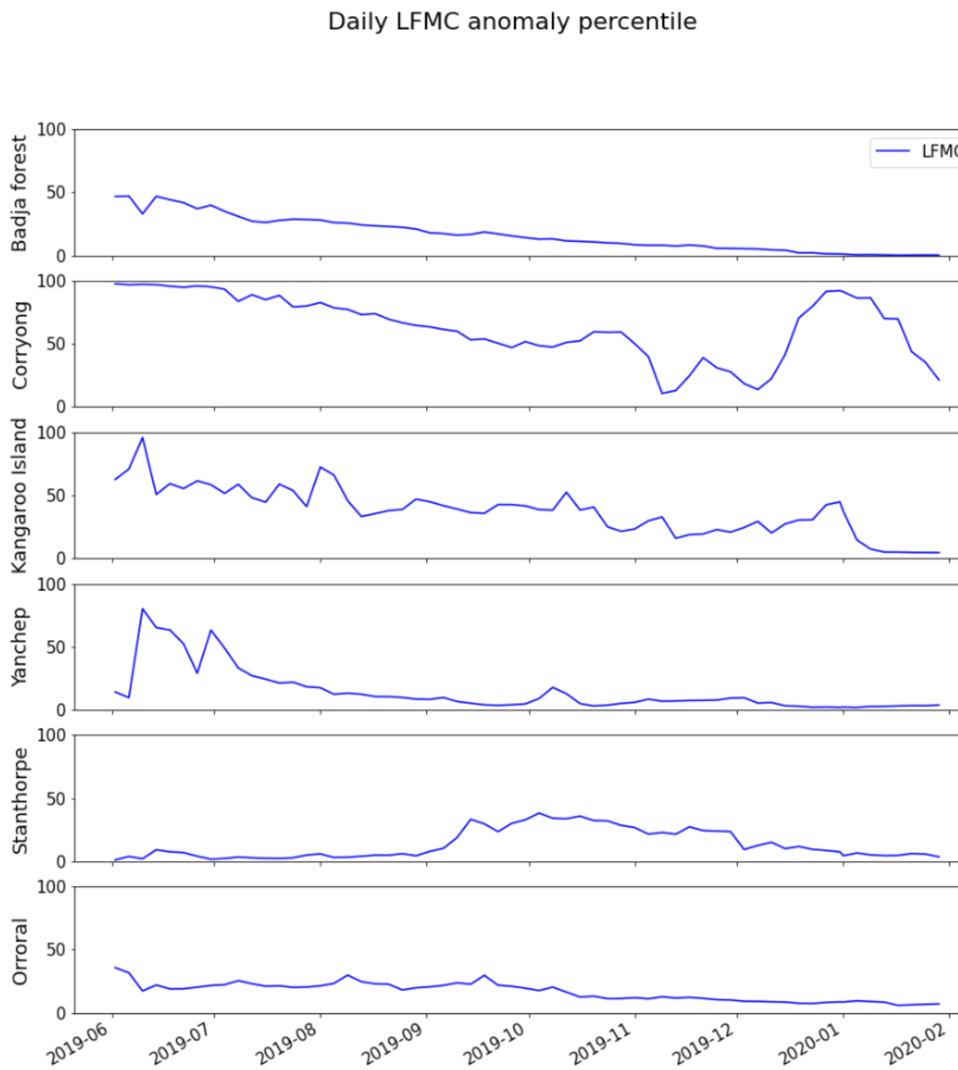


FIGURE 10: LIVE FUEL MOISTURE CONTENT DAILY PERCENTILE RANK JUNE '19 TO FEB '20.

Finally, in this overview section, we examine the monthly FMC anomaly percentiles for each fire in the period from July 2016 to January 2020 (Figure 11). Again, there is substantial variability within each region but with a uniform decline in FMC towards the times of fire ignitions. In some cases, this decline was prolonged: Badja was close to 100% anomaly in early 2019, declining steadily through the year to be at 1% by the end of December (noting that by the end of that month FMC may be influenced by the occurrence of the fire), whereas Corryong displays quite high percentile anomaly as late as November 2019 before declining very steeply to below 20% by the time of the fire in that region.

This latter series of plots again highlights that the circumstances of each fire varied quite substantially and that, while we may be able to generalize to some broadly applicable conclusions, there will be factors unique to each site. This is hardly surprising considering that the fires extend across the width of the Australian continent, from subtropics to the midlatitudes and from the continental interior to strongly maritime environments.

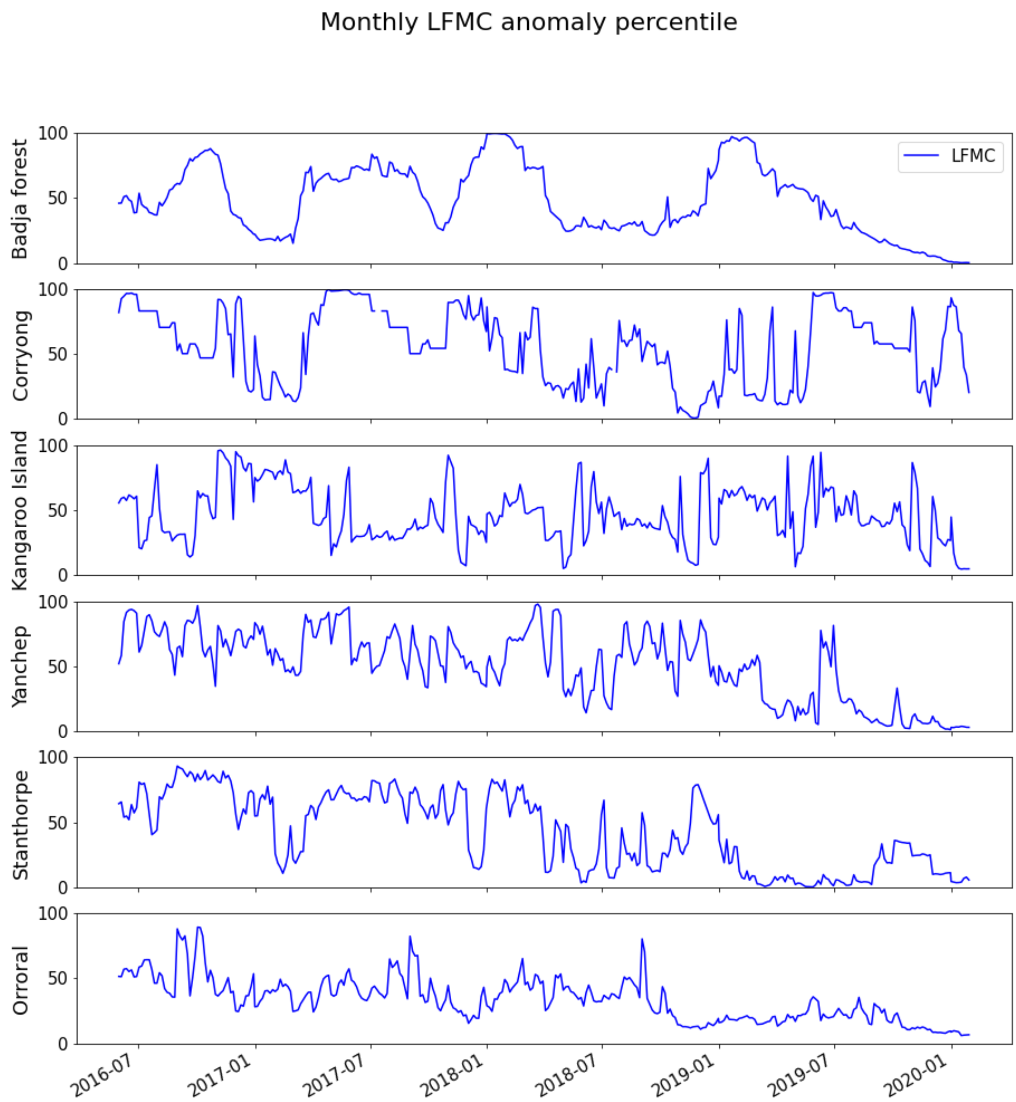


FIGURE 11: FMC MONTHLY PERCENTILE RANK JUNE '16 TO FEB '20.

In the individual fire sections, we include detailed plots of Sentinel-derived FMC, highlighting its variability spatially and temporally.

INDIVIDUAL FIRE ANALYSES

For each fire we present figures to show the broad-scale conditions around the time of the fires, including rainfall, temperature, and moisture measures. Synoptic features based on national mean sea level pressure (MSLP) charts are also shown, included to highlight the weather systems that contributed to the severity of those conditions.

We then present time series of anomalies of meteorological, and moisture (soil and fuel) variables averaged over the fire areas for the periods of availability of the respective variables. Maximum (tmax) and minimum (tmin) temperature and precipitation (precip) are available from 1950, for example.

The impact of heatwaves on fuel moisture content at short timescales was an important goal of the project. The Excess Heat Factor (EHF)[22] is used as an indicator of the presence of heatwaves for this purpose. We produce EHF vs fuel moisture plots for each fire.

Finally, we present a timeseries of high-resolution maps of FMC for the week before and a few days after each fire to observe the moisture condition variability within the fires' perimeters.

STANTHORPE

Broad-scale weather and climate context

Around the time leading up to the peak fire activity (6th - 7th September 2019), there were strong northwesterly winds associated with the passage of a cold front with a pre-frontal trough approaching from the west (Figure 12). This led to very hot and dry air (e.g., low values of vapour pressure) in southeast QLD (Figures 13-14) advecting from further inland over the continent, contributing to maximum temperatures more than 10 °C above average in some areas. As an additional contribution to this dangerous set of fire weather conditions, many locations in the fire-affected areas had been experiencing their driest conditions on record since at least 1900, including for the rainfall deficits over the January to August period in 2019 and over multi-year time periods (Figure 18).

Based on these figures showing the broad-scale conditions, it is evident that it had been an exceptionally dry 2-year period (i.e., meteorological drought based on rainfall deficits), including at a somewhat shorter time period for the months leading up to the fire period. Additionally, it is also clear that the extreme dry conditions were exacerbated even further at shorter timescales, due to the exceptionally hot and dry air associated with the passage of the trough/front system around 6th September 2019. This combination of extreme conditions over that broad range of time scales led to extremely low moisture content of fuels as a key factor for the devastating fire conditions that occurred, with the following section providing details on the temporal evolution of those moisture conditions based on several metrics.

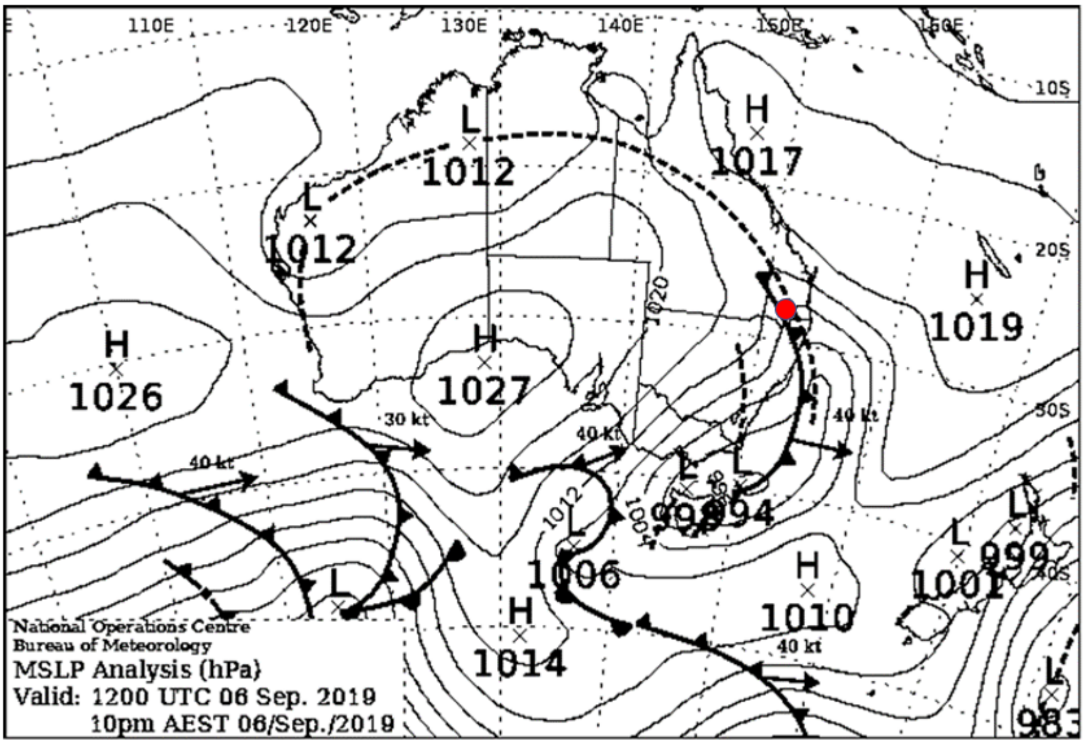
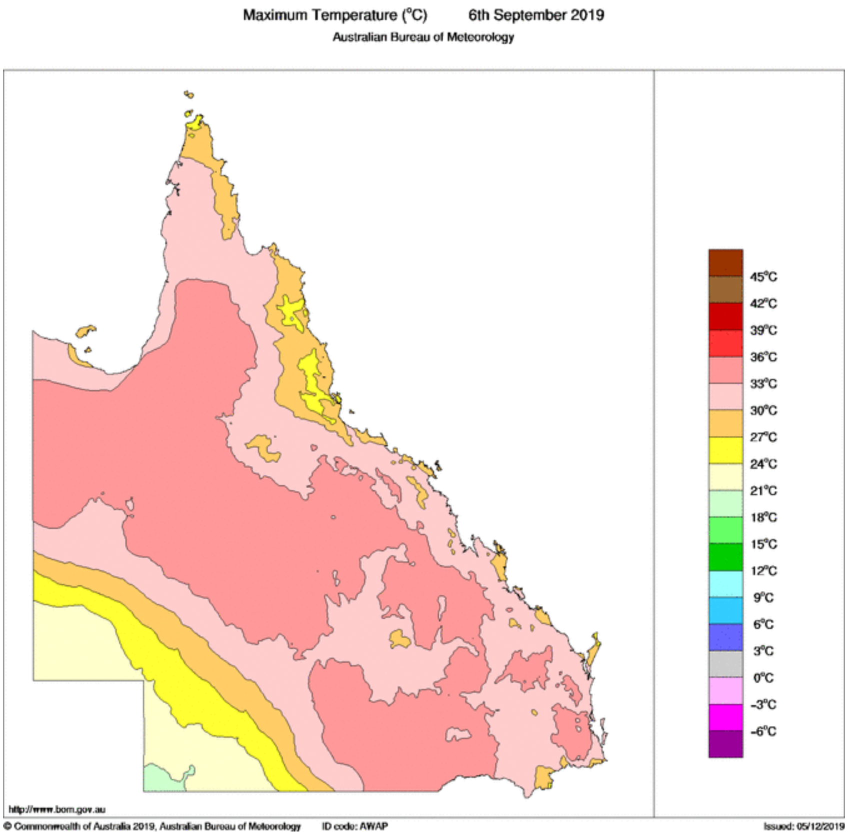


FIGURE 12: WEATHER SYSTEMS AROUND THE TIME OF THE STANTHORPE FIRE. THIS IS SHOWN FOR THE SYNOPTIC MEAN SEA LEVEL PRESSURE (MSLP) CHART PRODUCED BY THE BUREAU OF METEOROLOGY FOR 6TH SEPTEMBER 2019 AT 1200 UTC. APPROXIMATE LOCATION OF STANTHORPE INDICATED BY RED DOT.



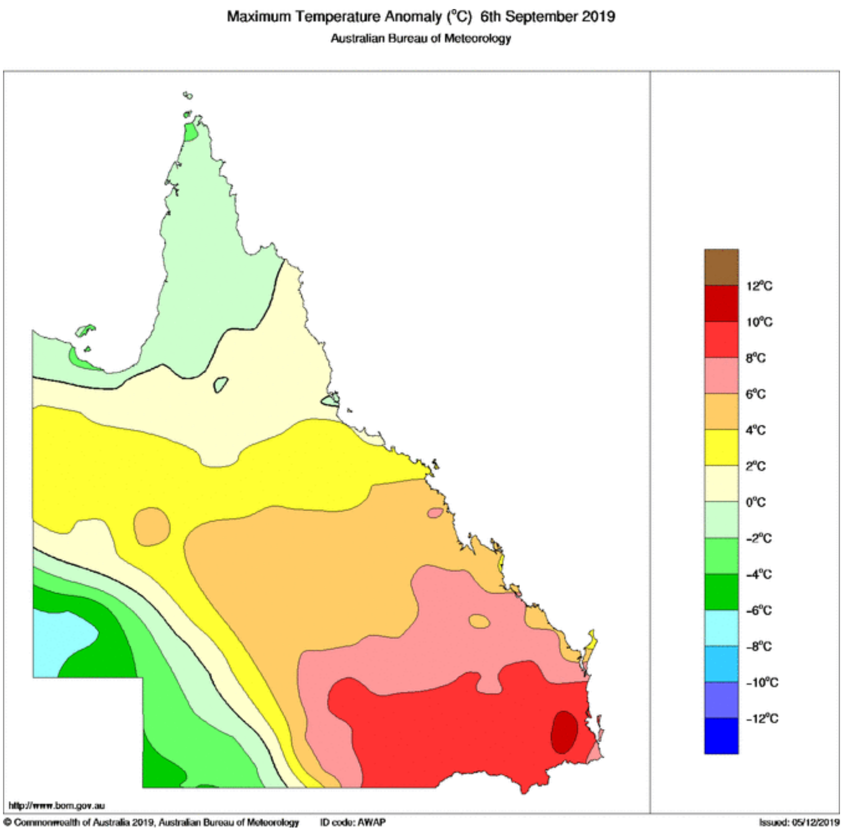


FIGURE 13: DAILY MAXIMUM TEMPERATURE (UPPER PANEL) AND DAILY MAXIMUM TEMPERATURE ANOMALY (LOWER PANEL) FOR 6TH SEPTEMBER 2019.

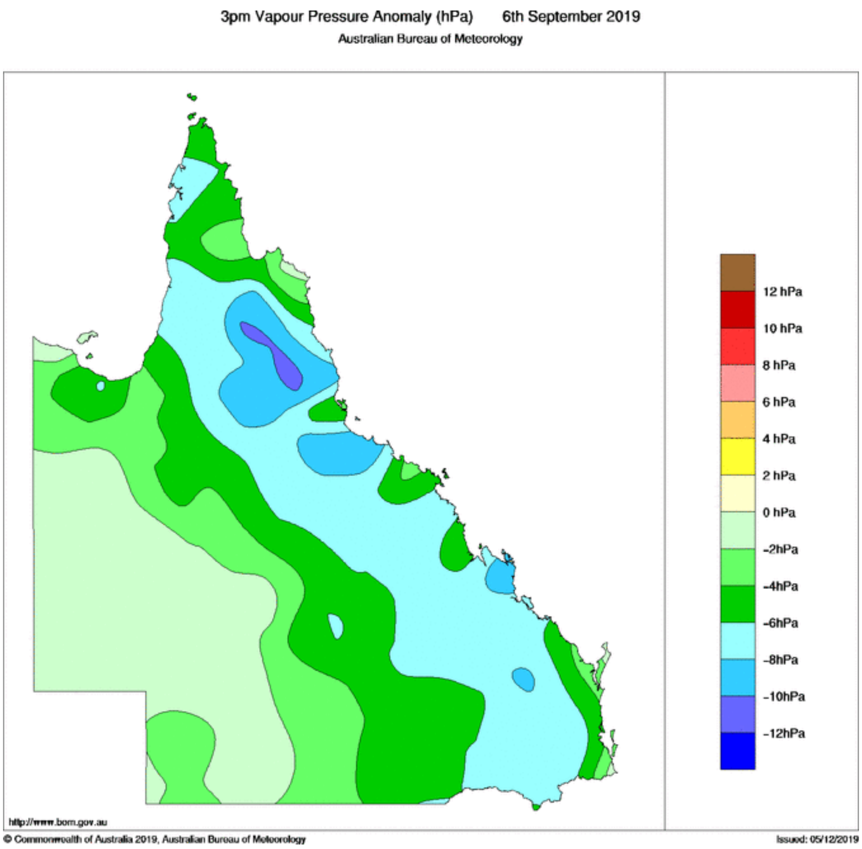


FIGURE 14: VAPOUR PRESSURE ANOMALY ON 6TH SEPTEMBER 2019 AT 3 PM LOCAL TIME.

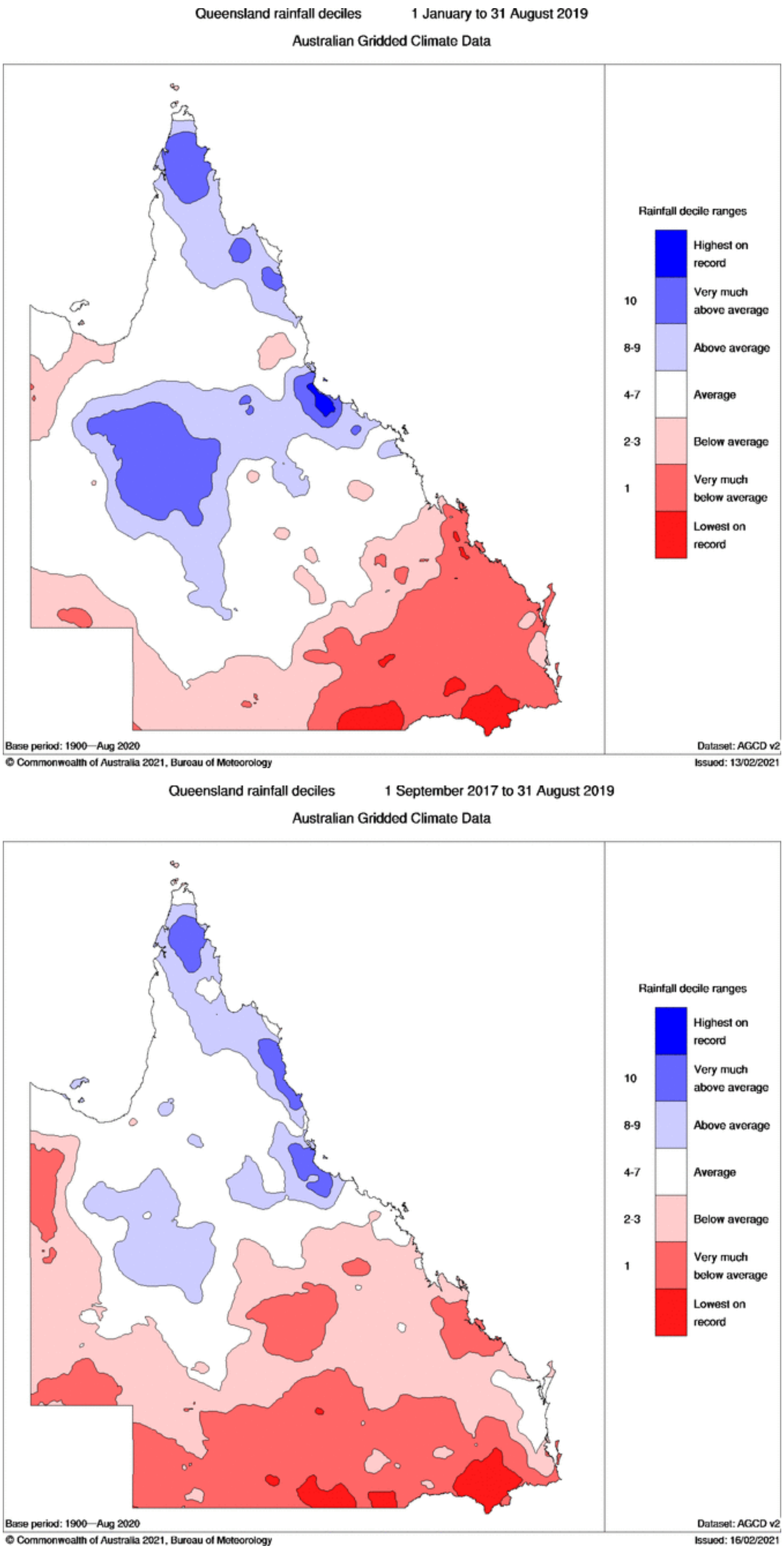


FIGURE 15: RAINFALL ANOMALIES FOR QLD LEADING UP TO THE STANTHORPE FIRES IN SEPTEMBER 2019. THIS IS SHOWN FOR THE MONTHS FROM JANUARY TO AUGUST 2019 LEADING UP TO THE FIRES (UPPER PANEL), AS WELL AS FOR THE 2-YEAR PERIOD FROM SEPTEMBER 2017 TO AUGUST 2019 (LOWER PANEL).

Multi-year development of conditions suitable for landscape fires (drought)

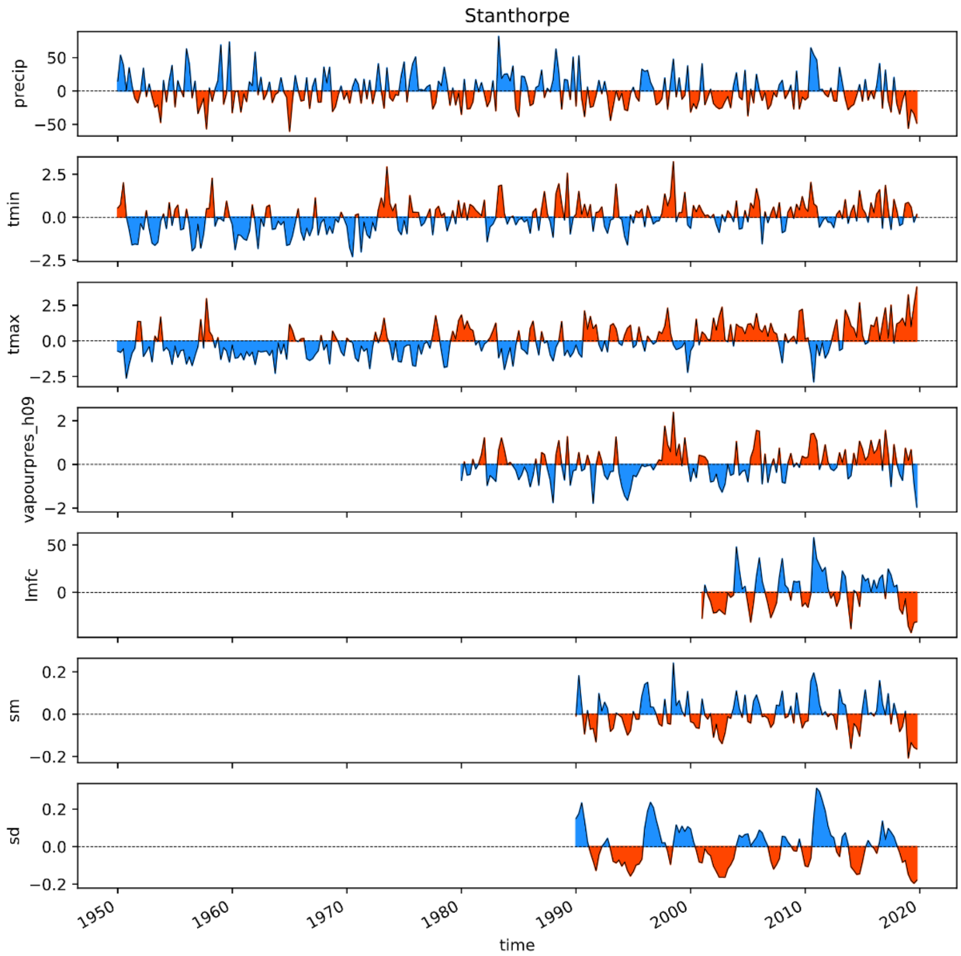


FIGURE 16: TIME SERIES OF 3-MONTHLY ANOMALIES OF METEOROLOGICAL VARIABLES AND SOIL AND FUEL MOISTURE.

Precipitation varied quasi-periodically through time but following a strong peak in 2010 has been generally lower than average with strongly lower than average precipitation since 2018, as discussed in the above section. Both minimum and maximum temperature, on the other hand, have shown a steadily increasing trend since about 1970 consistent with a warming climate. In particular, maximum temperature has been strongly above the average of the entire series for extended periods since 2010. Similarly, 9 a.m. vapour pressure (vapourpres_h09) has increased through time in line with temperature, noting that higher temperatures permit higher vapour pressure if sufficient moisture is available. Near the end of the sequence, however, a series of strong negative spikes are evident for Stanthorpe, indicating historically dry airmasses over the area.

The influence of broad-scale climate drivers (in addition to the warming climate signal) are also evident in these plots. For example, the strong La Nina events in 1974-76 and 2010-12 are clear in peaks in precipitation during those periods, accompanied by lower than average maximum temperatures due to increased cloud and rainfall.

Live fuel moisture content (lfmc), together with AWRA-L root-zone (0-1 m denoted by sm) and deep layer (1-6 m denoted by sd) soil moisture broadly reflect variation in precipitation, although deep layer soil moisture displays less variability than the other parameters. Notably, too, the negative anomalies of the latter three variables are strongest of the available record, and certainly stronger than the immediately prior two seasons, for the latter part of 2019 (noting that following the fire, FMC values will be influenced by the fire occurrence, due to canopy scorch or consumption).

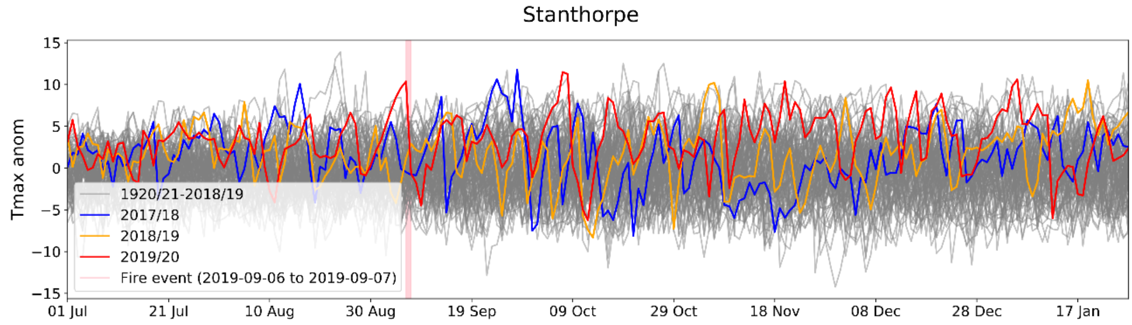
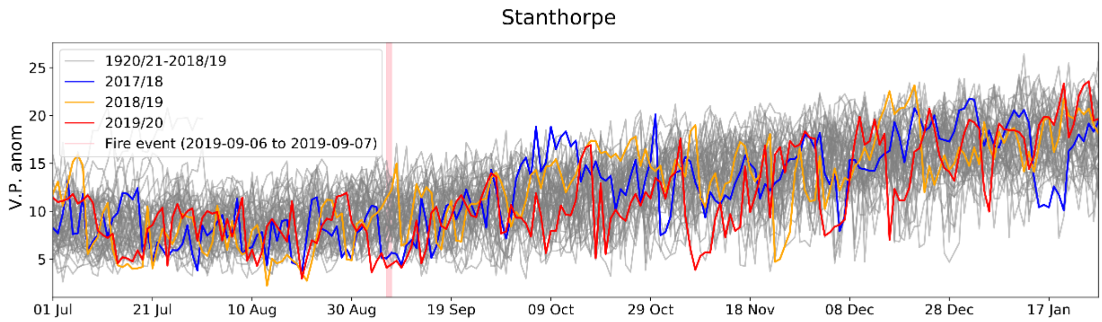


FIGURE 17: TIME SERIES OF MAXIMUM TEMPERATURE (DEGREES C, TOP) AND 0900 VAPOUR PRESSURE (HPA, BOTTOM) ANOMALIES FROM 1 JULY TO 31 JANUARY FOLLOWING, FOR EACH AVAILABLE YEAR. THE PERIOD OF FIRE OCCURRENCE IS HIGHLIGHTED WITH A VERTICAL PINK BAR.



Time series of maximum temperature (degrees C) and 0900 vapour pressure (hPa) anomaly for 01 July – 31 January for each available year are presented in Figure 17. The period of the Stanthorpe fire is represented by a vertical pink bar in both the maximum temperature and vapour pressure anomaly charts. The time series for 2017-18 is in blue, 2018-19 in yellow and 2019-20 in red. All other years are in grey for historical context. Each of the three latter years experienced peaks of temperature prior to (and after) the fire and were persistently warmer than the historical average. A broad, historically significant peak occurred immediately prior to the fire in 2019. Meanwhile, vapour pressure was at historically low values around the time of fire ignition in 2019 (as it was during 2017). This was a broad feature, as can be seen from the synoptic summary sections Figure 14. The combination of these factors was substantially more conducive to fire occurrence in 2019 than was the case in the earlier two seasons.

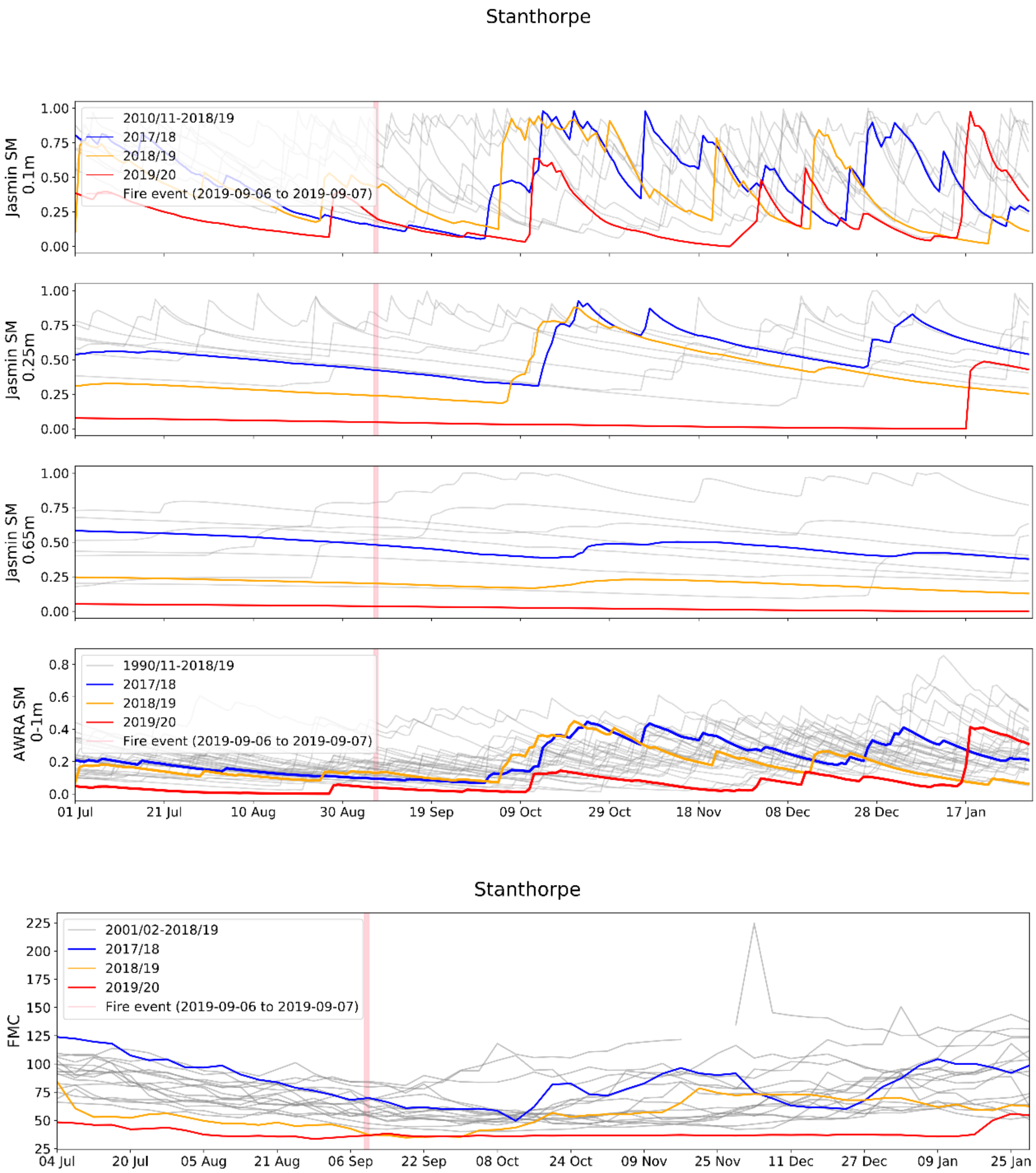


FIGURE 18: TIME SERIES OF SOIL AND FUEL MOISTURE AS PER FIGURE 17.

Integrating the effects of the meteorological factors as suggested above, soil and fuel moisture parameters (Figure 18) show historically low values for all measures approaching the time of fire ignition, noting that the period of record is shorter than for the meteorological parameters. The immediately previous two seasons were also relatively dry, but 2019-20 displayed more consistently dry soil and fuel conditions than those seasons.

The time series of annual fire area-averaged fuel moisture content (Figure 19) shows strong variability through time, with a peak value corresponding to the 2010-11 La Niña, and lowest value in 2019. In particular, the decrease from 2017 and 2018 is the steepest in the available time series, reflecting the underlying extremity of soil dryness conditions. Potentially, the rate of change of fuel moisture content could be a useful indicator of fire potential.

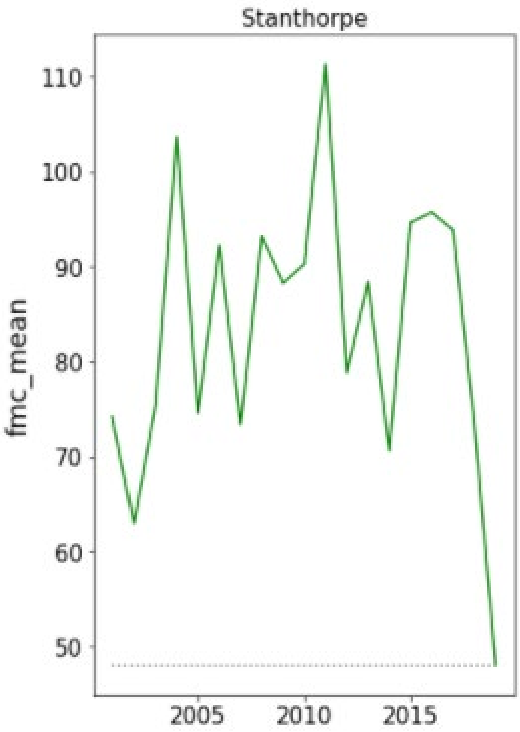


FIGURE 19: TIME SERIES OF ANNUAL AND FIRE AREA-AVERAGED FUEL MOISTURE CONTENT FOR STANTHORPE.

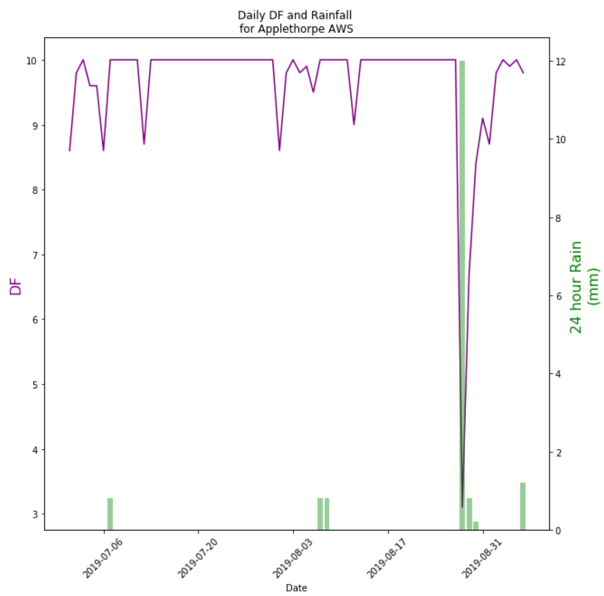


FIGURE 20: TIME SERIES OF THE DROUGHT FACTOR (PURPLE) AND PRECIPITATION (GREEN) AT APPLETHORPE AWS FOR THE TWO MONTHS IMMEDIATELY PRIOR TO STANTHORPE FIRE IGNITION.

For comparison with other fuel moisture measures, we present time series of Drought Factor (purple line) and precipitation (green bars) for Applethorpe Automatic Weather Station (AWS), close to Stanthorpe, in the two months leading to fire ignition (Figure 20). DF was 10 apart from brief periods when precipitation occurred. As such, it provided similar information to the top layer of JASMIN, responding rapidly to precipitation events, and returning quickly to a dry state.

EHF vs fuel moisture plots were prepared for Stanthorpe but displayed confusing results and will require further analysis to ensure there is no data corruption. As such, they are not displayed here.

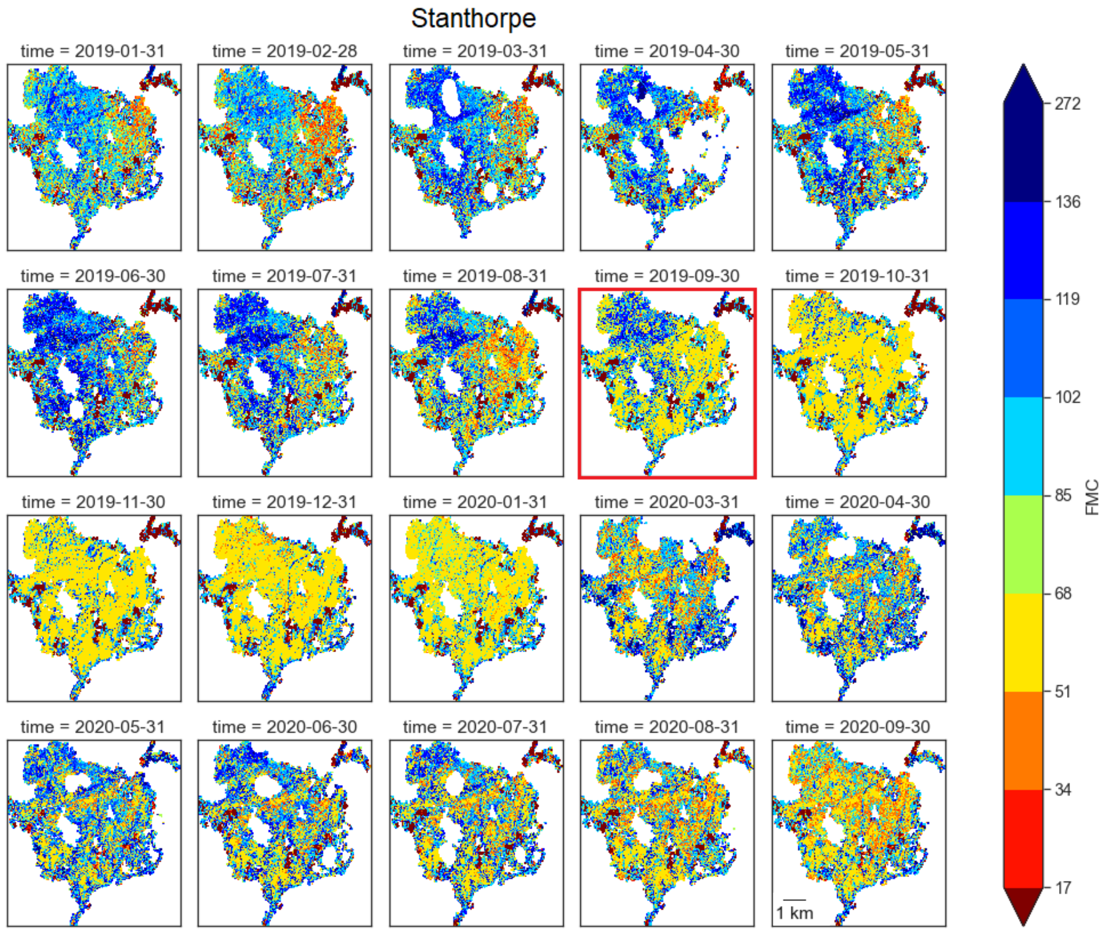


FIGURE 21: MAPS OF SPATIAL AND TEMPORAL VARIATION OF HIGH-RESOLUTION FMC (25M) OVER THE STANTHORPE BURN AREA FROM SENTINEL-2 SATELLITE DATA. FUEL MOISTURE CONTENT IS MEASURED IN PERCENT, WITH HIGH MOISTURE CONTENT IN BLUE AND LOW MOISTURE CONTENT IN YELLOW/RED. HIGHLIGHTED IN RED IS THE MAP CLOSEST TO THE DATE THAN THE FIRE STARTED.

Areas of very dry vegetation are visible on the time series maps of FMC for the Stanthorpe fireground (Figure 21), particularly in August 2019, immediately prior to the fire occurrence. There is, however, a substantial variability in fuel moisture across the fireground. From October 2019 till January 2020 the impact of the fire is clearly visible as a region of very dry vegetation. Afterwards we see progressive increased in the moisture conditions related to revegetation and rains.

In summary, observation of individual meteorological parameters showed the presence of an extended rainfall deficit combined with higher-than-normal temperatures and periods of low vapour pressure, one such period coinciding with the cold front crossing the region on 06 September. Soil and fuel moisture parameters integrated these effects, highlighting that soils and fuels were at clearly lower levels than at the same times in the previous seasons, which had also been dry and warm.

BADJA

Broad-scale weather and climate context

For the Badja fire event there was a period of peak fire activity around the end of 2019, including during the last couple of days in December. Leading up to that period there was a high-pressure system located in the Tasman Sea and an approaching cold front and trough from the southwest (Figure 22), causing strong northwesterly winds over southeast NSW. This caused exceptionally hot and dry air (Figures 23-24), including maximum temperatures more than 12 °C above average in some areas, with this being more pronounced inland on the 30th and along the coast of NSW on the 31st. In addition to these extreme temperatures and dry air, many locations in the fire-affected areas experienced rainfall totals that were driest on record for 2019, as well as record rainfall deficits over longer time periods such as for the 2-year period leading up to December 2019 (Figure 25), noting some regional variation based on those figures (e.g., somewhat less extreme drought for a region near Sydney rated as 'below average' as a potential contributing factor to the Sydney region being somewhat less effected by fires in Black Summer than some other regions of NSW).

Based on these figures showing the broad-scale conditions in the region near the Badja fire and extending to the south coast of NSW, it is evident that it had been an exceptionally dry 2-year period (i.e., meteorological drought based on rainfall deficits), including at a somewhat shorter time period for the months leading up to the fire period. Additionally, it is also clear that the extreme dry conditions were exacerbated even further at shorter timescales, due to the exceptionally hot and dry air associated with the passage of the trough/front system around 31st December 2019, with this being particularly the case near the coast on the 31st (whereas some relatively moist and cool air was present there on the 30th). This combination of extreme conditions over that broad range of time scales led to extremely dry moisture content of fuels as a key factor for the devastating fire conditions that occurred, with the following section providing details on the temporal evolution of those moisture conditions based on several metrics, including considering variations for different regions near the coast on the 31st and further inland on the 30th.

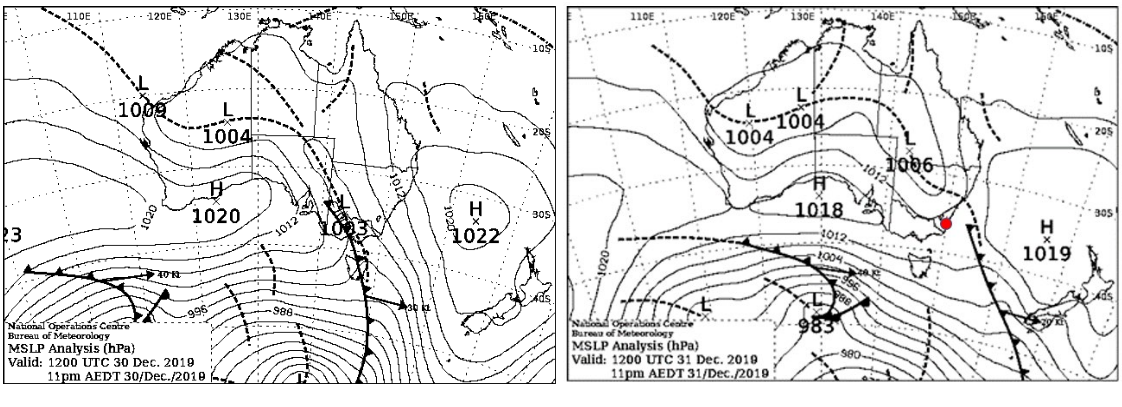


FIGURE 22: WEATHER SYSTEMS AROUND THE TIME OF THE BADJA FIRE EVENT. THIS IS SHOWN FOR THE SYNOPTIC MSLP CHARTS PRODUCED BY THE BUREAU OF METEOROLOGY FOR THE 30TH (LEFT PANEL) AND 31ST (RIGHT PANEL) DECEMBER 2019 AT 1200 UTC. APPROXIMATE LOCATION OF BADJA FOREST INDICATED BY RED DOT IN RIGHT-HAND CHART.

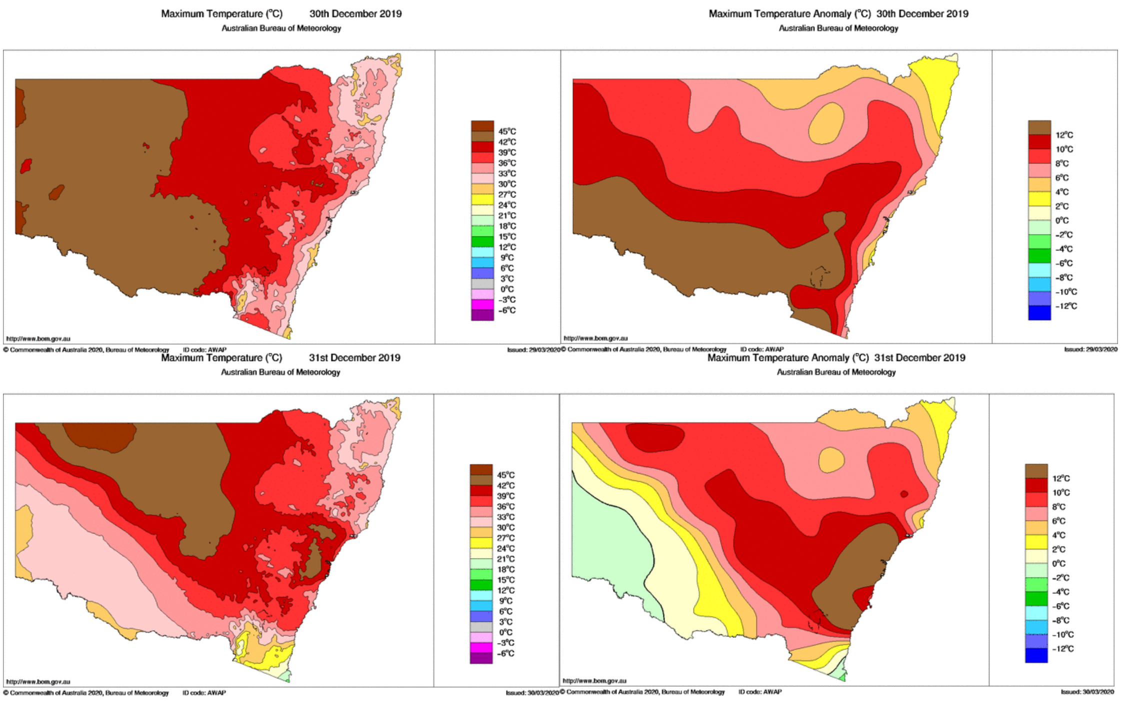


FIGURE 23: DAILY MAXIMUM TEMPERATURE (LEFT PANELS) AND TEMPERATURE ANOMALY (RIGHT PANELS) FOR 30TH (UPPER PANELS) AND 31ST (LOWER PANELS) DECEMBER 2019 IN NSW.

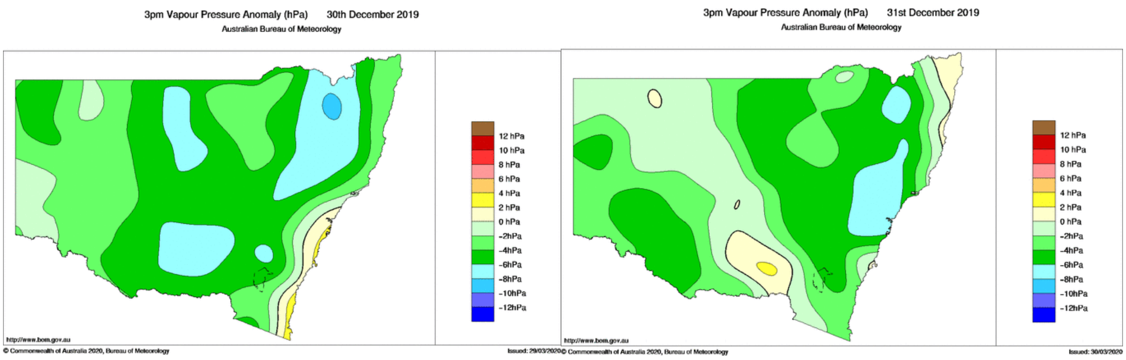


FIGURE 24: VAPOUR PRESSURE ANOMALY ON 30TH (LEFT PANEL) AND 31ST (RIGHT PANEL) DECEMBER 2019 AT 3 PM LOCAL TIME (WITH DAYLIGHT SAVINGS).

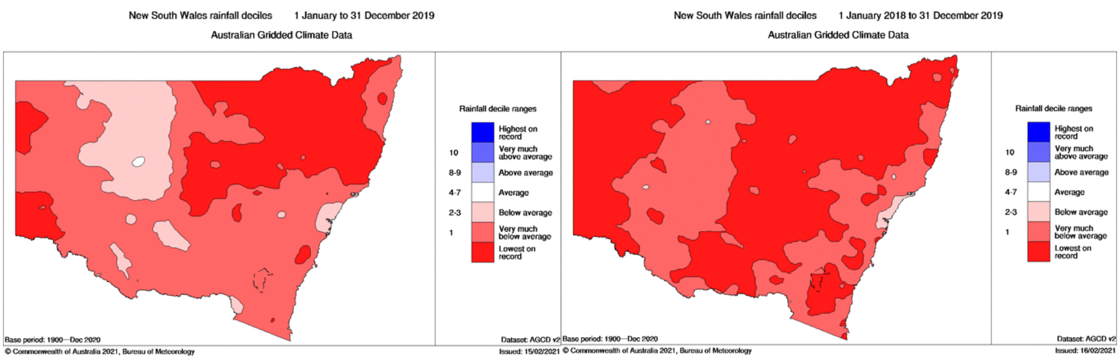


FIGURE 25: RAINFALL ANOMALIES FOR NSW LEADING UP TO THE BADJA FIRES. THIS IS SHOWN FOR THE PERIOD FROM JANUARY TO DECEMBER 2019 (LEFT PANEL), AS WELL AS FOR THE 2-YEAR PERIOD FROM JANUARY 2018 TO DECEMBER 2019 (RIGHT PANEL).

Multi-year development of conditions suitable for landscape fires (drought)

As with the Stanthorpe case, and as discussed in the synoptic summary above, an extended period of below average precipitation and above average minimum and particularly maximum temperature resulted in very low root-zone

(SM) and deep layer (SD) soil moisture over the Badja fireground (Figure 26). A sharp spike of low vapour pressure in late 2019 also would have contributed to a very rapid decrease in FMC over the same period.

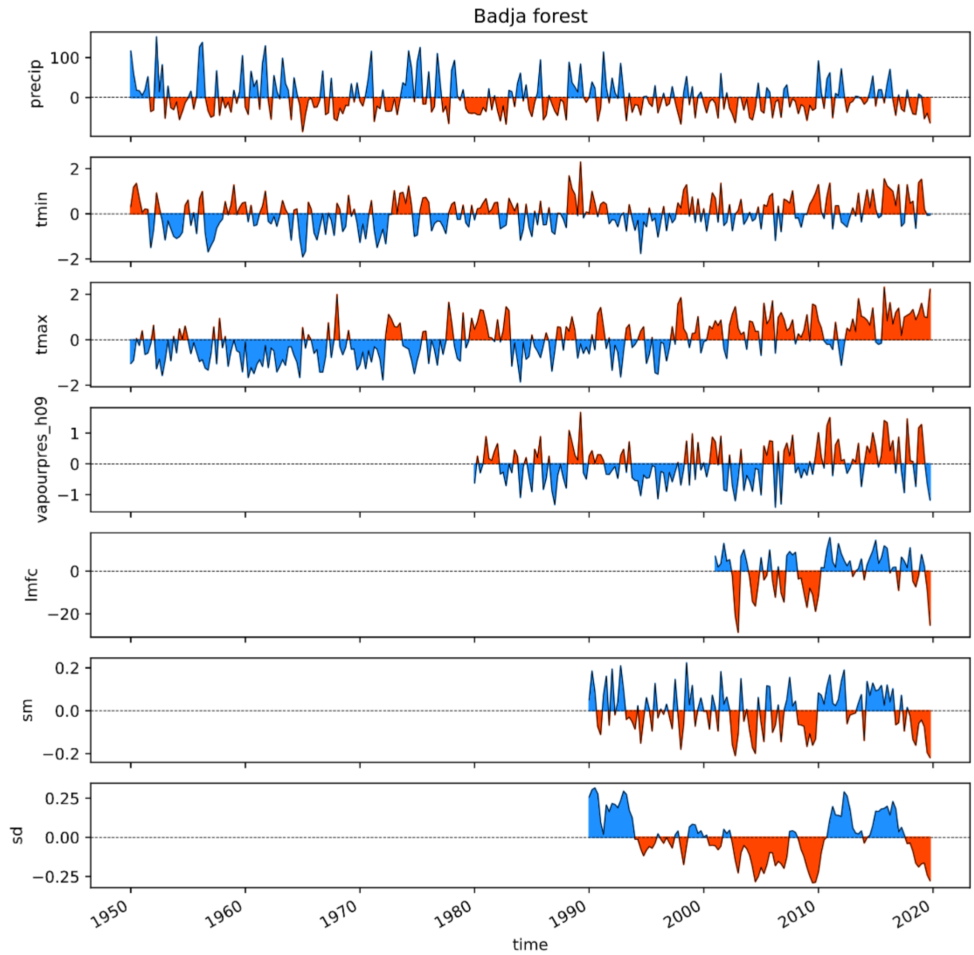
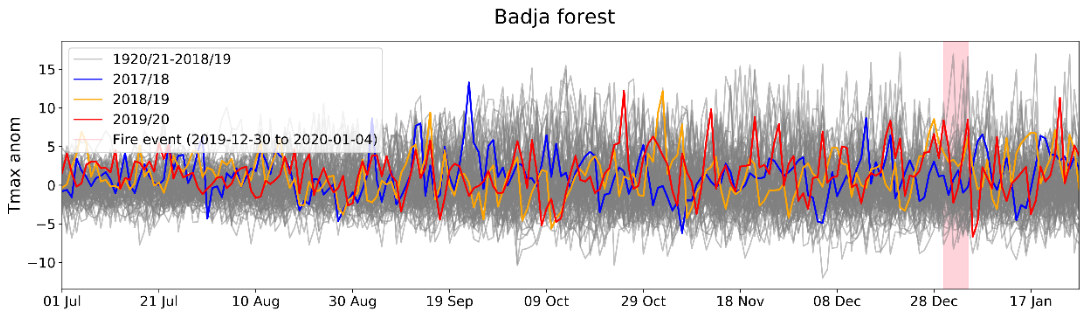


FIGURE 26: TIME SERIES OF 3-MONTHLY ANOMALIES OF METEOROLOGICAL VARIABLES AND SOIL AND FUEL MOISTURE FOR BADJA FOREST.



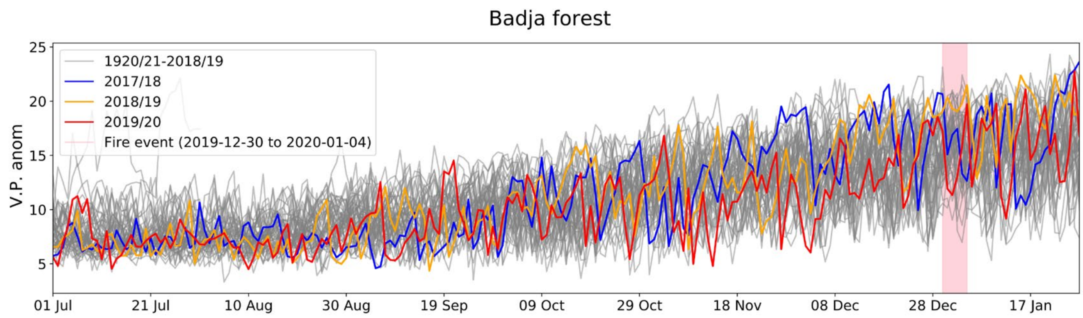


FIGURE 27: TIME SERIES OF MAXIMUM TEMPERATURE (DEGREES C, TOP) AND 0900 VAPOUR PRESSURE (HPA, BOTTOM) ANOMALIES FROM 1 JULY TO 31 JANUARY FOLLOWING, FOR EACH AVAILABLE YEAR. THE PERIOD OF PEAK FIRE ACTIVITY IS HIGHLIGHTED WITH A VERTICAL PINK BAR.

Meteorological parameters are plotted for the months leading to late January in Figure 27. While 2017 was close to average temperature in late December 2018 and 2019 were progressively warmer with hot days around the time of the fire ignition, although not historically significant peaks (there were warmer days in previous years). Similarly, vapour pressure was not exceptional around the time of the fire, although it had been quite low over preceding months in 2019 and, in particular, lower than in 2017 and 2018.

As with Stanthorpe, the integration of meteorological parameters over time that naturally occurred to affect soil and fuel moisture reveals a starker picture than that of the individual weather parameters (Figure 28). Soil and fuel moisture were largely unexceptional during November and December in 2017 and 2018, but by late December 2019, in a period of ongoing dry and hot conditions, all JASMIN layers and FMC were at their lowest levels in their respective records for that time.

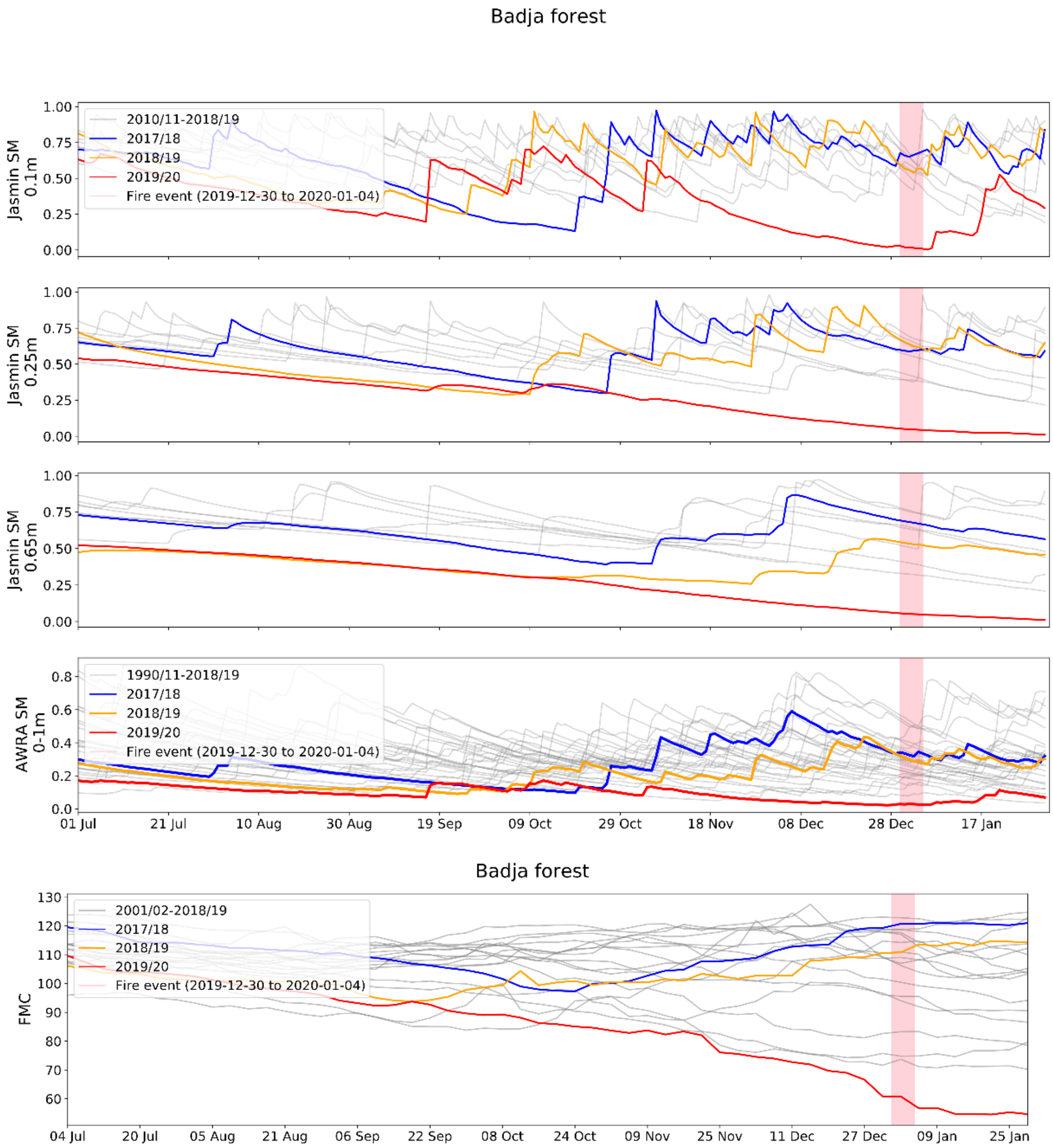


FIGURE 28: TIME SERIES OF SOIL AND FUEL MOISTURE FOR BADJA FOREST AS PER FIGURE 27.

The time series of annually and fire area-averaged fuel moisture content is displayed in Figure 29 for the Badja fireground. Notably the FMC declines steadily from its 2016 value to 2019. The 2019 value, however, was not the lowest in the 20 years record. Values were lower during 2002-03 and 2009-10 during the Millennium drought during late summer (outside of the time range displayed in Figure 28). Both of these latter periods were notable for extensive fires in southeastern Australia, of course.

Braidwood AWS DF and precipitation are presented in Figure 30 for the two months immediately preceding the fire. Interestingly, DF does not reflect the underlying significant dryness displayed by all JASMIN layers, even the shallowest 0-0.1 m layer, and by the FMC plot in Figure 28. While DF is an indicator of the availability of fine fuel to burn, rather than an indicator of soil moisture, the two quantities are related, and both provide information on the capacity of the landscape to support fire. The generally small but frequent bursts of precipitation in earlier weeks had been sufficient to keep DF calculation below 10, while not ameliorating the substantial underlying landscape dryness, or the satellite-measurement derived FMC.

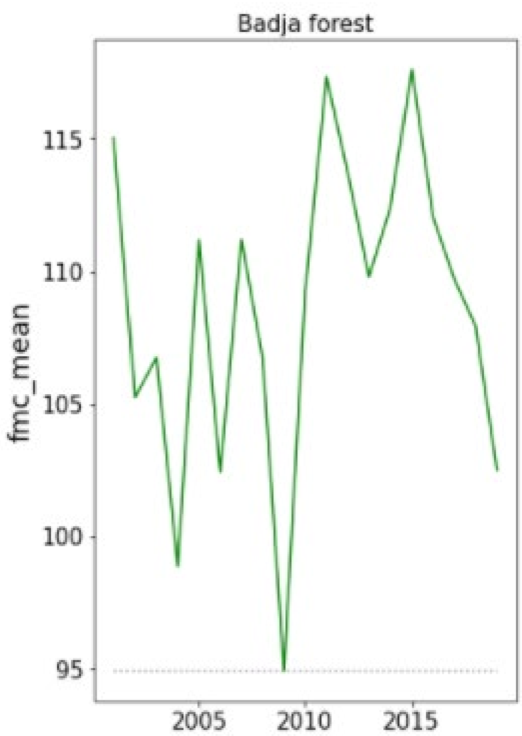


FIGURE 29: TIME SERIES OF ANNUAL AND FIRE AREA-AVERAGED FUEL MOISTURE CONTENT FOR BADJA FOREST.

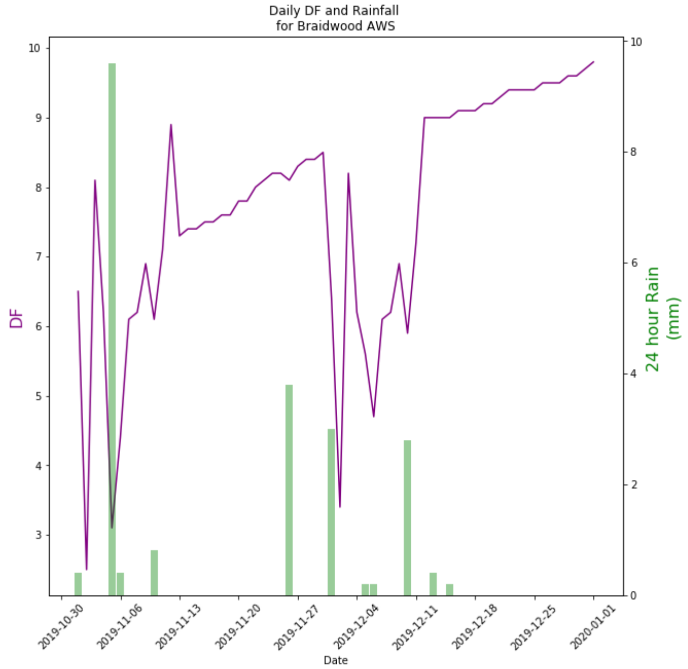


FIGURE 30: TIME SERIES OF THE DROUGHT FACTOR (PURPLE) AND PRECIPITATION (GREEN) AT BRAIDWOOD AWS FOR THE TWO MONTHS IMMEDIATELY PRIOR TO BADJA FIRE IGNITION.

Figure 32 displays EHF (as a measure of the occurrence of heatwaves) from selected grid points near Numeralla (in red) and Cooma (in green) in the top figure panel for the nine-month period from 01 July 2019. These sites were selected as being broadly representative of conditions in the vicinity of the fire ground. Two heatwave episodes are evident in the weeks leading to the Badja fire ignition, with a third occurring at the end of January 2020. Live fuel moisture content is displayed in the second panel, averaged over the fire ground. Individual observations are separated by several days, allowing for the satellite overpass interval. Notwithstanding the intermittency of the observations, the LFMC plot shows that subsequent to the late December heatwave events, live fuel moisture decreases more sharply that it had been doing prior to the heatwaves. Following the fire in January 2020, LFMC appears very low reflecting the burnt vegetation, prior to an apparent rapid increase in moisture content in the wake of substantial rainfall.

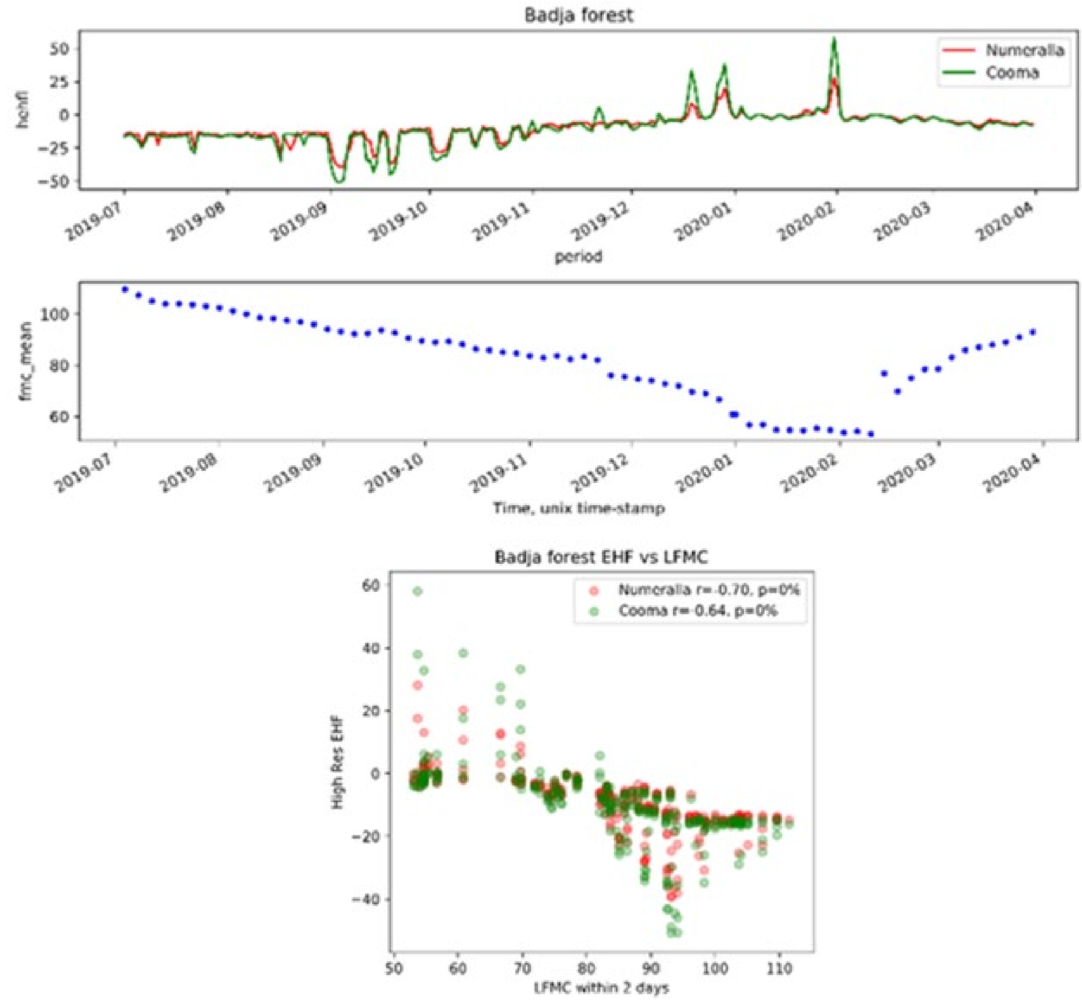


FIGURE 32: CORRELATION BETWEEN EHF AND FUEL MOISTURE CONTENT FOR BADJA FIREGROUND. TOP PANEL: EHF VALUES FOR TWO SITES NEAR THE FIREGROUND FROM JULY 2019 TO APRIL 2020. MIDDLE PANEL: FIRE AREA AVERAGED LFMC FOR THE SAME PERIOD. BOTTOM PANEL: PLOT OF EHF AGAINST FIRE AVERAGED LFMC FOR BOTH SITES, LISTING CALCULATED CORRELATIONS.

The third panel of Figure 32 plots LFMC values within two days of EHF calculations for Numeralla and Cooma, coloured as in panel one, and lists correlations calculated between LFMS and EHF. There are negative correlations (r of -0.70 and -0.64) between EHF and LFMC at the two sites, suggesting a relationship between the variables.

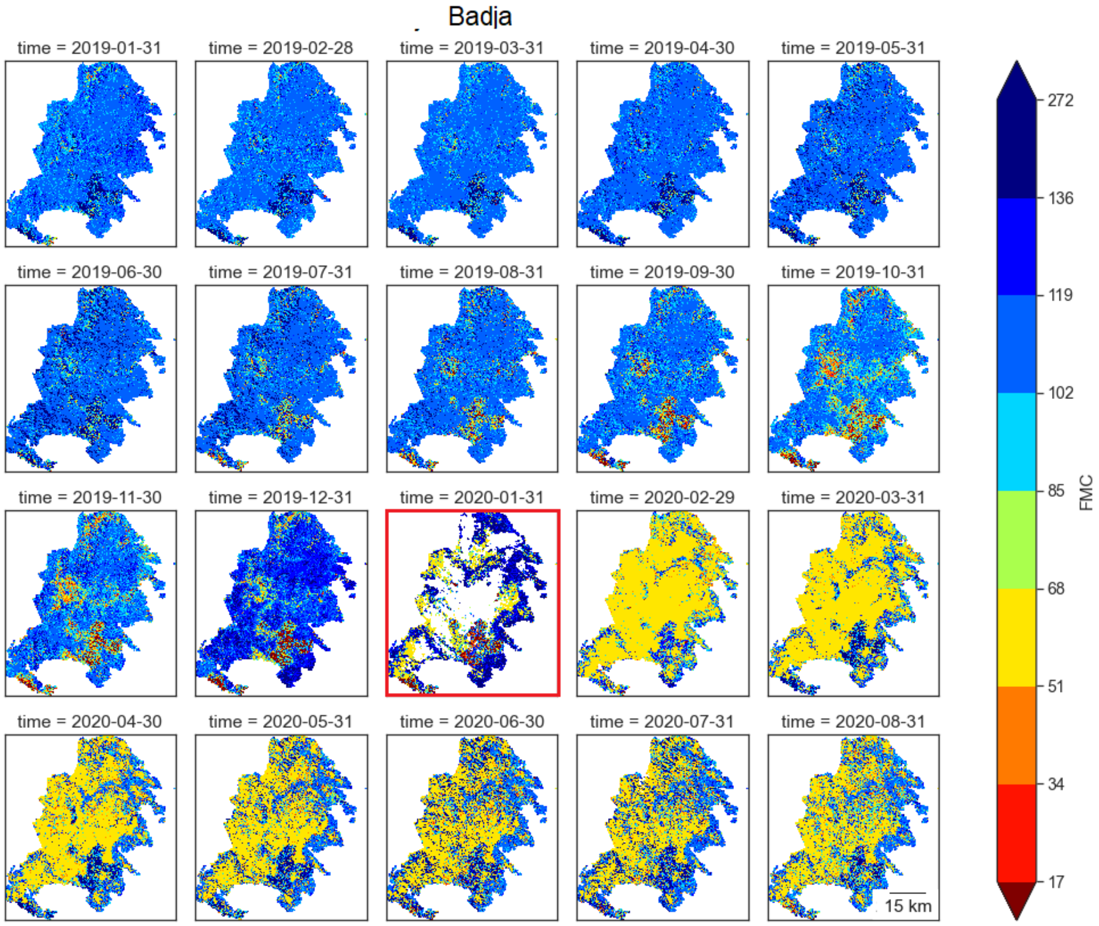


FIGURE 33: MAPS OF SPATIAL AND TEMPORAL VARIATION OF HIGH-RESOLUTION FMC (25M) OVER THE BADJA BURN AREA FROM SENTINEL-2 SATELLITE DATA. FUEL MOISTURE CONTENT IS MEASURED IN PERCENT, WITH HIGH MOISTURE CONTENT IN BLUE AND LOW MOISTURE CONTENT IN YELLOW/RED. HIGHLIGHTED IN RED IS THE MAP CLOSEST TO THE DATE THAN THE FIRE STARTED.

Maps of spatial variability through time of LFMC for Badja (Figure 33) show the development of patches of critically dry vegetation during the latter months of 2019. Initially, this driest region is limited to the southeast of the fireground but extends more widely by the end of 2019. Some missing data occurs during January 2020, likely due to the persistent presence of smoke. In February 2020 and onwards, the impact of the fire is clearly visible as a region of very dry vegetation.

In summary-, short- and long-term spikes in meteorological quantities occurred that were conducive to fire ignition and spread, so that annual and seasonal warming and drying trends were focused on a scale of days by the passage of cold fronts around the time of rapid fire development. Soil and fuel moisture levels integrated these influences, such that by December 2019 soil moisture had reached near historic low levels (as far as the record exists), and certainly lower than the previous two seasons. Fuel moisture content consequently dropped year on year from a 2016 high, with evidence that heat waves near the time of the fire contributed to this drying trend.

KANGAROO ISLAND

Broad-scale weather and climate context

Around the time of the Kangaroo Island fires in the first few days of January 2020, there was a persistent series of high-pressure systems near southern Australia associated with large-scale descent of air, leading to dry air and clear skies in general. A key feature associated with this, including in relation to variations in the severity of the fire weather conditions, is a trough and front system between the highs that passed over Kangaroo Island around the 3rd of January. This included the rapid intensification of a low-pressure system to the south that helped intensify the front (Figure 34), thereby contributing to strong northwesterly winds. These conditions then caused hotter and drier conditions around that time (Figures 35-37) due to advection of hot dry air from inland regions of the continent, resulting in large areas of South Australia exceeding 45 degrees on the 3rd of January.

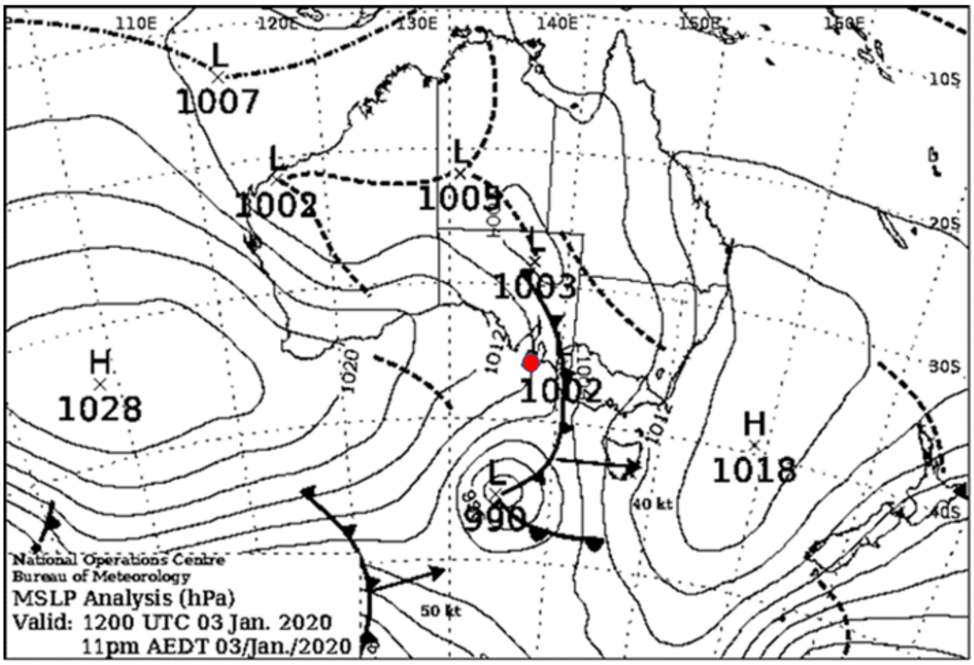


FIGURE 34: WEATHER SYSTEMS AROUND THE TIME OF THE KANGAROO ISLAND FIRES. THIS IS SHOWN FOR THE SYNOPTIC MSLP CHART PRODUCED BY THE BUREAU OF METEOROLOGY FOR 3RD JANUARY 2020, 1200 UTC. APPROXIMATE LOCATION OF KANGAROO ISLAND INDICATED BY RED DOT.

The influence of the weather systems described above can be seen when examining maps of the weather conditions, including for temperature and humidity as shown in Figures 35-38. This includes very hot conditions in the Kangaroo Island region, peaking on 3rd January for daily maximum temperature, with little recovery overnight as shown by relatively high minimum temperatures for both the 3rd and 4th of January shown here. The vapour pressure map also shows very dry air around this time, particularly for the 2nd and 3rd of January prior to the passage of the front over the fire ground. These are key factors that can influence fuel moisture conditions, with potential for drying that can lead to enhanced fuel availability for fire occurrence. In addition to these conditions around the time of the fire, the longer-term rainfall deficiencies were also a key contributing factor for fuel moisture content, noting the dry conditions over a range of time scales from months to years as shown in Figure 38. Fuel moisture and related factors are examined in more detail in the following sections for the Kangaroo Island fires.

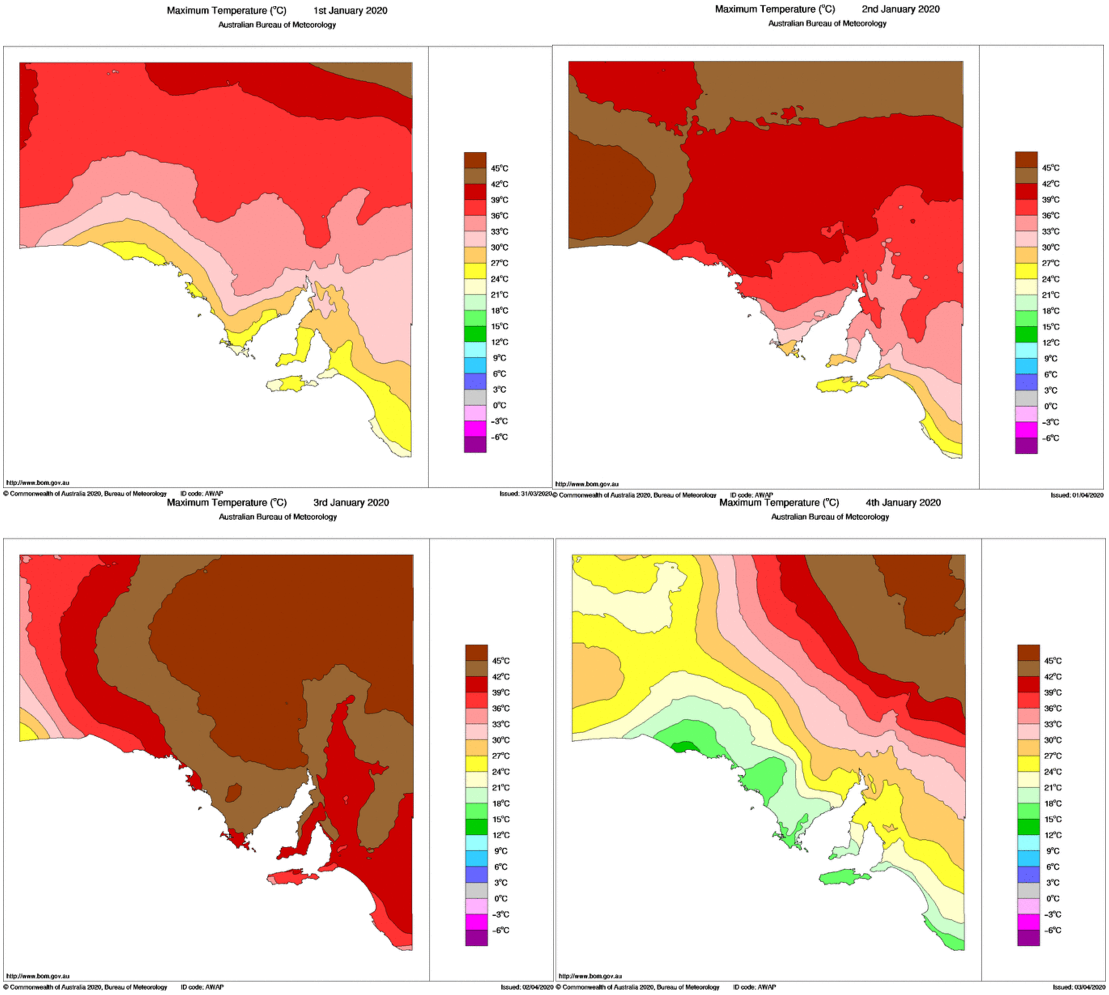


FIGURE 35: DAILY MAXIMUM TEMPERATURE FOR 1ST – 4TH JANUARY 2020.

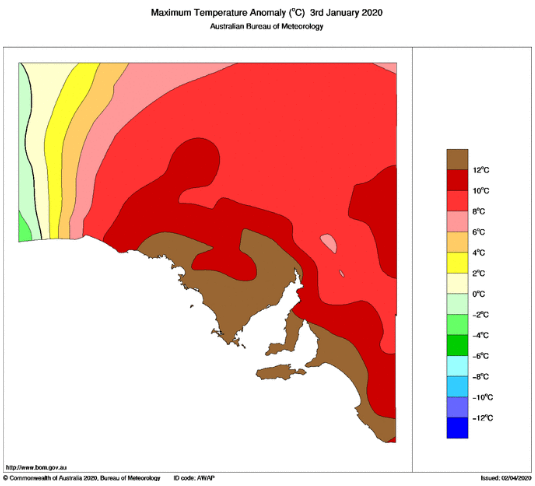


FIGURE 36: DAILY MAXIMUM TEMPERATURE ANOMALY ON 3RD JANUARY 2020.

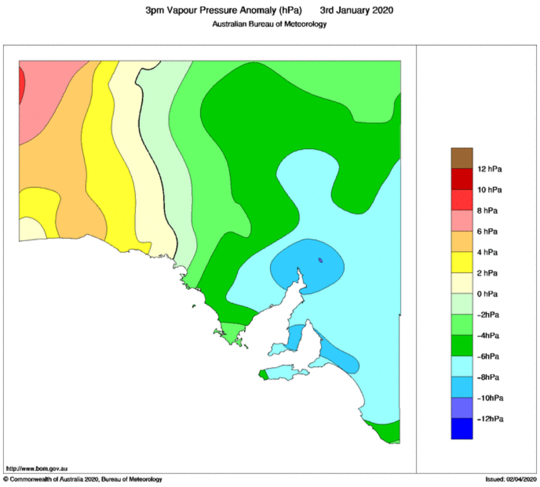
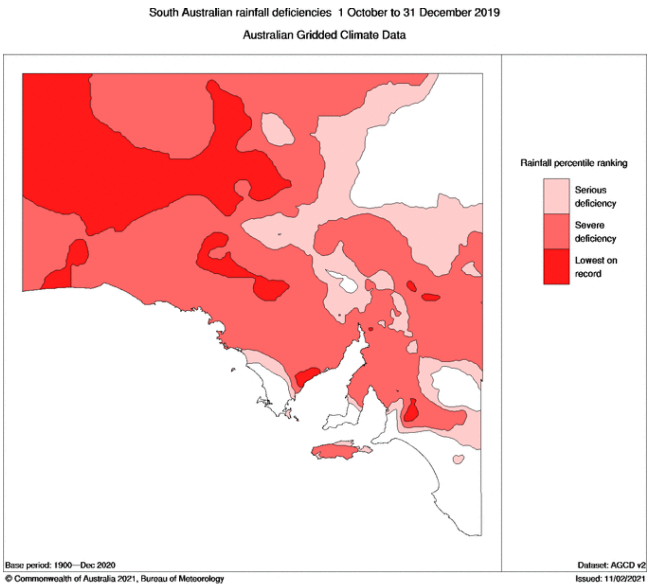
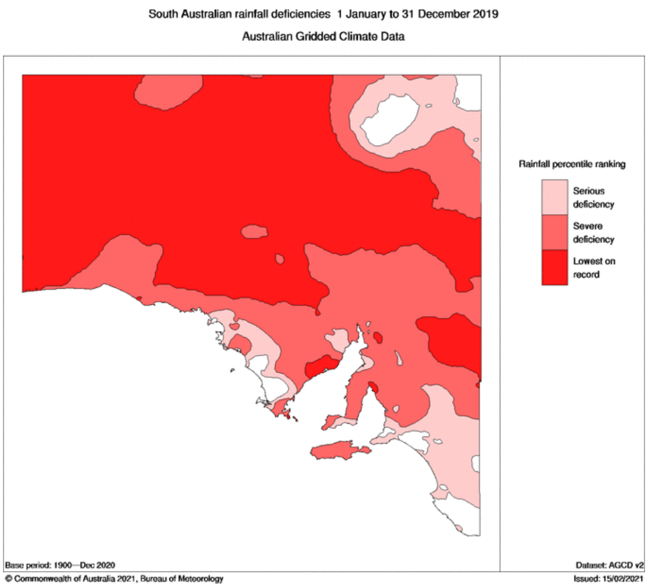


FIGURE 37: VAPOUR PRESSURE ANOMALY FOR SOUTH AUSTRALIA FOR 3RD JANUARY 2020 AT 3 PM LOCAL TIME (WITH DAYLIGHT SAVINGS).





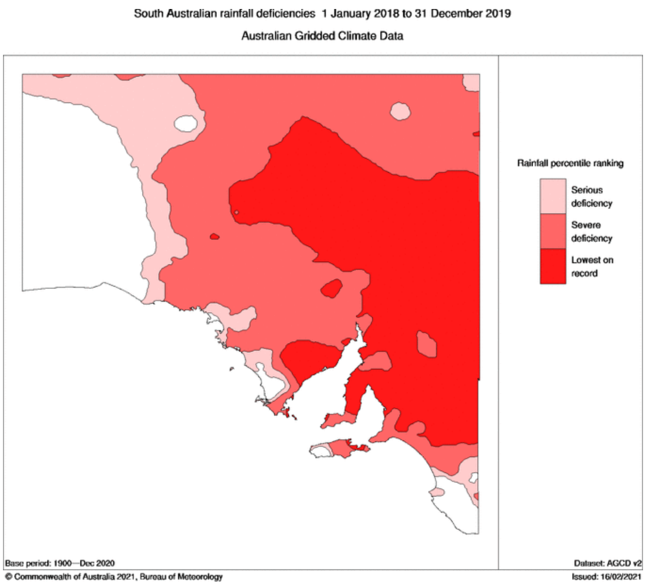


FIGURE 38: RAINFALL ANOMALIES FOR SOUTH AUSTRALIA, SHOWN FOR OCTOBER-DECEMBER 2019 (UPPER PANEL), THE YEAR OF 2019 (MIDDLE PANEL) AND THE YEARS 2018-2019 (LOWER PANEL).

Multi-year development of conditions suitable for landscape fires (drought)

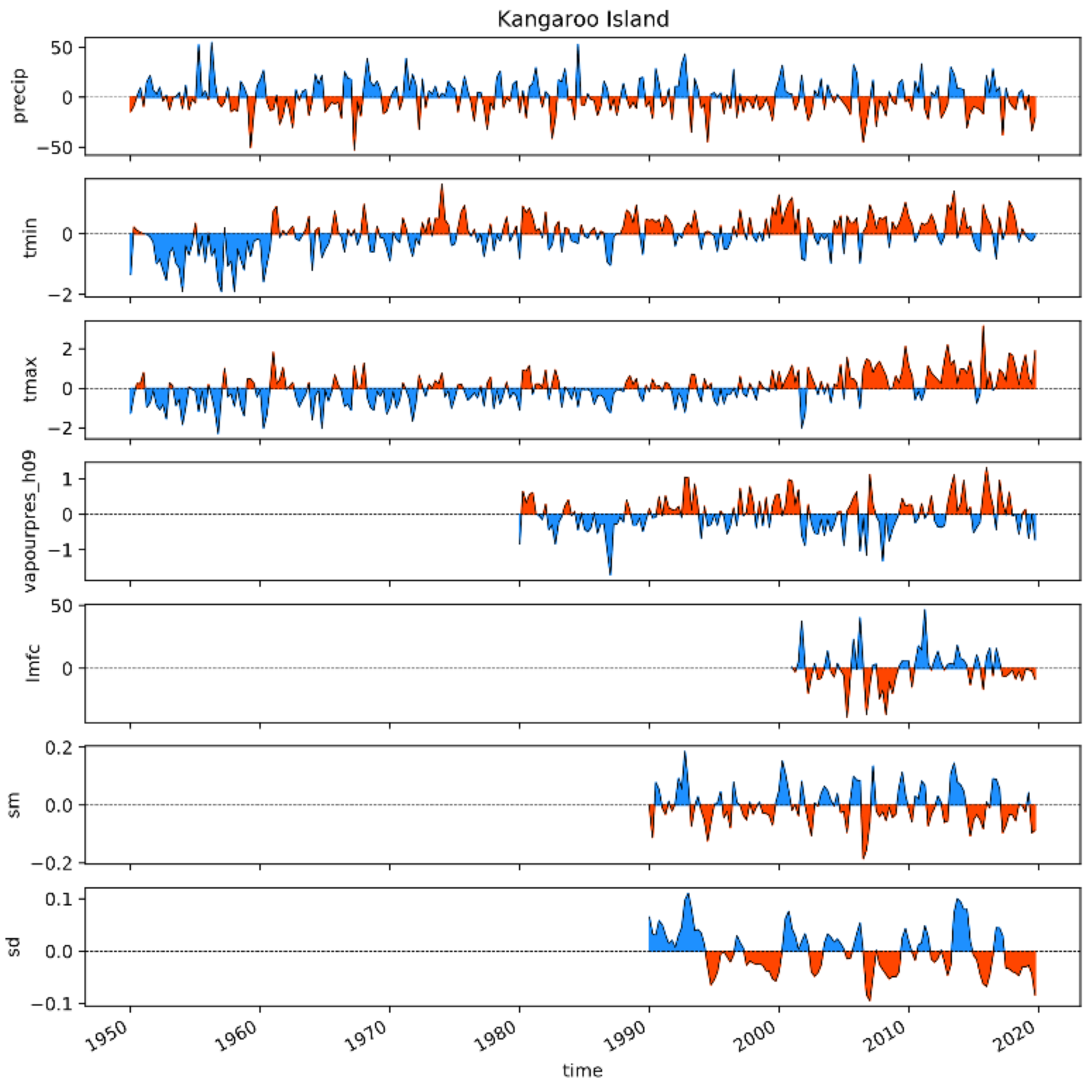


FIGURE 39: TIME SERIES OF 3-MONTHLY ANOMALIES OF METEOROLOGICAL VARIABLES AND SOIL AND FUEL MOISTURE FOR KANGAROO ISLAND.

The time series of anomalies for Kangaroo Island (Figure 39) displays interesting similarities and differences to that of the previous two continental, east coast fire events, Stanthorpe and Badja. In particular, antecedent precipitation deficit and minimum and maximum temperature anomalies were similar, as described in the synoptic summary above, but of a smaller magnitude. As a result, soil moisture deficits were less extreme, and FMC anomaly especially, while negative, was much smaller. Live fuel moisture deficit was considerably less extreme than was the case around the time of, and prior to, the December 2007 Kangaroo Island fires.

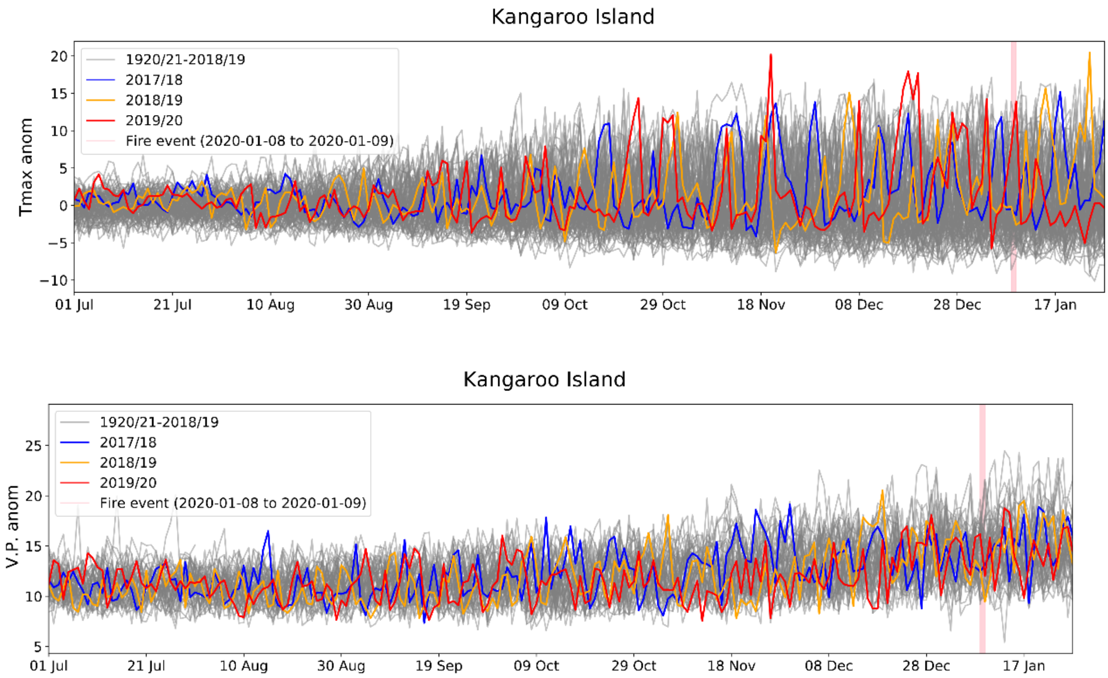
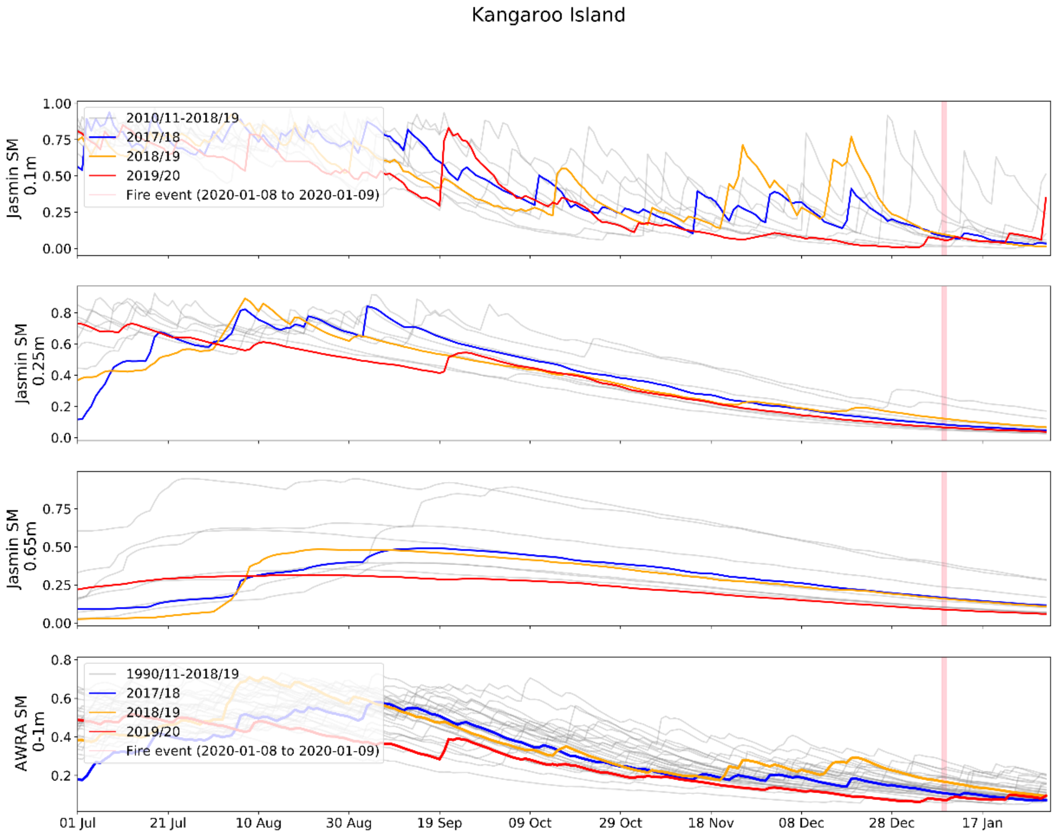


FIGURE 40: TIME SERIES OF MAXIMUM TEMPERATURE (DEGREES C, TOP) AND 0900 VAPOUR PRESSURE (HPA, BOTTOM) ANOMALIES FROM 1 JULY TO 31 JANUARY FOLLOWING, FOR EACH AVAILABLE YEAR. THE PEAK PERIOD OF FIRE ACTIVITY IS HIGHLIGHTED WITH A VERTICAL PINK BAR.

Time series of maximum temperature and 9 am vapour pressure anomaly for Kangaroo Island again show there weren't extended extremes of either variable during the latter months of 2019 in comparison to previous years. There were several short-term spikes of heat during December 2019 in the weeks immediately preceding the fire ignition and the mean maximum temperature during the period was higher than immediately preceding years but not exceptionally so.

Figure 41 shows that the integration of these factors via the soil and fuel moisture (together with the limited precipitation deficit) resulted in deficits of soil moisture that were slightly lower than the immediately preceding years. Similarly, fuel moisture was comparable to previous years. A steep dip in observed fuel moisture in early January is very likely a consequence of the fires themselves.



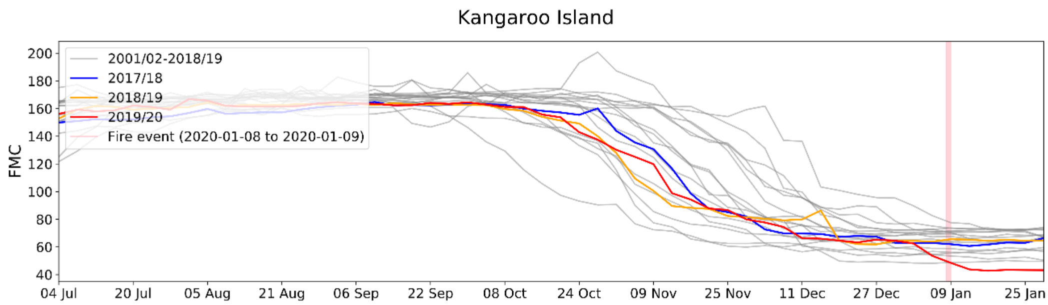


FIGURE 41: TIME SERIES OF SOIL AND FUEL MOISTURE AS PER FIGURE 17.

Examination of the time series of annual average fuel moisture (Figure 42) shows that previous years had experienced lower fuel moisture. As above, the strong dip to low levels in 2007, while reflective of low actual values, should also be considered contaminated by the 2007 Kangaroo Fire which occurred over a similar but smaller area than in early 2020. On the other hand, DF (Figure 43) was generally close to 10, apart from immediately following brief periods of rainfall in November and early December.

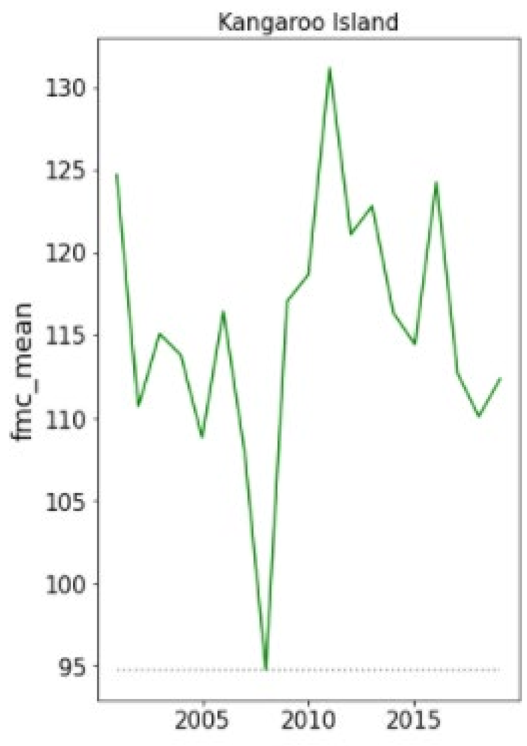


FIGURE 42: TIME SERIES OF ANNUAL AND FIRE AREA-AVERAGED FUEL MOISTURE CONTENT FOR KANGAROO ISLAND.

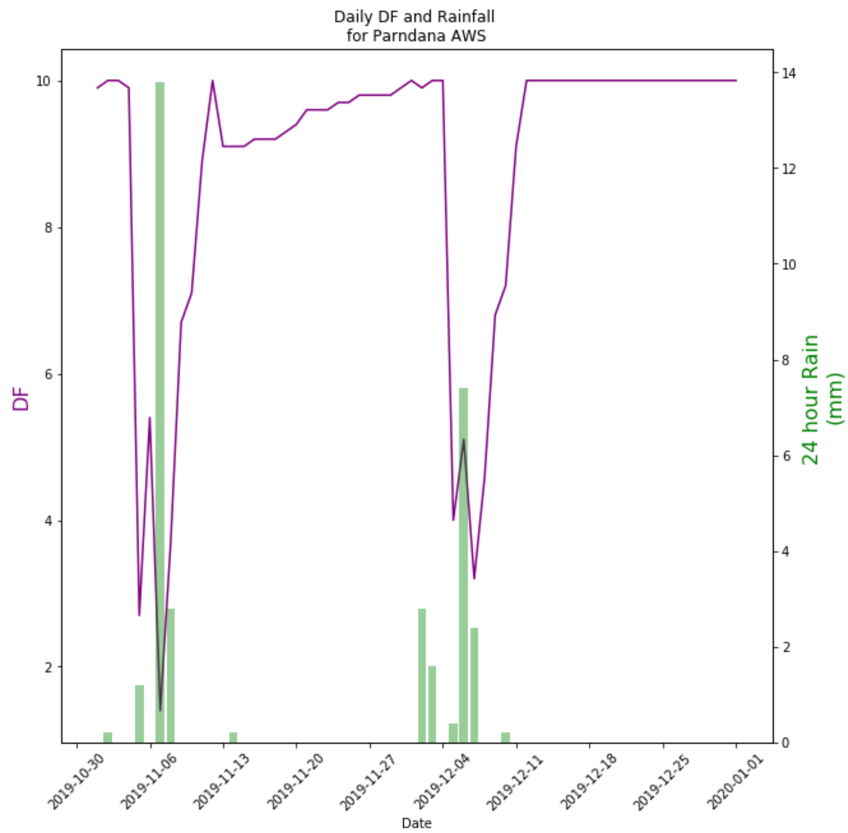


FIGURE 43: TIME SERIES OF THE DROUGHT FACTOR (PURPLE) AND PRECIPITATION (GREEN) AT PARNDANA AWS FOR THE TWO MONTHS IMMEDIATELY PRIOR TO KANGAROO ISLAND FIRE IGNITION.

Plots of spatial variation of JASMIN soil layers (not shown) indicate that, consistent with earlier plots, the extent of soil moisture deficit was not as great as earlier cases. The nature of the variability was different, however, and prompted an investigation of the underlying land surface model characteristics.

Exploring uncertainty and processes in JASMIN data

In this project, we use soil moisture products from JASMIN and AWRA-L to investigate land-surface dryness prior to these fires. The models used in generating these products are different in many aspects, with JASMIN products being generated by land-surface model JULES (Dharssi and Kumar 2017) while AWRA-L uses a landscape water balance model (Frost et al. 2016). In general, there are three key components determining the quality of these products: (i) the parameterisation of physical processes controlling water and energy cycles in these models; (ii) the soil and vegetation parameters used by these models; (ii) the meteorological forcing data used to drive the models. Therefore, when we use soil moisture products for specific events at particular locations, we need to explore uncertainties in these model-based results. This helps the end-users to gain the necessary knowledge about the potential errors in these products for their operational applications. It can also provide some insights for potentially producing multi-model or blended products in the future. While thoroughly exploring the full aspects of these sources of uncertainties and evaluating processes represented in these models is an ongoing research task, in this project we have started to explore sensitivity of JASMIN to soil and vegetation parameters used in its configuration, study physical processes governing its soil moisture variations at different depths. The knowledge gained from such analyses will be value for the Bureau's future development of integrated and seamless hydrological modelling system and water information products based on JULES with enhanced hydrological components (hydro-JULES).

In addition to assess model sensitivity to parameters, we started to explore whether some physical processes represented in the land-surface model can be applicable for studying fires. For example, to realistically represent surface energy and water cycles, land-surface models such as JULES need to capture the fundamental process about how vegetation responses to soil water limits – a key process termed vegetation transpiration. In JULES, evapouration from transpiring vegetation is controlled by canopy conductance which is calculated by a photosynthesis model depending on temperature, humidity deficit, incident radiation, soil moisture availability, vegetation type and root depth/density. If vegetations are supported by abundant water in its root zone, its growth would be promoted, with greener leaves and higher water content and likely to produce higher transpiration. If the root-zone soil water content reaches its wilting point, then the amounts of water accessible for vegetation will be very limited, further transpiration from vegetation leads to drier canopies, and vegetation leaves will be less green and become "wilting". This clearly has a close connection with our study of vegetation conditions prior to bushfires.

As documented in Best et al. (2011), the vegetation transpiration flux extracted from each soil layer k is determined by a beta factor obtained as:

$$\beta_k = \begin{cases} 1 & \theta_k \geq \theta_c \\ (\theta_k - \theta_w)/(\theta_c - \theta_w) & \theta_w < \theta_k < \theta_c, \\ 0 & \theta_k \leq \theta_w \end{cases}$$

In this expression, θk is unfrozen volumetric soil moisture content at level k, θc is soil moisture critical point in JULES below which vegetation starts to have water stress in its transpiration. Θw is the wilting point which is the minimum amount of water in the soil that the plant requires not to wilt. Therefore, the beta factor is an important parameterisation in representing vegetation transpiration responses to soil water limit in JULES. Therefore, the beta factor analysis can provide a link between processes represented in JULES and a product used for fire studies.

Using the KI event as an example, here we examine some detailed features in the JASMIN soil moisture product over the island. Firstly, there are significant spatial variations of vegetation and soil properties over the island. Figure 44 shows the fractions of broadleaf forest, C3 grass used in the JASMIN system within each of its 5kmx5km grid box. Figure 45 shows the spatial distribution of two important properties in calculating the beta factor: critical point and wilting point.

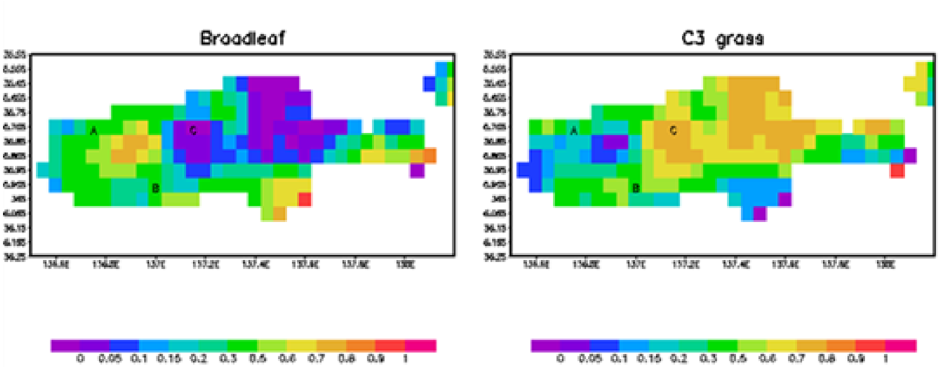


FIGURE 44: THE FRACTION OF TWO DOMINANT VEGETATION TYPES USED IN JASMIN OVER THE 5X5KM MODEL GRID BOX OVER KI.

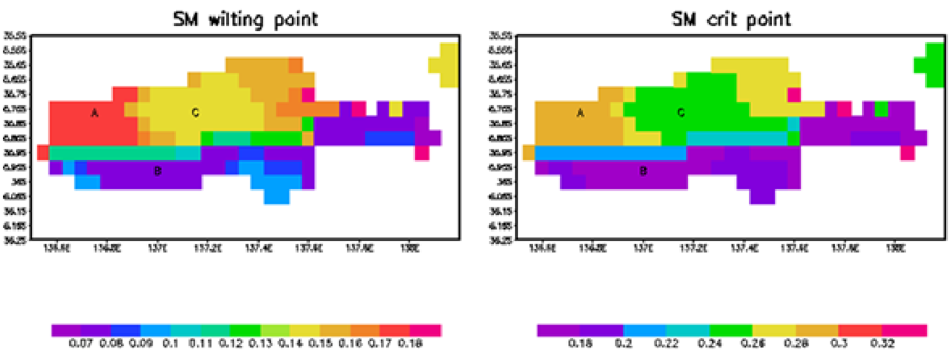


FIGURE 45: THE VOLUMETRIC SOIL MOISTURE CONCENTRATION AT CRITICAL POINT (M3/M3) AND WILTING POINT (M3/M3) OVER KI AS USED IN JASMIN. SEE THE TEXT FOR DETAILED DESCRIPTIONS OF SYMBOLS A, B AND C.

From these two figures we can see significant spatial variations of soil and vegetation properties across the island. The combination of these two would yield even larger spatial variations of soil moisture in its simulations. We need to assess to what extent its soil moisture products can vary in a domain close to the burning area with varying soil and vegetation properties. For this purpose, we have selected three locations shown as "A", "B" and "C" in Figures 44 and 45.

Location A:	136.75E 35.75S	Wilting Point = 0.174345; Critical Point = 0.283797
Location B:	137E 35.95S	Wilting Point = 0.071432; Critical Point = 0.16605
Location C:	137.15E 35.75S	Wilting Point = 0.148833; Critical Point = 0.255943

TABLE 1: WILTING POINT AND CRITICAL POINT VALUES FOR THE THREE LOCATIONS SHOWN IN FIGURES 44 AND 45.

Combining the information from the two Figures and Table 1, one can see that locations A and B share similar vegetation properties (both dominated by broadleaf forest) but very different soil parameters (A has much higher wilting and critical point than B which is dominated by sandy soil), while A and C share similar soil properties but very different vegetation coverage (location C is dominated by C3 grass).

Figure 46 examines the volumetric soil moisture content at the top two layers (SM1 for layer 0-0.1m, SM2 for 0.1-0.35m) for the three locations during the three years by including year 2018 for prior bushfire conditions and 2020 for post bushfire conditions. As showed before, an overwhelming feature for the top thin layer is the continuous drying trend from 2018 through to the end of 2020. While soil water content at Site B (sandy soil) is much lower than the other two, the overall trends are similar. This can be understood as such that soil moisture at the top thin layer primarily responses to similar meteorological forcing over this area. For the subsurface layer 0.1-0.35m and deeper layer (0.35-1m), a notable feature is that there is a sub-surface soil moisture recharge-discharge process operation in its soil hydrology. Following its dry summer season there is often a sub-surface soil water recharge during the following cool season in June to October/November after receiving its cool season rainfall. However, a clear feature shown in Figure 47 is that for year 2019, the recharge process was much weaker compared with year 2018 and 2020. This feature is evident in all the three sites, but the patterns in location A and B are closer than in Site C which is dominated by grass. The results suggest that while soil properties dominate the soil moisture quantities in JULES, the vertical soil water movement and the vegetation-soil interactions are largely affected by vegetation properties.

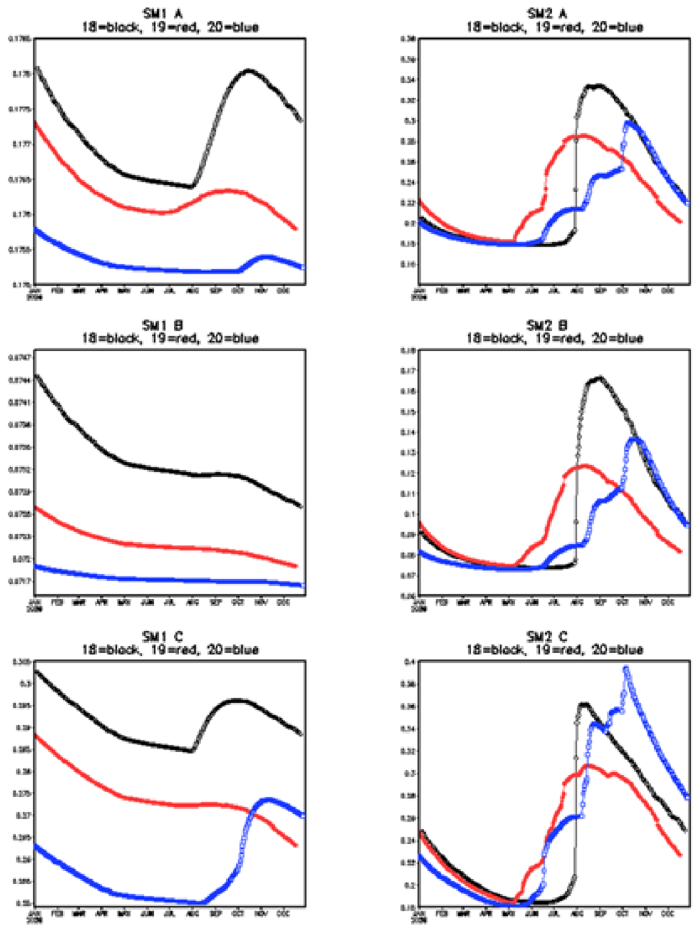


FIGURE 46: JASMIN DAILY (FROM 1ST JAN TO 31 DECEMBER) VOLUMETRIC SOIL MOISTURE CONTENT (M3/M3) AT THE TOP TWO LAYERS (SM1 FOR LAYER 0-0.1M, SM2 FOR 0.1-0.35M) AT THE THREE LOCATIONS SHOWN IN FIGURE 44 FOR THREE YEARS: BLACK LINES FOR 2018, RED LINES FOR 2019 AND BLUE LINES FOR 2020.

Furthermore, Figure 47 shows the beta factor derived from the JASMIN soil moisture data. We show the thickness-weighted averages for the top 0.35m (derived from layers 0-0.1m and 0.1-0.35m), and for top 1m (derived from layers 0.-0.1, 0.1-0.35, 0.35-1m). We concentrate on the comparisons across the three locations for year 2018 and 2019. The beta factor results show a very clear feature that the forest was very stressed even during its cool and wet season in year 2019 for the two forest sites (A and B), while for the grass site the beta factor remained largely similar. For example, for the beta factor of top 0.35m thickness, its value dropped from 1 (unstressed) to 0.7 (stressed) for site A, and from about 0.7 (stress) to 0.3 (highly stressed) for site B. The already stressed forest was then further stressed throughout the early summer leading to the bushfire season. The beta factor results are consistent with the analysis of LFMC as presented earlier. Therefore, in addition to the use of JASMIN soil moisture products for fire dryness and fuel load studies, the land-surface model JULES can be potentially used for studying some details of fire potential.

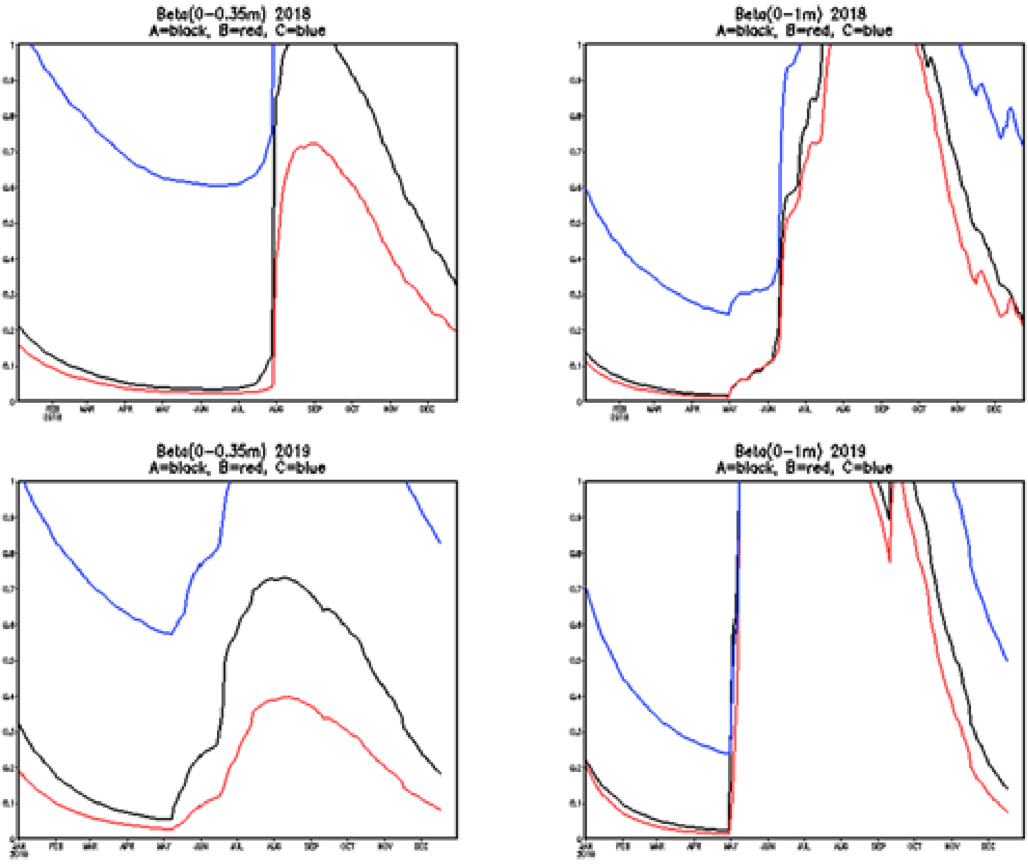


FIGURE 47: THE JASMIN SOIL MOISTURE BETA FACTOR FOR YEAR 2018 AND 2019 AT THE THREE LOCATIONS (BLACK LINE FOR LOCATION A, RED LINE FOR LOCATION B AND BLUE LINE FOR LOCATION C) AT SOIL LAYER 0-0.35M (LEFT COLUMN) AND 0-1M (RIGHT COLUMN).

We return to the investigation of the potential impact of heatwaves on preconditioning fuels ahead of fire ignition. In the case of Kangaroo Island, three locations were chosen from the gridded EHF dataset to represent the occurrence of heatwaves.

There are negative correlations (r around -0.50) between EHF and fuel moisture content at the three Kangaroo Island AWS (Capes Willoughby and Borda and at Kingscote) for the seven-month period from 01 July 2019 for Kangaroo Island (Figure 48). Time series and scatter plots show the occurrence of a heatwave at the three AWS contributing to the decline in fuel moisture, particularly immediately following the two significant heatwave events grouped close together in late December 2019. We note that the fire itself may be affecting the average FMC recorded, for the period following ignition. This is worth investigating further, were there to be related follow-on research on this fire.

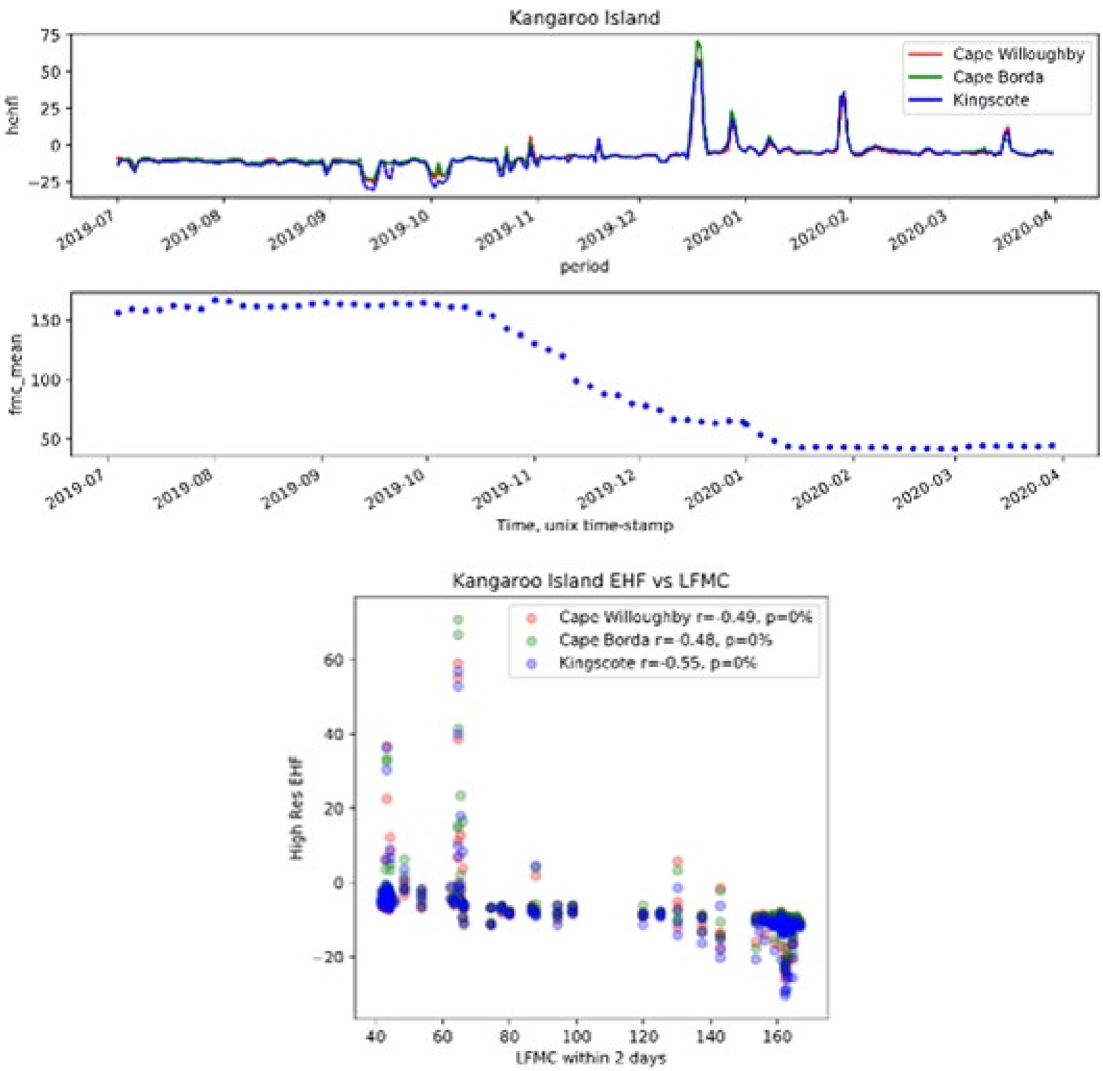


FIGURE 48: CORRELATION BETWEEN EHF AND FUEL MOISTURE CONTENT AT KANGAROO ISLAND. TOP PANEL: EHF VALUES FOR THREE SITES NEAR THE FIREGROUND FROM JULY 2019 TO APRIL 2020. MIDDLE PANEL: FIRE AREA AVERAGED LFMC FOR THE SAME PERIOD. BOTTOM PANEL: PLOT OF EHF AGAINST FIRE AVERAGED LFMC FOR ALL SITES, LISTING CALCULATED CORRELATIONS.

High resolution FMC maps through time for the Kangaroo Island fire area (Figure 49) highlight subtle variations of moisture content associated with seasonal progression and the occurrence of intermittent precipitation. A rapid transition in condition of vegetation is obvious with the occurrence of the fire in January 2020 (due to burning or scorching of leaves etc), followed by a gradual recovery. While there were variations during December in the vegetation moisture content over the area in the north-east (that mapping suggest is mainly dominated by shrublands and grasslands) which the fire later impacted, the more moist pockets of vegetation were clearly insufficient to prevent the subsequent spread of the fire. (We note here that some caution is required, as this region may also contain grassland, with a greater dynamic range in FMC variation. Also, FMC values displayed as lower than 105% in forests will not inhibit fire progression.)

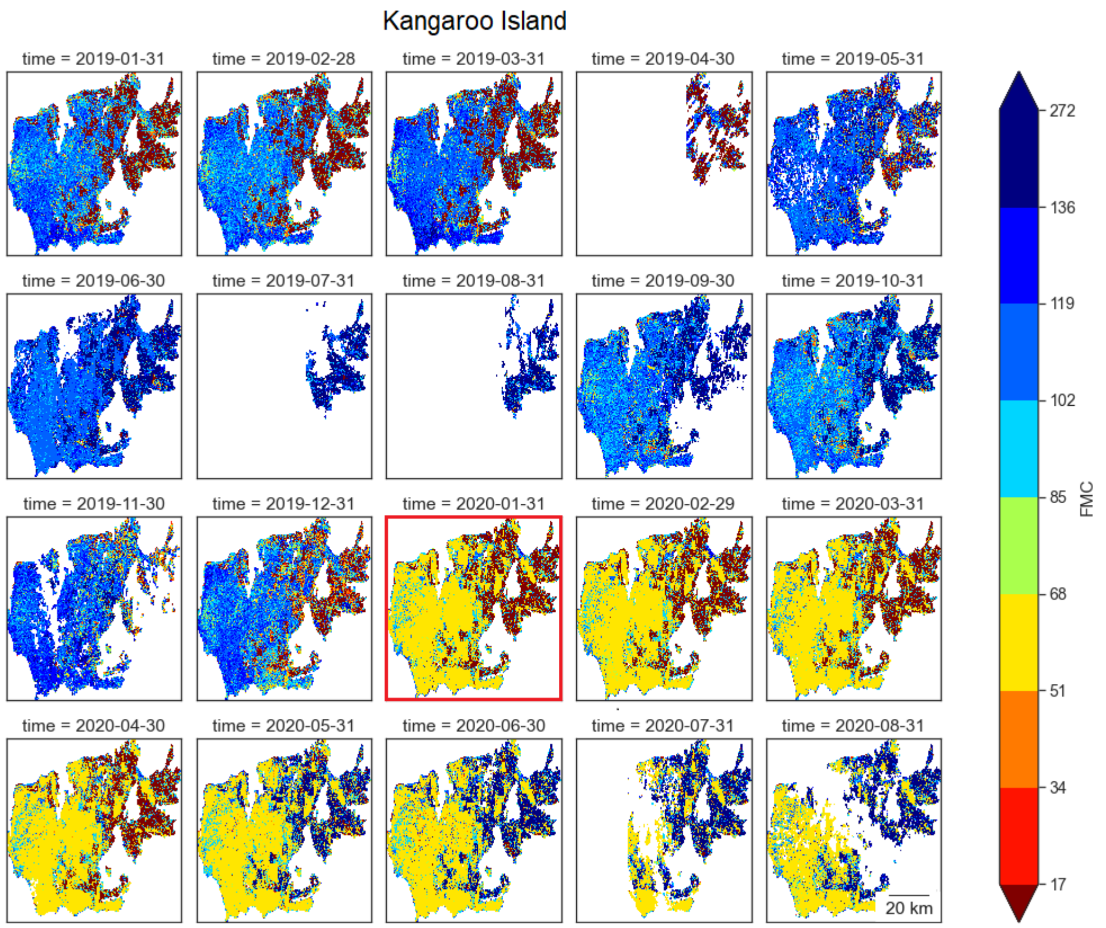


FIGURE 49: MAPS OF SPATIAL AND TEMPORAL VARIATION OF HIGH-RESOLUTION FMC (25M) OVER THE KANGAROO ISLAND BURN AREA FROM SENTINEL-2 SATELLITE DATA. FUEL MOISTURE CONTENT IS MEASURED IN PERCENT, WITH HIGH MOISTURE CONTENT IN BLUE AND LOW MOISTURE CONTENT IN YELLOW/RED. HIGHLIGHTED IN RED IS THE MAP CLOSEST TO THE DATE THAN THE FIRE STARTED. NOTE SOME DATA IS MISSING DUE TO CLOUD INTERFERENCE, PARTICULARLY DURING THE COOLER MONTHS.

In summary, with a different vegetation matrix to the east coast fires, Kangaroo Island responded differently to the dry and warm conditions experienced over the period preceding the fire, noting that antecedent precipitation deficits were not as extreme as experienced in eastern Australia. Hot, dry conditions prevailed around the time of the fire consistent with the other fire events, as identified in the synoptic setting for the event. Soil moisture was low prior to the fire, but not dramatically lower than the previous two seasons, while fuel moisture content was unexceptional. Again, there is some evidence that hot conditions contributed to fuel drying immediately prior to the period of fire ignition and rapid spread Characteristics of the land surface model underlying JASMIN were examined in some detail to identify key aspects affecting variability of JASMIN across the landscape.

CORRYONG

Broad-scale weather and climate context

This event had a high severity of fire weather conditions and observed fire behavior around 30th – 31st December 2019, which coincides with this period already presented for the Badja case above, showing the high-pressure system in the Tasman Sea and approaching cold front and trough from the southwest (Figure 22). This caused very hot and dry air in the Corryong region particularly on the 30th (Figure 50-51) with somewhat cooler conditions on the 31st. It is also noted that the temperature anomaly is so large on the 30th it exceeds the 12-degree maximum on the standard Bureau mapping tool throughout virtually all of Victoria (apart from the far eastern tip). Relating to this, the influence of extremely hot temperatures combined with low vapour pressure leading is noted as a key factor for reducing fuel moisture content, based on contributing to low relative humidity (vapour pressure deficit). In addition to these extreme temperatures and dry air leading up to this fire event, many locations in the fire-affected areas experienced their driest year on record in 2019 since at least 1900, as well as record rainfall deficits over longer time periods such as for the 2-year period for 2018-2019 (Figure 55).

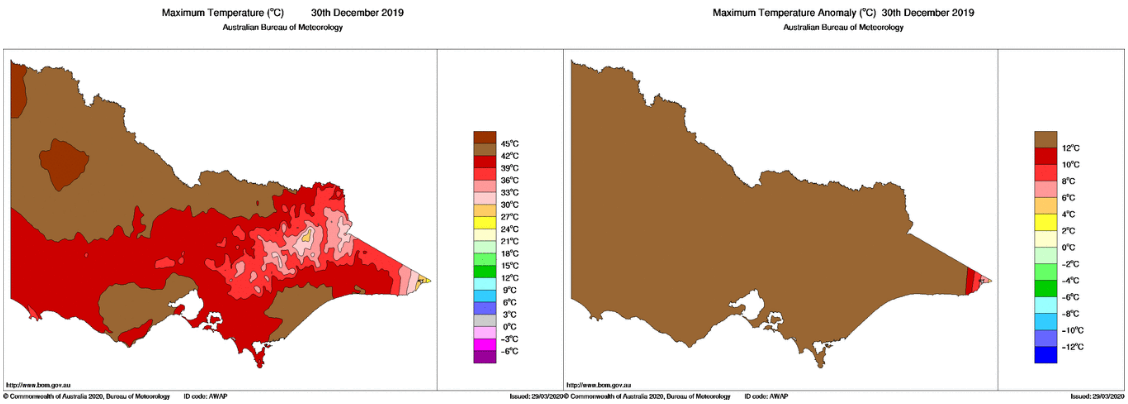


FIGURE 50: DAILY MAXIMUM TEMPERATURE (LEFT PANEL) AND DAILY MAXIMUM TEMPERATURE ANOMALY (RIGHT PANEL) FOR 30TH DECEMBER 2019.

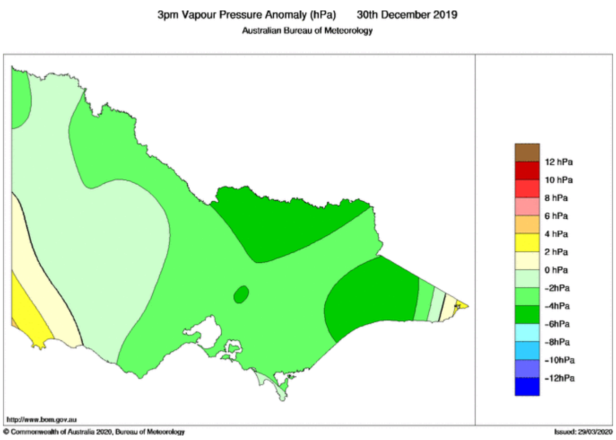


FIGURE 51: VAPOUR PRESSURE ANOMALY ON 30TH DECEMBER 2019 AT 3 PM LOCAL TIME.

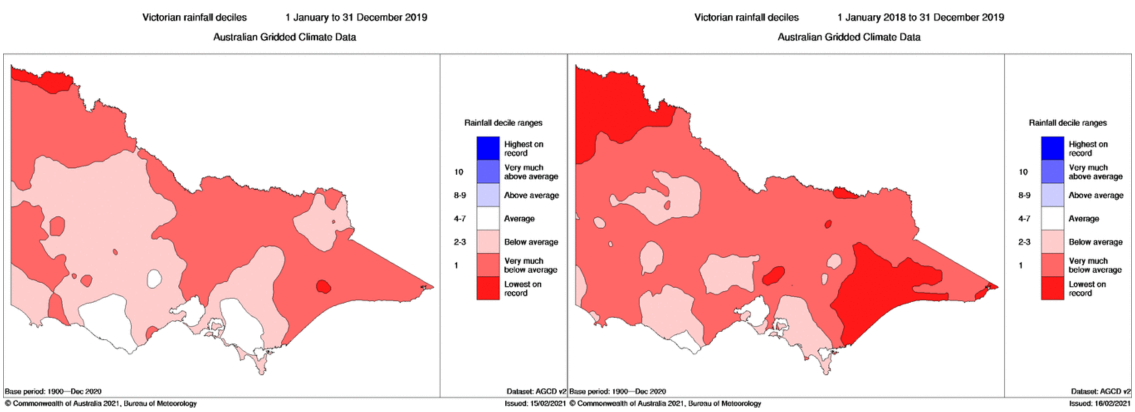


FIGURE 52: RAINFALL ANOMALIES FOR 2019 LEADING UP TO THE CORRYONG FIRES IN VICTORIA (LEFT PANEL), AS WELL AS FOR THE 2-YEAR PERIOD 2018-2019 (RIGHT PANEL).

Multi-year development of conditions suitable for landscape fires (drought)

Time series of relevant atmospheric parameters, averaged over the final boundary of the fire, are displayed below (Figure 53). Trends of increasing maximum and minimum temperature are clearly evident. This trend can also be seen in 0900 vapour pressure, reflecting the greater capacity of the atmosphere to hold water. Precipitation, AWRA-L root-zone (sm) and deep (sd) soil moisture and fuel moisture content all highlight the occurrence of the Millennium drought, 2010-2012 La Niña, 2016 heavy rainfall and subsequent drought periods, as described in the synoptic summary above. Notably, the signal of the Millennium drought was stronger in all of these fields than that of the 2017-2019 drought.

Figure 54 highlights the temperature anomaly for the latter half of 2019 through January 2020 (red) in comparison with the same period in 2017 (blue), 2018 (yellow) and all years 1920-21 to 2018-19. It can be seen that 2017-18 was generally warmer than the ensemble of previous years for this period, and 2018-19 was warmer again, containing arguably six events from October through January in which the temperature was close to or higher than previous such days. 2019-20, however, contained no fewer than 12 such peaks during the same period, with three in late November through early January exceeding temperatures on the same calendar day in earlier years. Interestingly, on the other hand, both 2018 and 2019 contained days in late November-early December close to the lowest in the plotted record.

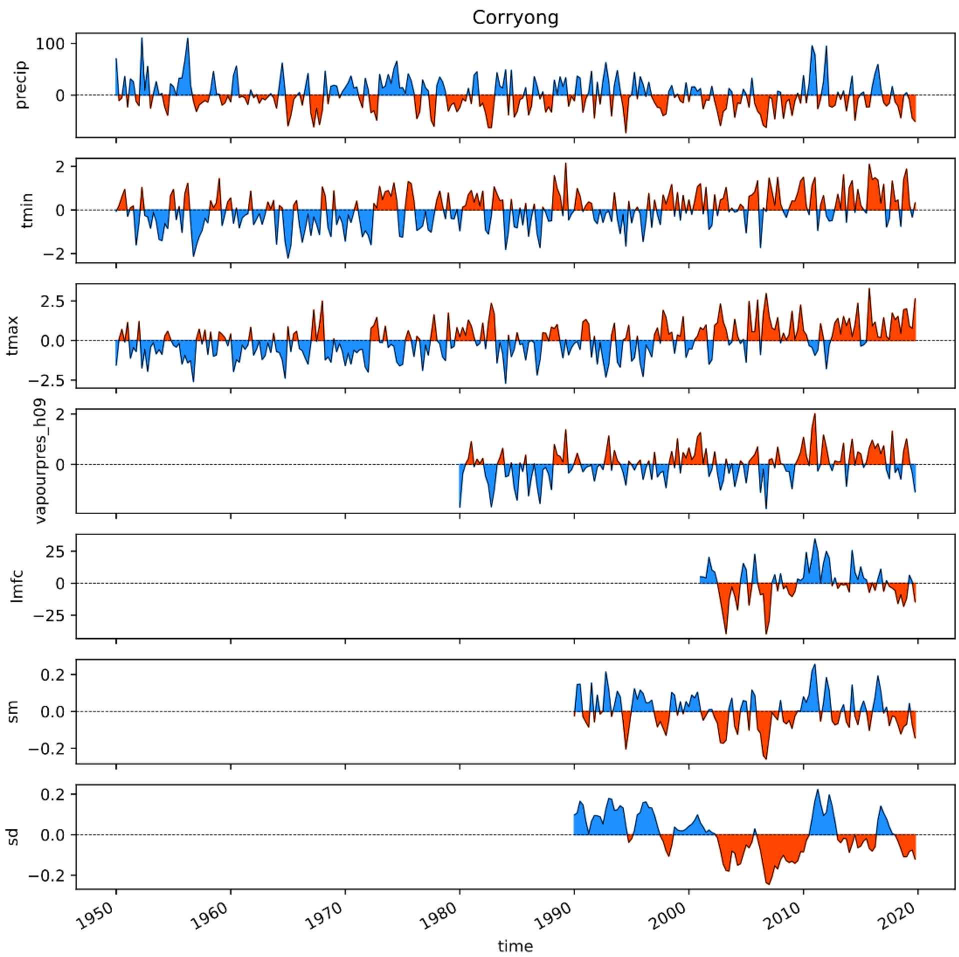


FIGURE 53: TIME SERIES OF 3-MONTHLY ANOMALIES OF METEOROLOGICAL VARIABLES AND SOIL AND FUEL MOISTURE FOR CORRYONG.

A similar analysis is presented for JASMIN and AWRA-L in Figure 55, noting that the period of record is much shorter, of course. Soil moisture will be influenced by (and influences) maximum temperature and precipitation, so it is unsurprising to find parallel trends in the soil moisture data when compared to precipitation and (maximum) temperature. We present the three top layers of JASMIN soil moisture (0-10 cm, 10-35 cm and 35-100 cm), together with AWRA-L root-zone soil moisture (0-1 m), with recent seasons colored the same as the previous plot for consistency and ease of interpretation. The period of peak fire activity is again denoted by a vertical pink line in the plots.

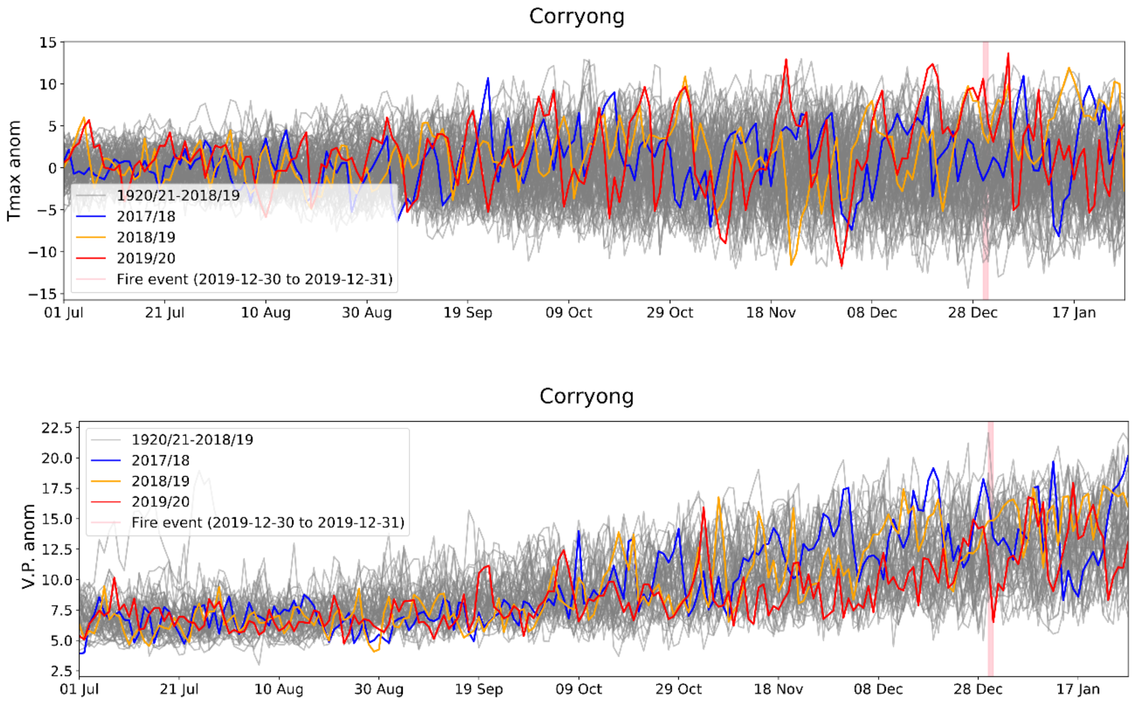


FIGURE 54: TIME SERIES OF MAXIMUM TEMPERATURE (DEGREES C, TOP) AND 0900 VAPOUR PRESSURE (HPA, BOTTOM) ANOMALIES FROM 1 JULY TO 31 JANUARY FOLLOWING, FOR EACH AVAILABLE YEAR. THE PEAK PERIOD OF FIRE ACTIVITY IS HIGHLIGHTED WITH A VERTICAL PINK BAR.

At each level and for both measures (JASMIN and AWRA-L, Figure 55), it can be seen that, ahead of the fire occurrence, 2017 and 2018 have comparable levels of soil moisture, varying as precipitation events occur. Generally, they are comparable also to earlier seasons, although the lowest JASMIN layer indicates lower soil moisture content than average for 2017, and lower still for 2018. Importantly, however, 2019, is markedly lower than 2017 and 2018 and all other season in the weeks leading to the fire and for much of the previous month. One exception to this occurs in the AWRA-L plot, for which a longer time series is available than for JASMIN. In terms of FMC, 2018-2019 had lower moisture content than 2019-2020 up to the middle of November but then 2019/2020 became drier. There is only one other season that had drier values than these two.

These trends are visible in the plot of annually and fire-area averaged FMC (Figure 56). Again, only one season had lower fuel moisture content than 2019, leading into the fires. In that season, FMC was lower than all other seasons from mid-September onwards. Figure 56 shows that the extreme outlier occurred during 2002-03 during the Millennium Drought, corresponding with the most significant precipitation shortfall, and also with the first of the large Alpine fires during the decade 2000-2010.

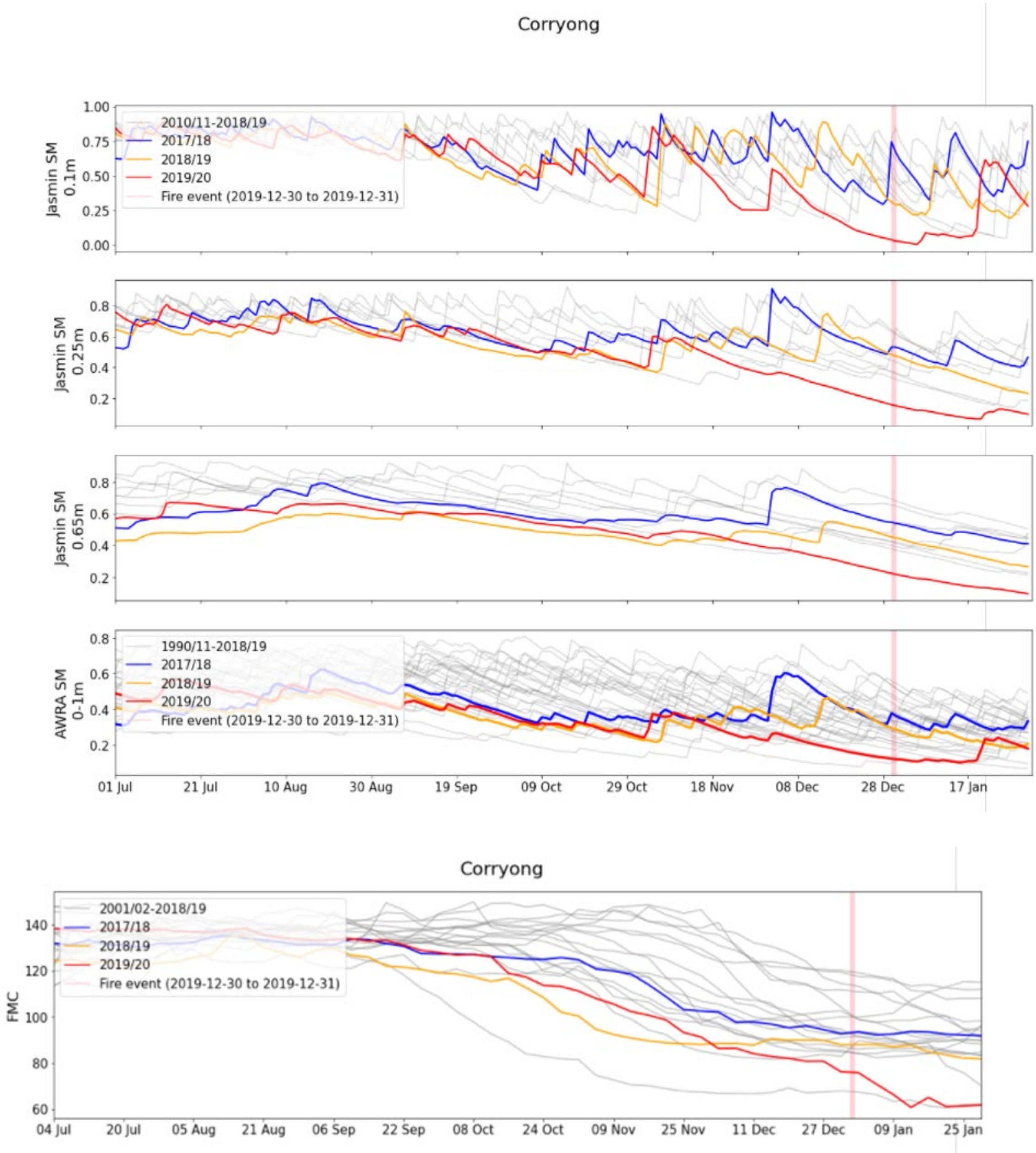


FIGURE 55: TIME SERIES OF CORRYONG SOIL AND FUEL MOISTURE AS PER FIGURE 18.

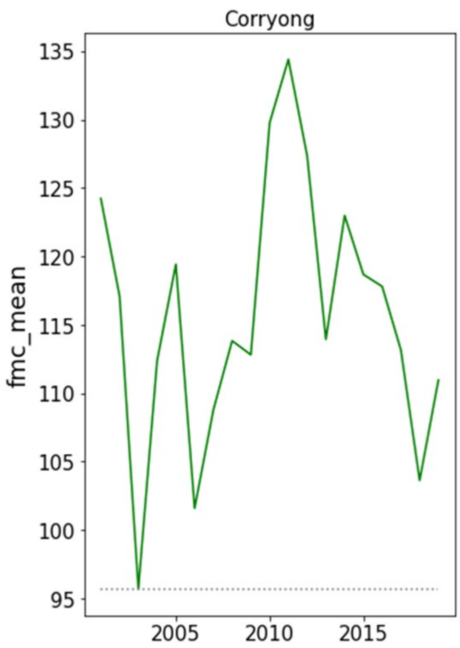


FIGURE 56: TIME SERIES OF ANNUAL AND FIRE AREA-AVERAGED FUEL MOISTURE CONTENT FOR CORRYONG.

For completeness, a plot of Drought Factor and corresponding precipitation from Corryong Airport AWS is included, for the two-month period leading to the outbreak of the fire (Figure 57). The DF reflects that not all fine fuel is available to burn until immediately prior to the fire ignition, as a consequence of a number of rainfall episodes in November and December. Importantly, however, it gives no real sense of the underlying dry conditions through the depth of the soil profile, highlighting the value of soil moisture and FMC in providing a more complete picture of the availability of fuels to burn.

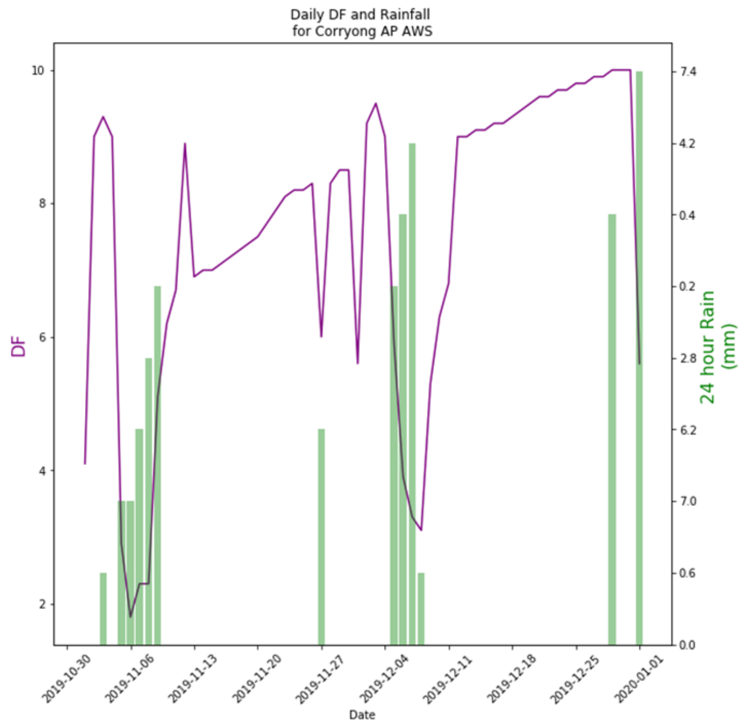


FIGURE 57: TIME SERIES OF THE DROUGHT FACTOR (PURPLE) AND PRECIPITATION (GREEN) AT CORRYONG AIRPORT AWS FOR THE TWO MONTHS IMMEDIATELY PRIOR TO CORRYONG FIRE IGNITION.

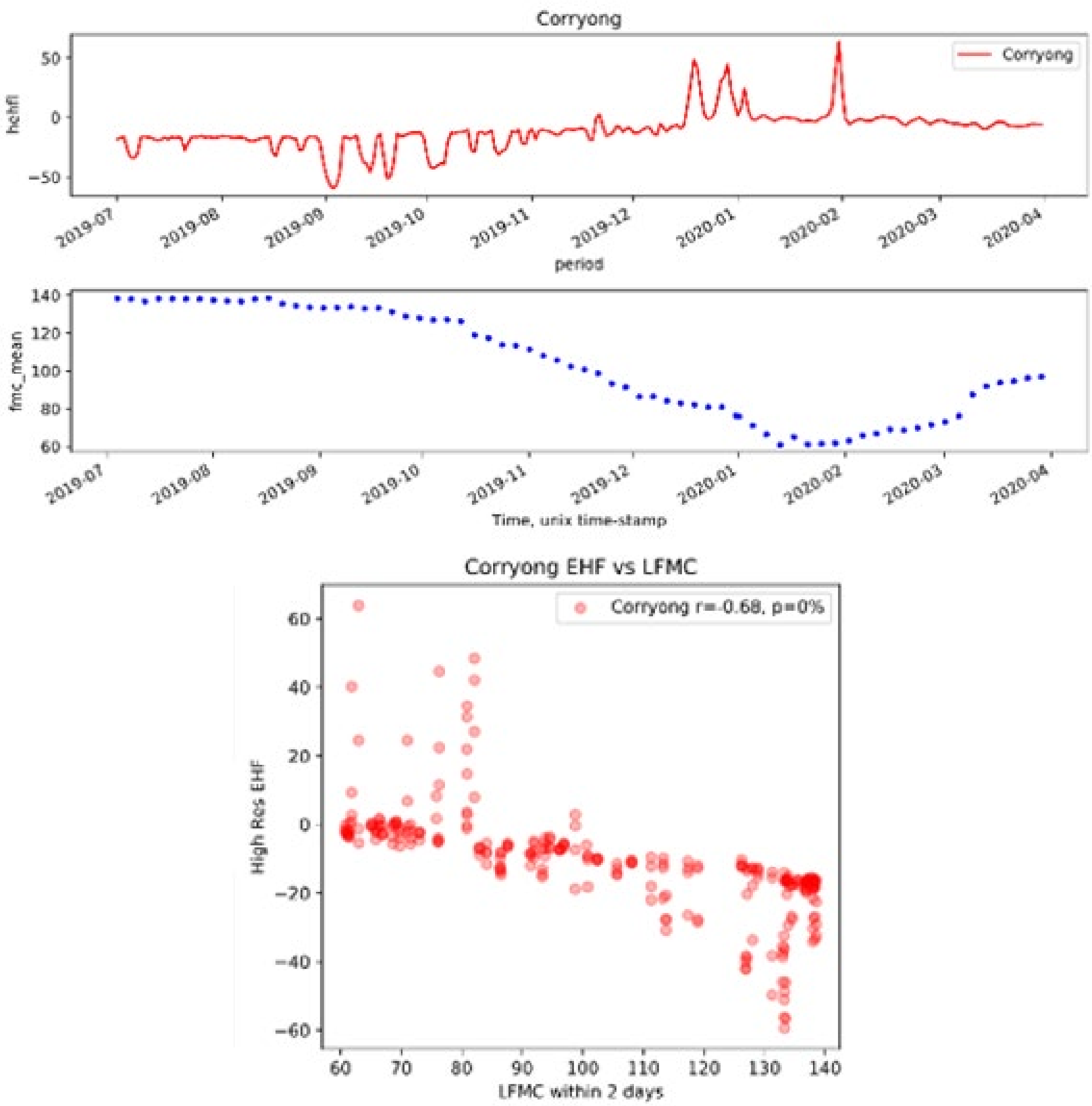


FIGURE 58: CORRELATION BETWEEN EHF AND FUEL MOISTURE CONTENT FOR CORRYONG FIRE. TOP PANEL: EHF VALUES FOR A SITE NEAR THE FIREGROUND (CORRYONG TOWNSHIP) FROM JULY 2019 TO APRIL 2020. MIDDLE PANEL: FIRE AREA AVERAGED FMC FOR THE SAME PERIOD. BOTTOM PANEL: PLOT OF EHF AGAINST FIRE AVERAGED FMC FOR THE SITE, LISTING CALCULATED CORRELATION.

There is a negative correlation (r=-0.68) between EHF and fire area-averaged fuel moisture content for the seven months period from 01 July 2019 for Corryong (Figure 58, panel 3). Note that the FMC at the end of this period is likely to include a degree of contamination by the fire itself as a result of leaf scorch or consumption. The time series and scatter plots show the occurrence of a heatwave at Corryong contributing to the decline in fuel moisture, particularly immediately following the two significant heatwave events grouped close together in late December 2019 and the third heatwave event in early January. This is very similar to the corresponding plot for the Badja fireground, unsurprising given their proximity and broadly similar geography. Again, as for Badja, the passage of cold fronts on 30-31December and 04 January as described in the synoptic summary contributed to the heatwave events and so to the additional preconditioning of fuels to burn. Note that much of the decline during January of remotely measured vegetation moisture content plotted is likely due to the passage of the fire, as noted in discussion of Figure 59 below.

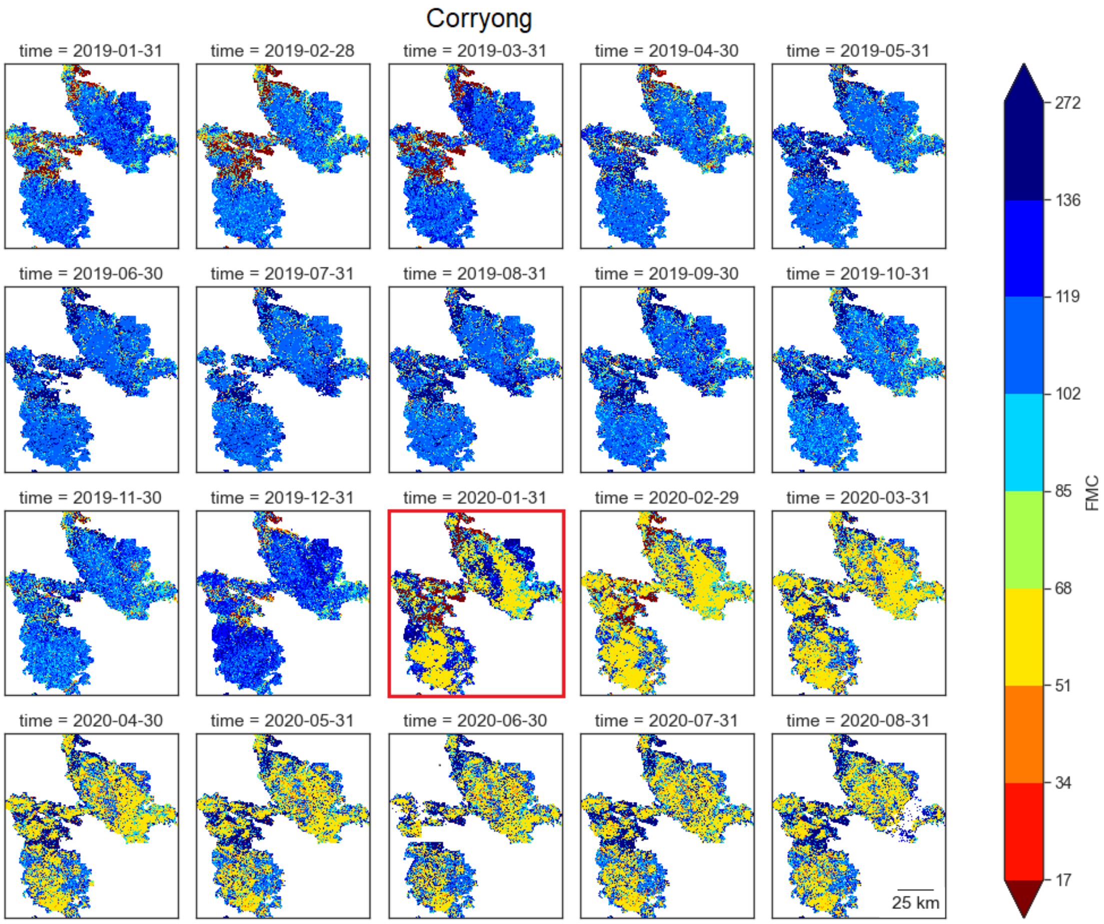


FIGURE 59: MAPS OF SPATIAL AND TEMPORAL VARIATION OF HIGH-RESOLUTION FMC (25M) OVER THE CORRYONG BURN AREA FROM SENTINEL-2 SATELLITE DATA. FUEL MOISTURE CONTENT IS MEASURED IN PERCENT, WITH HIGH MOISTURE CONTENT IN BLUE AND LOW MOISTURE CONTENT IN YELLOW/RED. HIGHLIGHTED IN RED IS THE MAP CLOSEST TO THE DATE THAN THE FIRE STARTED.

While a progressive decrease in FMC can be seen in the months ahead of the Corryong fire (Figure 59), the fireground was not as dramatically dry according to this measure as was the case with some other areas that burnt. Following the fire, however, there is a clear transition to a different regime associated with scorched or fully consumed vegetation, which gradually starts to recover over following months.

In summary, the Corryong region experienced similarly extreme warm and dry conditions across a range of timescales as occurred with the Badja event, including being affected by the same cold front on 30-31 December. Resulting extremes of soil and fuel moisture were comparably low relative to the available historic record, but interestingly were not as extreme in absolute terms. Again, there was evidence that fuel moisture content responded negatively to the occurrence of heatwaves during the period immediately preceding fire occurrence.

YANCHEP

Broad-scale weather and climate context

For the Yanchep fire events, around the time leading up to the peak fire activity from about 11th to 13th December 2019, there was a persistent trough over the west coast region (Figure 59). This trough was quasi-stationary for that period driven by a high-pressure system in the Great Australian Bight to the southeast (associated with the subtropical ridge and series of highs along southern Australia more broadly around this time). These conditions caused very hot and dry air over southwest WA (Figure 60-61), including maximum temperatures more than 10 °C above average in some areas. In addition to these extreme temperatures and dry air, many locations in the fire-affected areas experienced their driest January to August period on record since at least 1900, as well as record rainfall deficits over longer time periods such as for the 2-year period leading up to 2019 (Figure 62). These long-term drought conditions for this Yanchep region are classed as 'very much below average' (i.e., corresponding to the lowest decile range, i.e., the second highest category shown in Figure 62). The combined effect of these factors over different time scales led to the evolution of conditions that were very dangerous for fire behavior, including dry fuel conditions as detailed in the following section based on several different metrics.

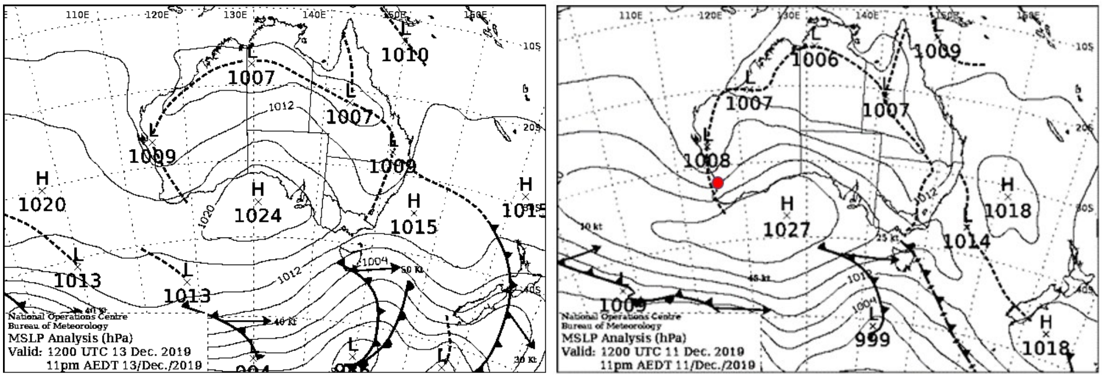
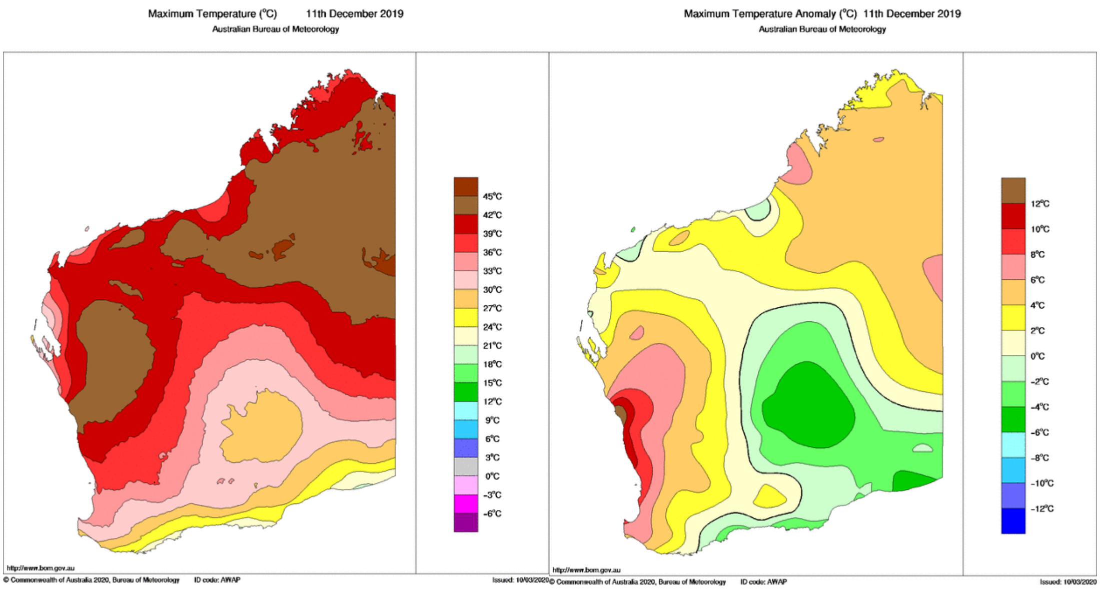


FIGURE 59: WEATHER SYSTEMS AROUND THE TIME OF THE YANCHEP FIRE EVENT. THIS IS SHOWN FOR THE SYNOPTIC MSLP CHARTS PRODUCED BY THE BUREAU OF METEOROLOGY FOR THE 11TH (LEFT PANEL) AND 13TH (RIGHT PANEL) OF DECEMBER 2019 AT 1200 UTC. THE APPROXIMATE POSITION OF YANCHEP IS INDICATED BY THE RED DOT IN THE RIGHT-HAND CHART.



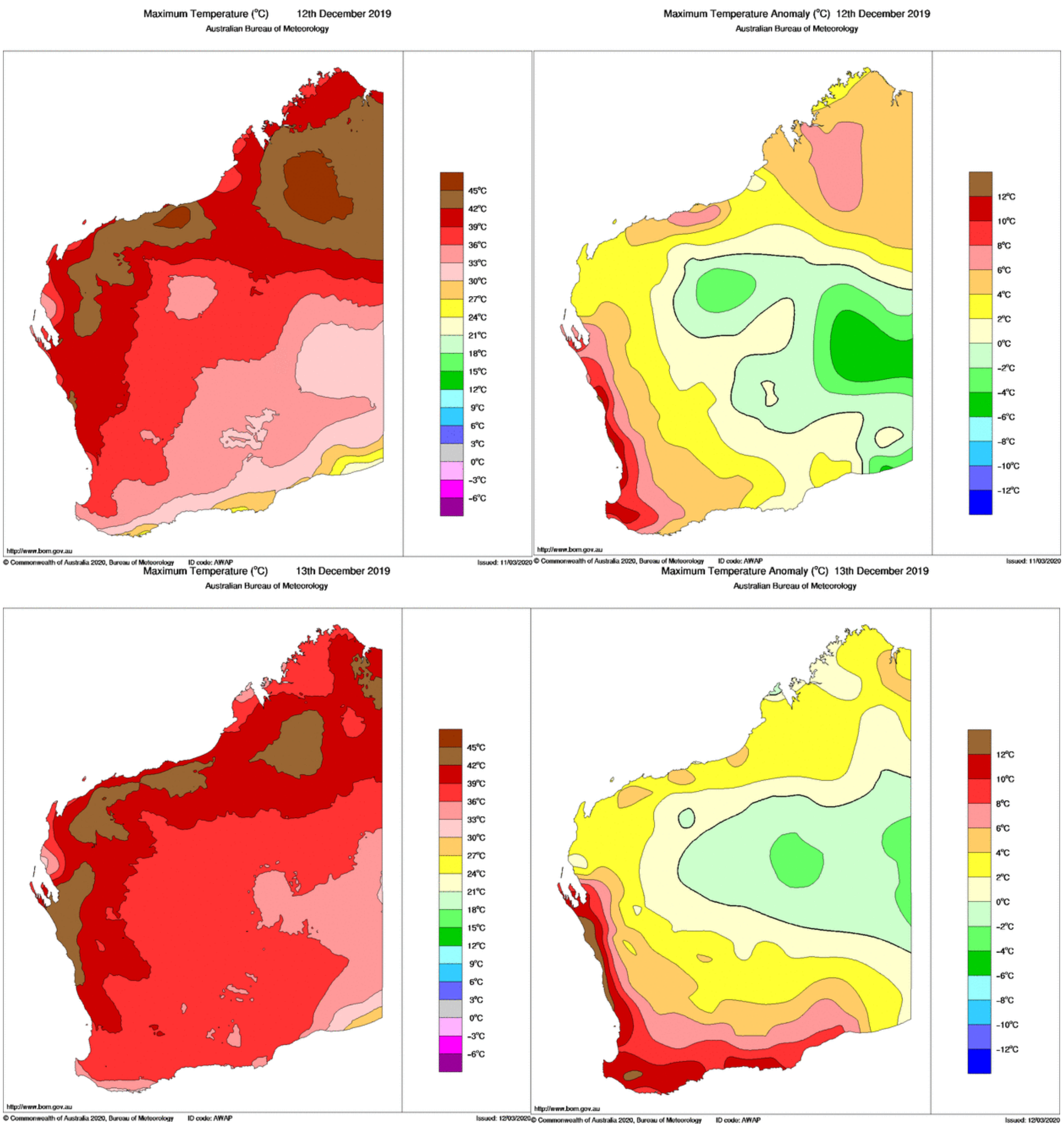


FIGURE 60: DAILY MAXIMUM TEMPERATURE (LEFT PANELS) AND TEMPERATURE ANOMALY (RIGHT PANELS) FOR THE 11TH (UPPER PANELS), 12TH (MIDDLE ROW PANELS) AND 13TH (LOWER PANELS) OF DECEMBER 2019.

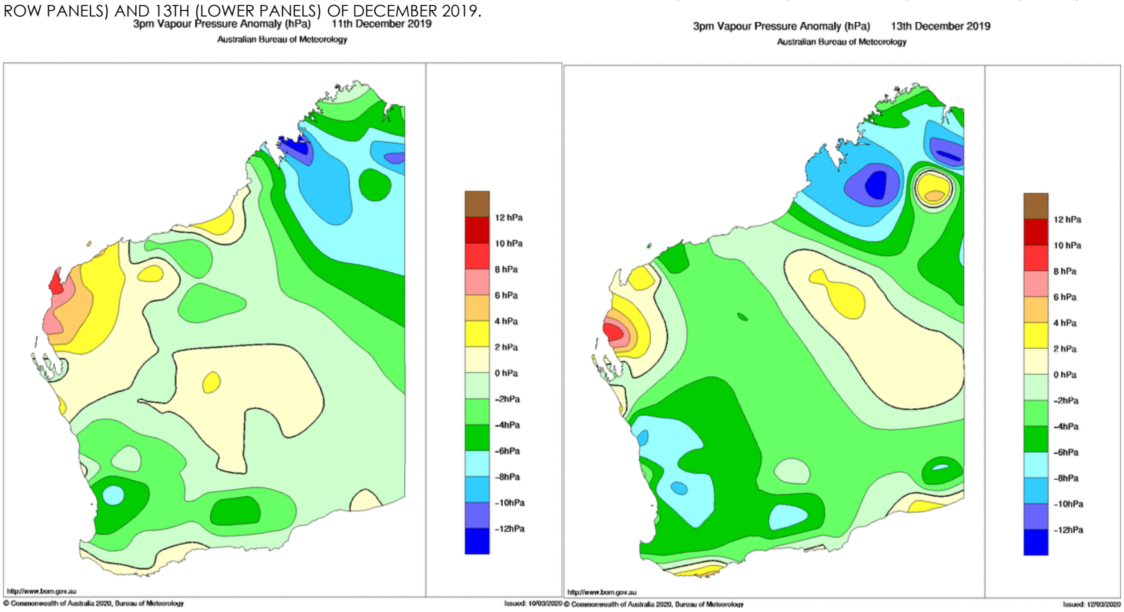


FIGURE 61: VAPOUR PRESSURE ANOMALY AT 3 PM LOCAL TIME (WITH DAYLIGHT SAVINGS) ON THE 11TH (LEFT PANEL) AND 13TH (RIGHT PANEL) OF DECEMBER 2019.

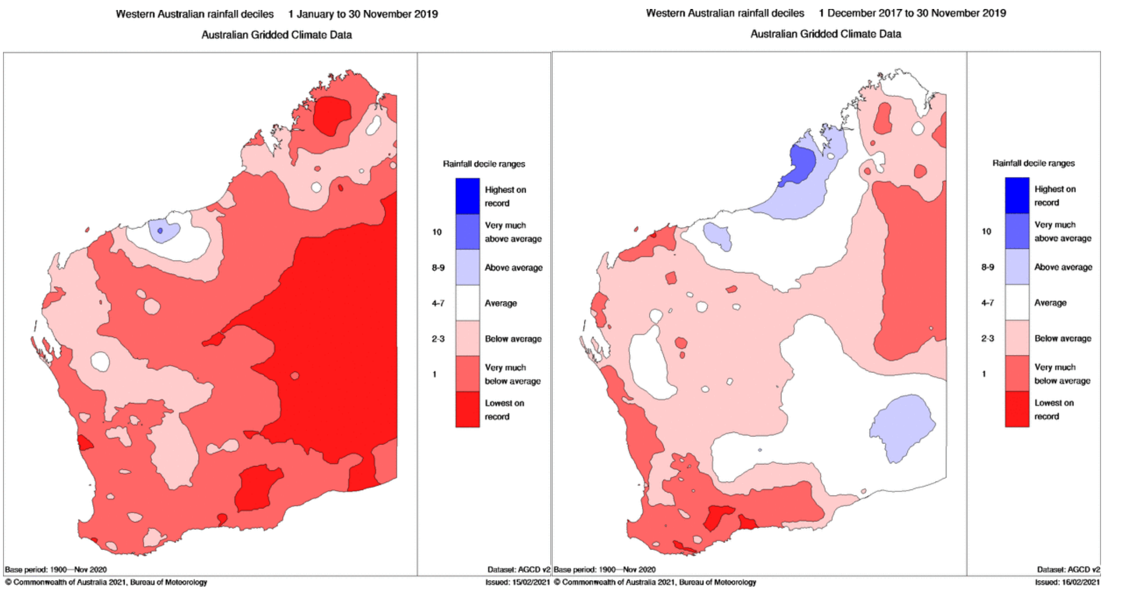


FIGURE 62: RAINFALL ANOMALIES FOR WA LEADING UP TO THE YANCHEP FIRES IN 2019. THIS IS SHOWN FOR THE 2019 FOR THE PERIOD FROM JANUARY TO NOVEMBER 2019 (LEFT PANEL) AS WELL AS FOR THE 2-YEAR PERIOD FROM DECEMBER 2017 TO NOVEMBER 2019 (RIGHT PANEL).

Multi-year development of conditions suitable for landscape fires (drought)

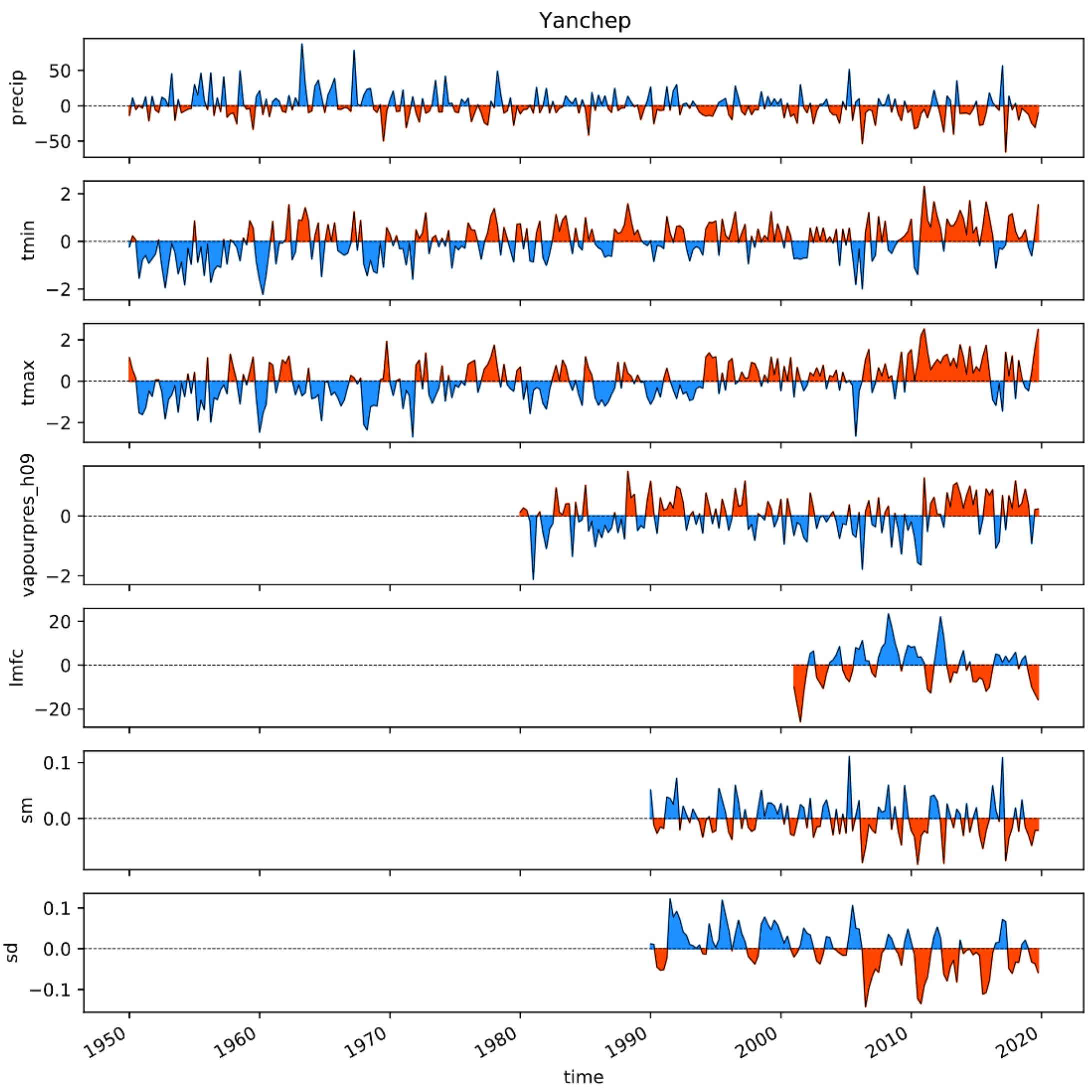


FIGURE 63: TIME SERIES OF 3-MONTHLY ANOMALIES OF METEOROLOGICAL VARIABLES AND SOIL AND FUEL MOISTURE FOR YANCHEP.

Yanchep displays a long-term precipitation deficit (Figure 63), as discussed in the synoptic summary. In particular, the months prior to December 2019 were dry. The trend of increasing temperature seen in other fire location plots is also evident in the Yanchep plots of meteorological anomalies. A spike of high minimum and maximum temperature in late 2019 is clearly visible, as is a period of anomalously low vapour pressure. Plots of daily maximum temperature and vapour pressure anomaly for the seven months from 01 July 2019 highlight these events in the weeks leading into the fire ignition.

These factors certainly contributed to the states of low soil and fuel moisture evident in Figure 65 during 2019. Deep soil moisture especially had been anomalously low for several extended periods since the mid-2000's.

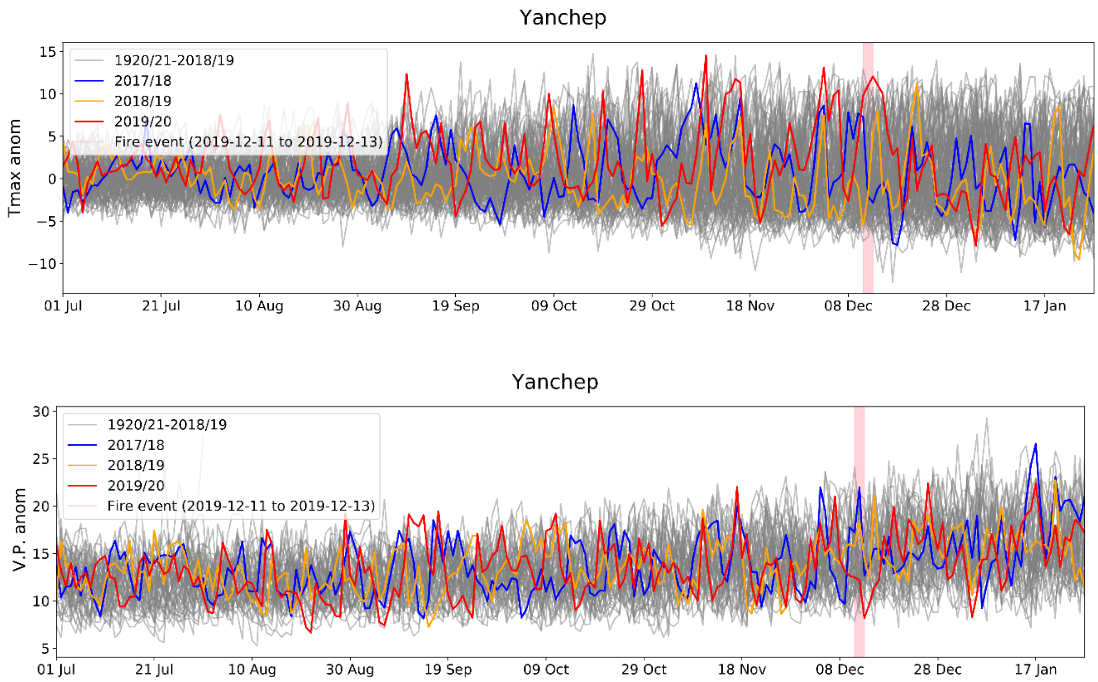


FIGURE 64: TIME SERIES OF MAXIMUM TEMPERATURE (DEGREES C, TOP) AND 0900 VAPOUR PRESSURE (HPA, BOTTOM) ANOMALIES FROM 1 JULY TO 31 JANUARY FOLLOWING, FOR EACH AVAILABLE YEAR. THE PERIOD OF FIRE OCCURRENCE IS HIGHLIGHTED WITH A VERTICAL PINK BAR.

As a result of the long term precipitation deficit and generally above average temperatures, all soil moisture measures displayed in Figure 65 for 01 July – 31 January the following year, show similarly low values, although 2019 was marginally lower at most times than the earlier two seasons. Live fuel moisture content, however, was clearly lower in the latter half of 2019 than in the immediately antecedent two years and lowest in the available record for much of the period displayed.

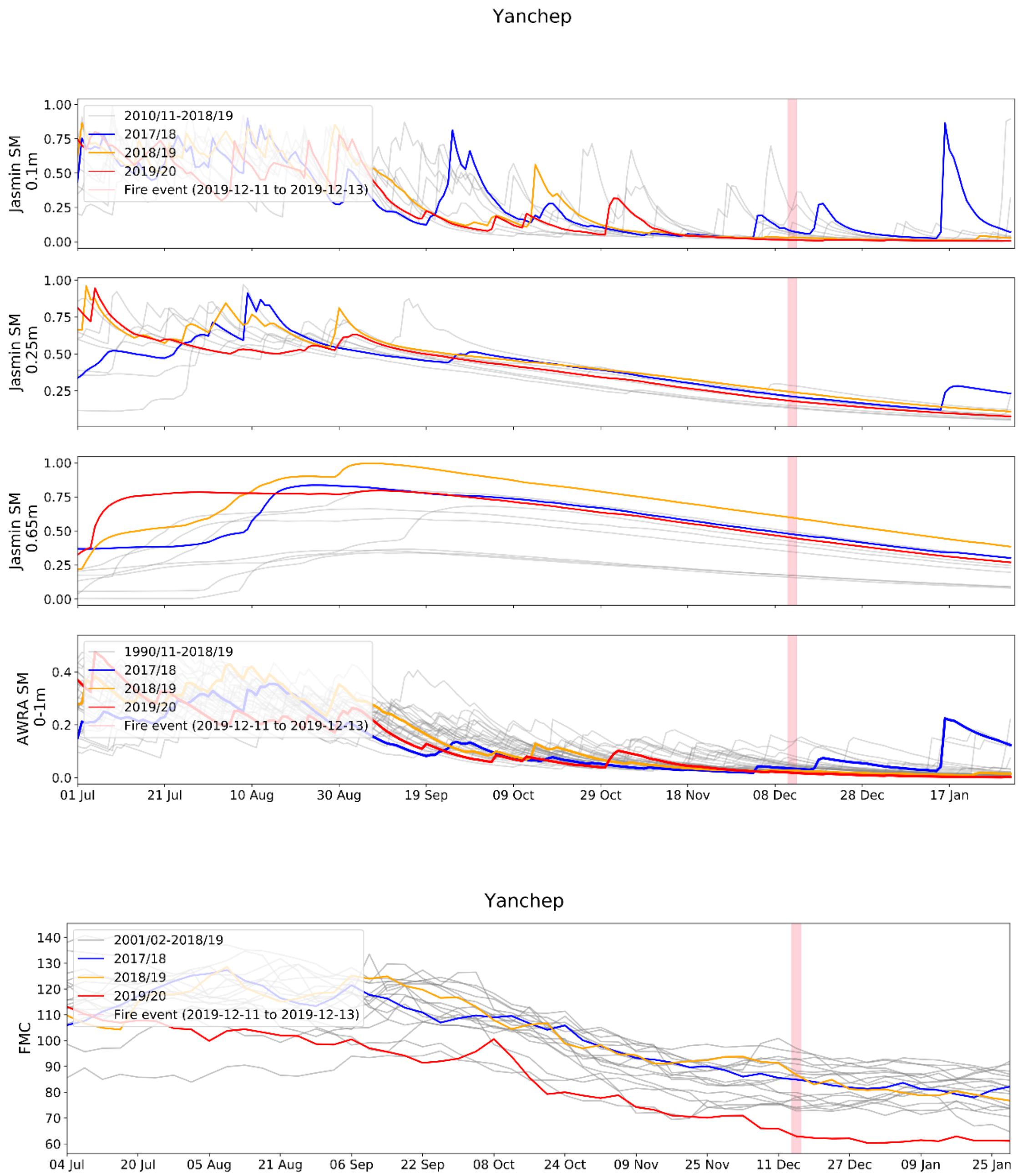


FIGURE 65: TIME SERIES OF SOIL AND FUEL MOISTURE AS PER FIGURE 21.

Examining this more closely, fire area-averaged fuel moisture for the Yanchep fire domain (Figure 66) was lower in late 2019 than all years other than in the very early 2000's, having declined in a series of steps from the late 2000's.

Daily DF for Nov-Dec 2019 is plotted in Figure 67. The figure demonstrates the limited impact of small amounts of rainfall leading to the time of the fire ignition, with DF rapidly returning to the maximum value of 10 shortly after the rain. The 75th percentile value of Pearce AWS DF over the last two decades is 10. This is a reflection of the drying trend in southwest Western Australia over the last several decades, evident in Figure 63. It also points to the fact that DF under persistent dry conditions is unable to identify the worst conditions. This is entirely understandable: DF was designed to indicate the availability of light fuel to burn, and once all the light fuel is available, DF remains at its maximum value. This does raise the point, identified in operational discussions and in other situations, that it would be valuable to have the capacity to measure and incorporate into fire danger ratings conditions under which larger fuels are also available to burn.

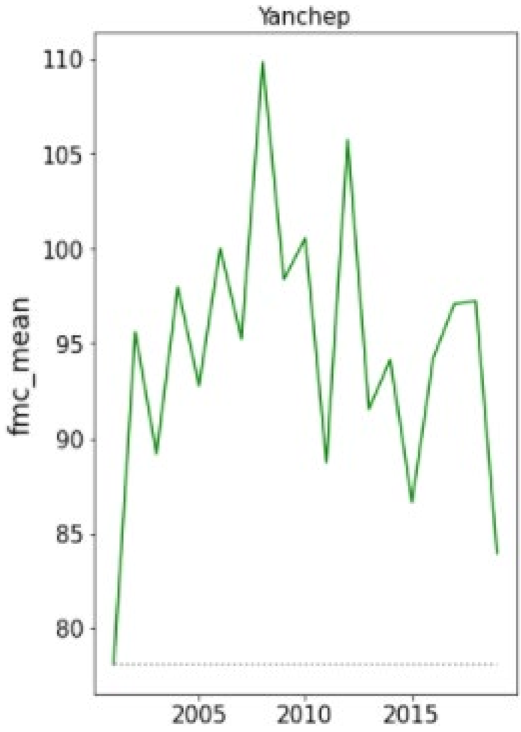


FIGURE 66: TIME SERIES OF ANNUAL AND FIRE AREA-AVERAGED FUEL MOISTURE CONTENT FOR YANCHEP.

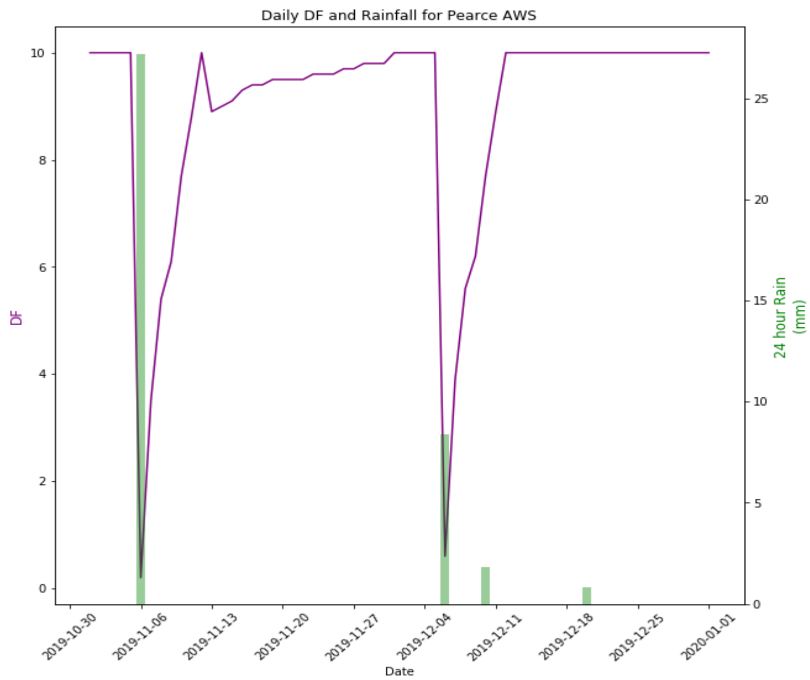


FIGURE 67: TIME SERIES OF THE DROUGHT FACTOR (PURPLE) AND PRECIPITATION (GREEN) AT PEARCE AWS FOR THE TWO MONTHS IMMEDIATELY PRIOR TO YANCHEP FIRE IGNITION.

There is a negative correlation (r=-0.65) between EHF and fuel moisture content for the seven-month period from 01 July 2019 for Yanchep (Figure 68). Time series and scatter plots show the occurrence of a heatwave contributing to the decline in fuel moisture, for both Yanchep and nearby Gingin AWS. A fraction of this correlation, again, may relate to changes in FMC resulting from the fire.

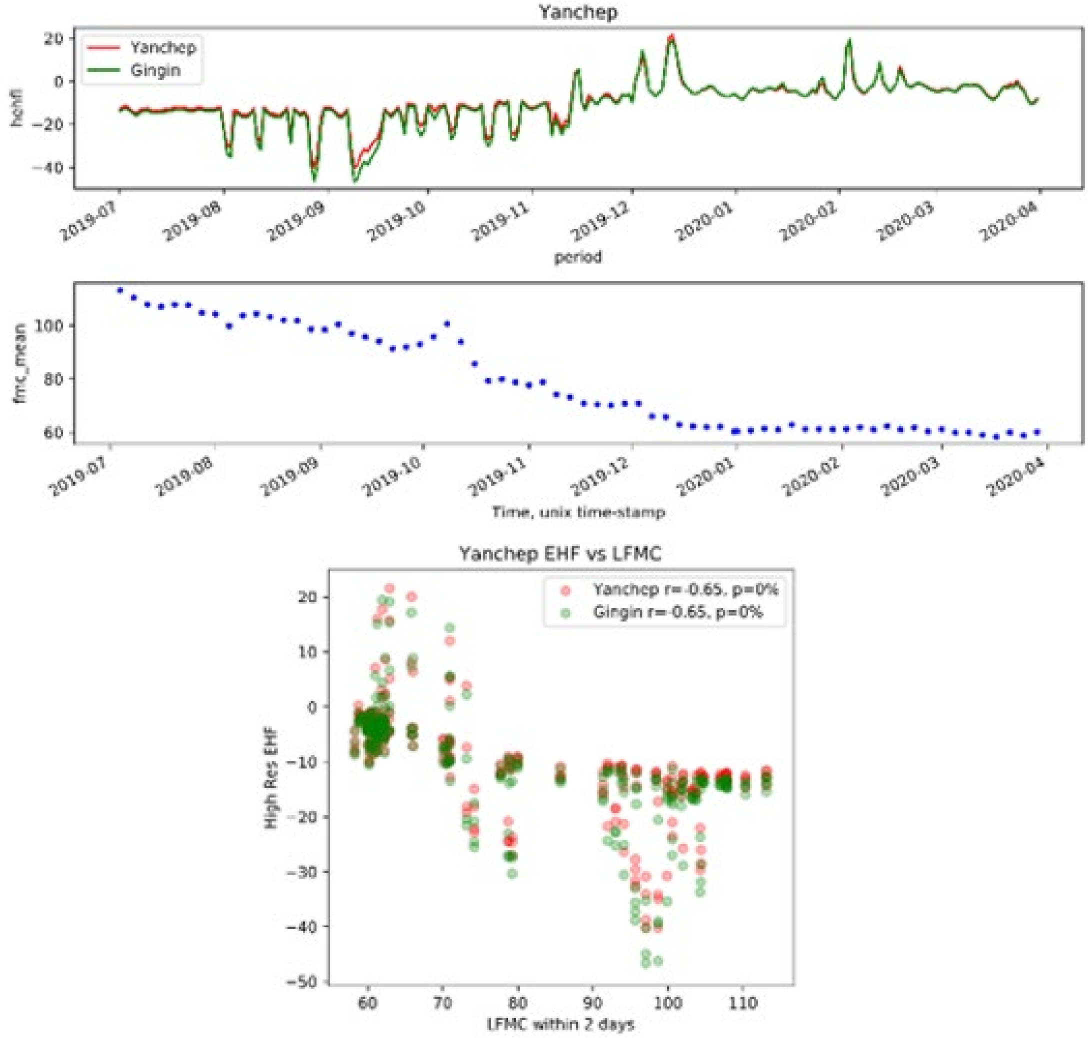


FIGURE 68: CORRELATION BETWEEN EHF AND FUEL MOISTURE CONTENT AT YANCHEP. TOP PANEL: EHF VALUES FOR TWO SITES NEAR THE FIREGROUND (YANCHEP AND GINGIN) FROM JULY 2019 TO APRIL 2020. MIDDLE PANEL: FIRE AREA AVERAGED FMC FOR THE SAME PERIOD. BOTTOM PANEL: PLOT OF EHF AGAINST FIRE AVERAGED FMC FOR THE TWO SITES, LISTING CALCULATED CORRELATIONS.

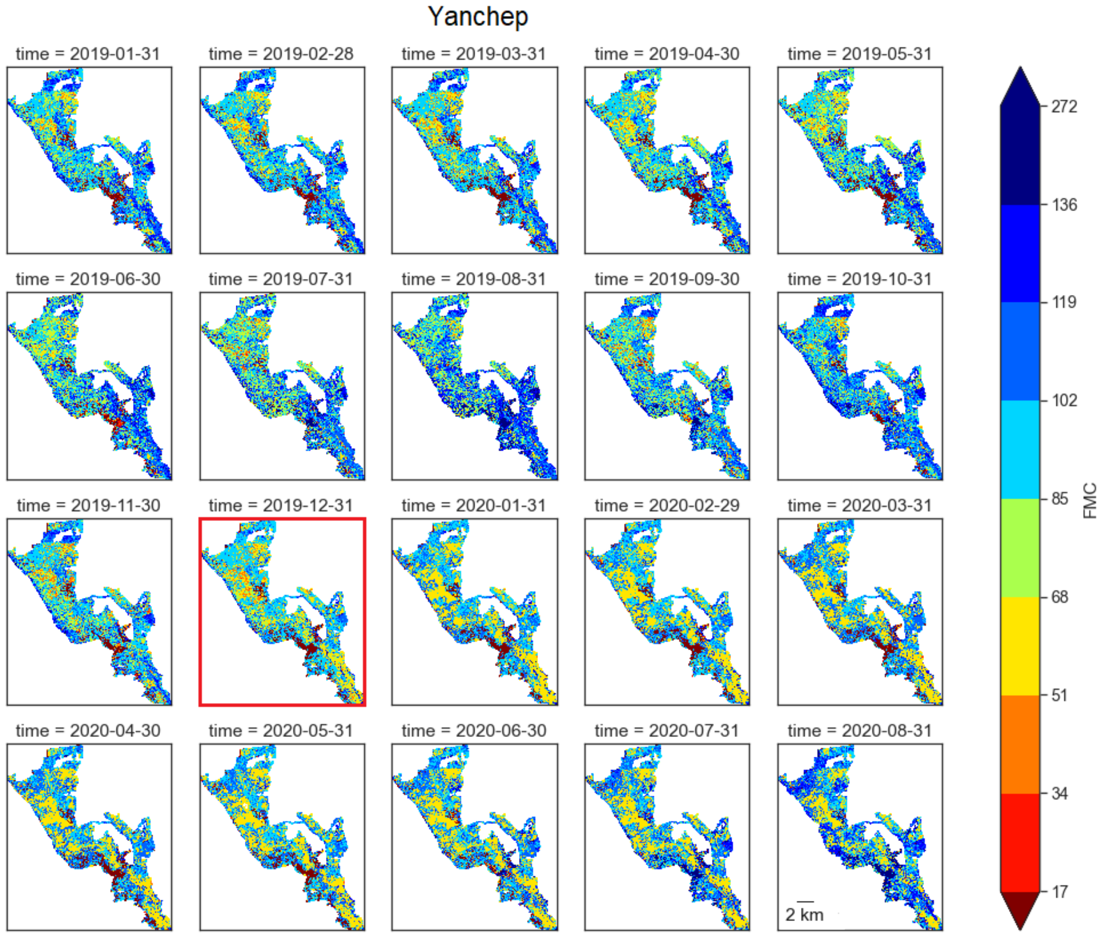


FIGURE 69: MAPS OF SPATIAL AND TEMPORAL VARIATION OF HIGH-RESOLUTION FMC (25M) OVER THE YANCHEP BURN AREA FROM SENTINEL-2 SATELLITE DATA. FUEL MOISTURE CONTENT IS MEASURED IN PERCENT, WITH HIGH MOISTURE CONTENT IN BLUE AND LOW MOISTURE CONTENT IN YELLOW/RED. HIGHLIGHTED IN RED IS THE MAP CLOSEST TO THE DATE THAN THE FIRE STARTED.

Drying can be seen across the Yanchep fireground in the months immediately preceding the fire in December 2019 (Figure 69). Notable also is a considerable spatial variability across the fireground in FMC at any specific time period. This variability to some extent masks the change in FMC plots following fire that were evident in the other fires examined. Recovery of the fireground is still visible in the months following the Yanchep fire, however.

In summary, as with the other fires examined, an interplay of warm and dry atmospheric conditions and precipitation deficit occurred on several timescales leading into the Yanchep fire, with a number of heatwaves in particular developing in the weeks preceding the fire. These conditions were integrated again in the soil moisture, typically low at the time of year of the fire, but lower than the previous seasons. It was clearer that fuel moisture was lower in 2019 than in most earlier years for which data was available, suggesting that, in the environment of the Yanchep fire, fuel moisture content may be a better discriminant of potential fire conditions than soil moisture.

ORRORAL VALLEY

Broad-scale weather and climate context

Around the time leading up to the ignition and peak fire activity on 27th January 2020 for the Orroral Valley fire, there was a trough over the region (Figure 70) with very hot and dry air (Figures 71-72). In addition to extreme temperatures and dry air, many locations around the fire-affected areas had experienced in 2019 their driest year on record (since at least 1900), in additional to record rainfall deficits over multi-year time periods leading up to the Orroral Valley fire (Figure 73, as well as figures shown for this region in the section on the Badja fire). The combination of extreme conditions over these different time scales led to exceptionally dangerous fire conditions, including in relation to dry fuel moisture as detailed in the following content based on several different metrics.

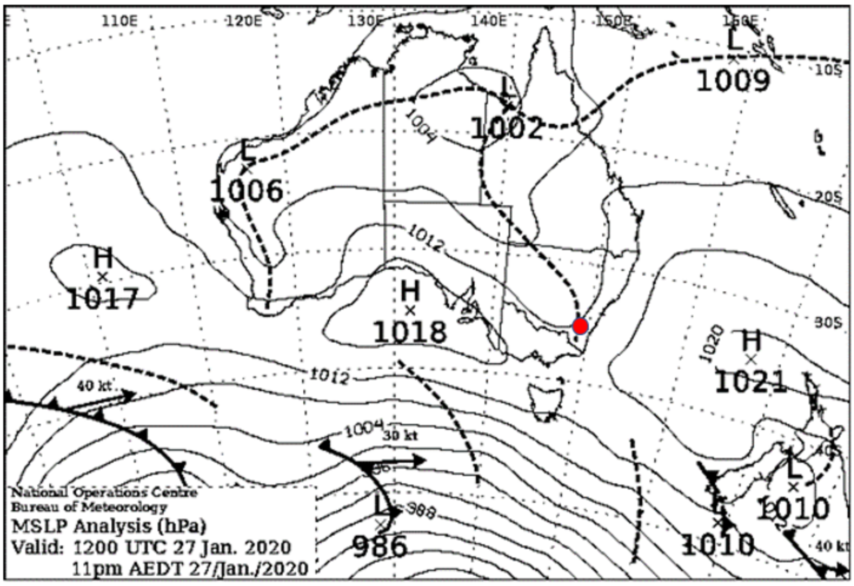


FIGURE 70: WEATHER SYSTEMS AROUND THE TIME OF THE ORRORAL VALLEY FIRE EVENT. THIS IS SHOWN FOR THE SYNOPTIC MSLP CHARTS PRODUCED BY THE BUREAU OF METEOROLOGY FOR 27TH JANUARY 2020 AT 1200 UTC. THE RED DOT INDICATES THE APPROXIMATE POSITION OF THE ORRORAL VALLEY FIRE.

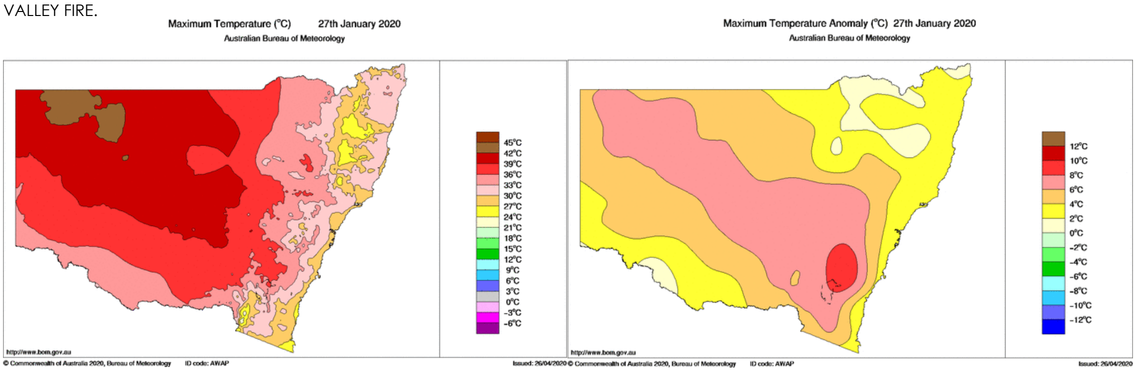


FIGURE 71: DAILY MAXIMUM TEMPERATURE (LEFT PANEL) AND TEMPERATURE ANOMALY (RIGHT PANEL) FOR 27TH JANUARY 2020.

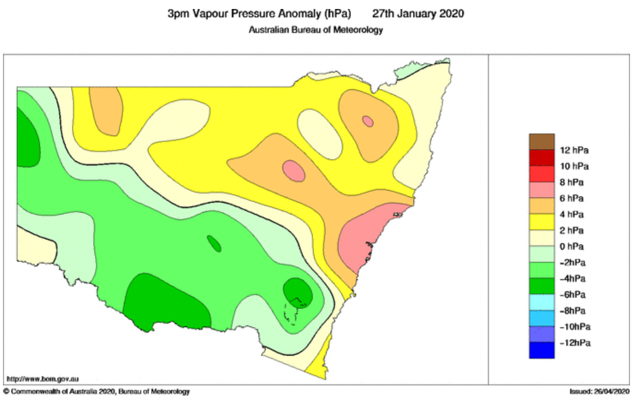


FIGURE 72: VAPOUR PRESSURE ANOMALY ON 27TH JANUARY 2020 AT 3 PM LOCAL TIME (WITH DAYLIGHT SAVINGS).

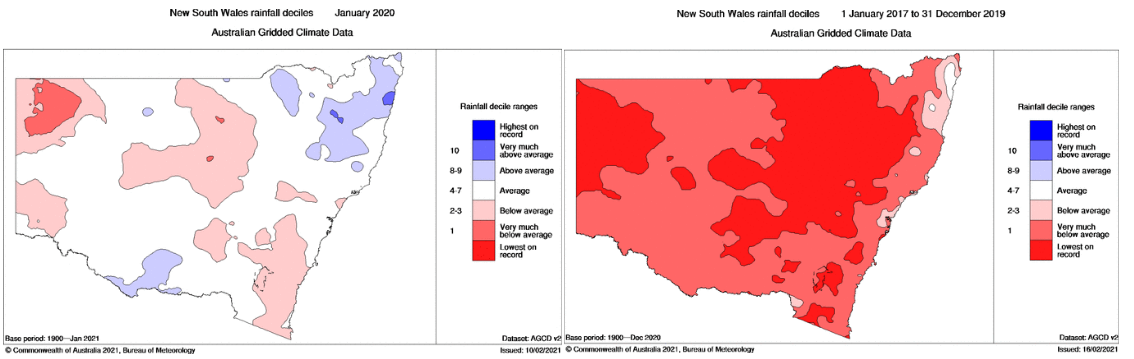


FIGURE 73: RAINFALL ANOMALIES LEADING UP TO THE ORRORAL VALLEY FIRE REGION IN JANUARY 2020. THIS IS SHOWN FOR THE MONTH OF JANUARY 2020 (LEFT PANEL), AS WELL AS FOR THE 3-YEAR PERIOD FROM JANUARY 2017 TO DECEMBER 2019 (RIGHT PANEL).

As with other fire events studied in this report, to a greater or lesser extent, negative precipitation and vapour pressure anomalies and positive temperature anomalies over the Orroral Valley fireground contributed to marked soil and fuel moisture deficits (Figure 74). In particular, a strong positive maximum temperature anomaly is evident in the years leading to 2019. This may be because of the exclusively continental location of Orroral Valley, well away from the moderating influence of the seas surrounding Australia. Spikes of each of these meteorological parameters are evident towards the end of 2019, contributing to longer term influences preconditioning fuels to burn. Notably, however, neither soil or fuel moisture content reached historic low levels associated with the Millennium drought and with the period of the Canberra fire in January 2003.

Multi-year development of conditions suitable for landscape fires (drought)

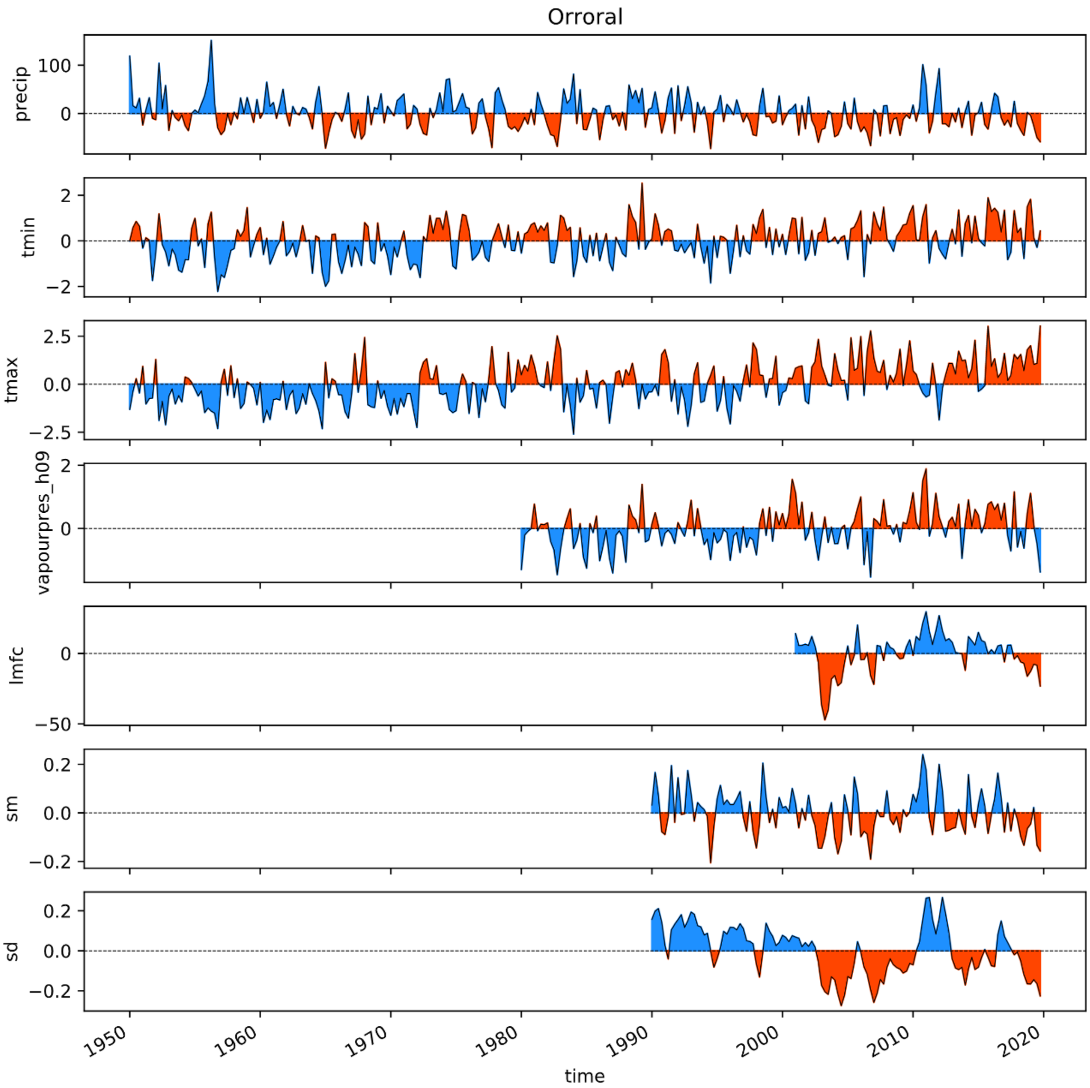


FIGURE 74: TIME SERIES OF 3-MONTHLY ANOMALIES OF METEOROLOGICAL VARIABLES AND SOIL AND FUEL MOISTURE FOR ORRORAL VALLEY.

Examination of the daily maximum temperature and 0900 vapour pressure in the seven months from 01 July 2019 (Figure 75) highlights several periods of maximum temperature at or near record levels for the respective days, but close to average temperature in the days immediately prior to the fire ignition. For much of this time 2019 was warmer than the preceding two years and substantially above average (consistent with the long-term plots shown above), as noted in the synoptic discussion section. Vapour pressure was also lower than average and lower than 2017 and 2018 for much of December. It was relatively high during mid-January but dropped to very low values in late January near the time of fire ignition (Figure 75).

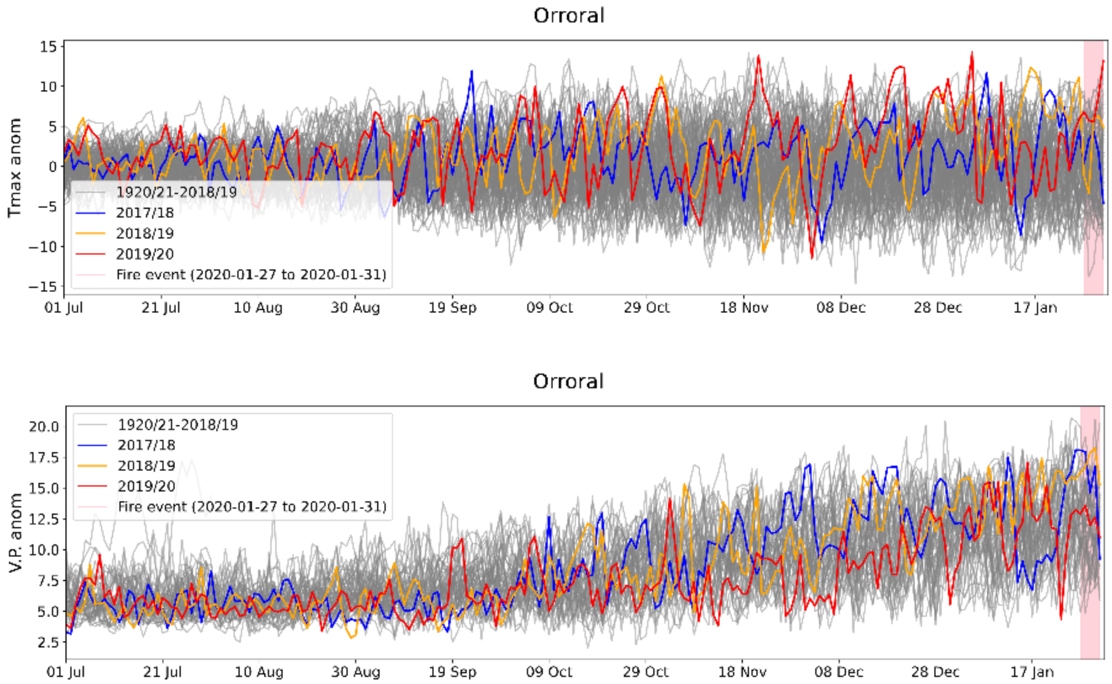


FIGURE 75: TIME SERIES OF MAXIMUM TEMPERATURE (DEGREES C, TOP) AND 0900 VAPOUR PRESSURE (HPA, BOTTOM) ANOMALIES FROM 1 JULY TO 31 JANUARY FOLLOWING, FOR EACH AVAILABLE YEAR. THE PEAK PERIOD OF FIRE ACTIVITY IS HIGHLIGHTED WITH A VERTICAL PINK BAR.

Soil and fuel moisture levels for the corresponding period (Figure 76) provide a stark reflection of the meteorological conditions. All soil moisture layers for JASMIN and AWRA-L root-zone soil moisture is below 2017 and 2018 values, in particular, and below all other years for much of the period displayed but especially the latter three months. The only variation to this was a small uptick in 0-0.1 m JASMIN soil moisture in early January associated with a small, short-lived rain event. This event didn't influence deeper layers and only marginally influenced AWRA-L root-zone soil moisture values. Fuel moisture content was consequently extremely low, and for most of the period from mid-November 2019 below 2018 levels which were in turn below that of 2017 and most other years.

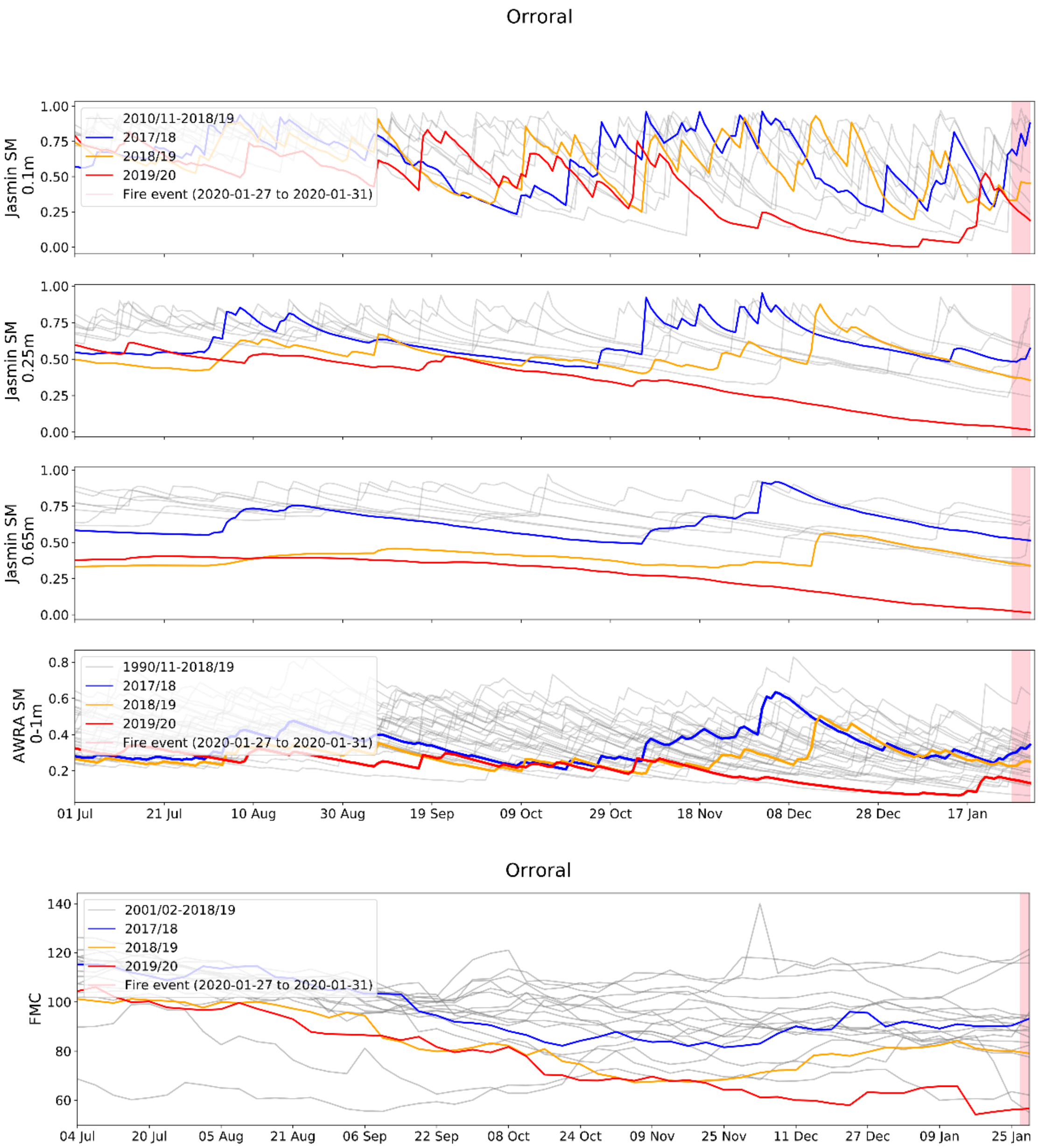


FIGURE 76: TIME SERIES OF SOIL AND FUEL MOISTURE AS PER FIGURE 17.

Annually and fire area-averaged fuel moisture content for the Orroral Valley fire (Figure 77) shows that fuel moisture values, having peaked during the 2010-11 La Niña event, were substantially lower than recent previous years but, again, not as low as those recorded during 2002-03.

Apart from a brief period after 01 January, DF (Figure 78) doesn't reflect the underlying extremity of the dry conditions but does highlight a rapid recovery in dryness from the brief rainfall event noted earlier.

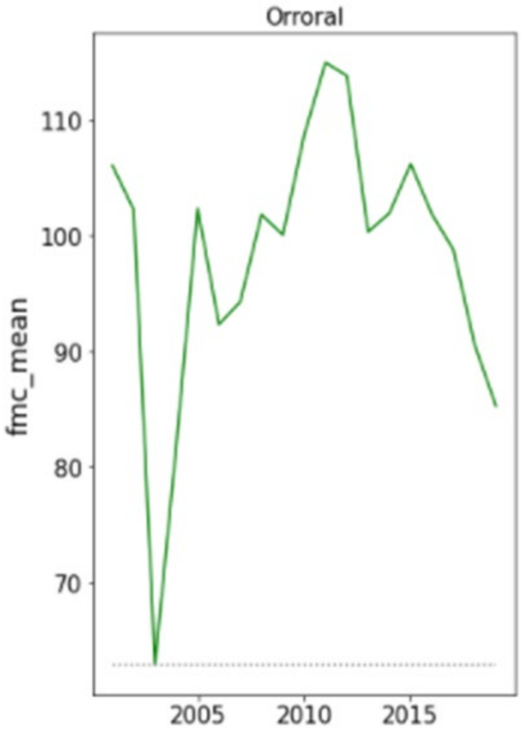


FIGURE 77: TIME SERIES OF ANNUAL AND FIRE AREA-AVERAGED FUEL MOISTURE CONTENT FOR ORRORAL VALLEY.

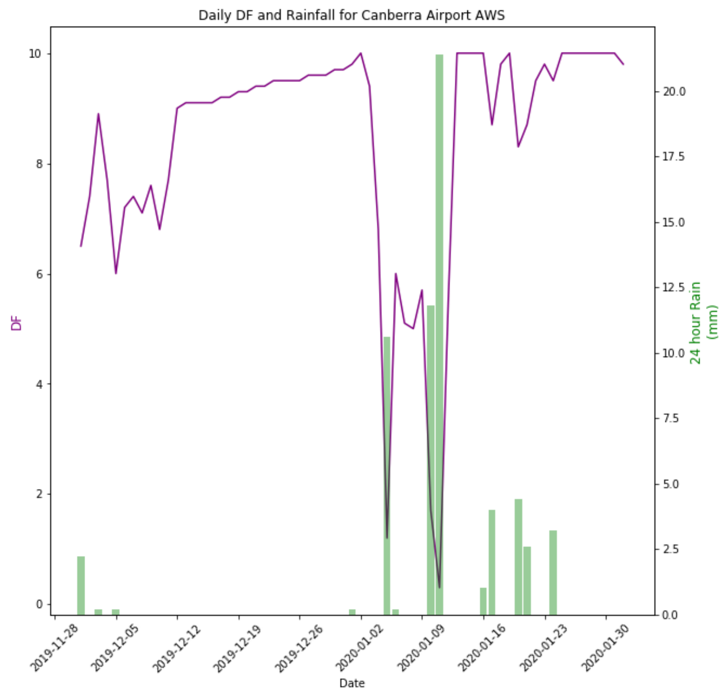


FIGURE 78: TIME SERIES OF THE DROUGHT FACTOR (PURPLE) AND PRECIPITATION (GREEN) AT CANBERRA AIRPORT AWS FOR THE TWO MONTHS IMMEDIATELY PRIOR TO ORRORAL VALLEY FIRE IGNITION.

High resolution FMC plots (Figure 79) indicate progressive drying of the vegetation through the sequence of plots ahead of the fire, moderated slightly by the occurrence of the brief rain event in early January. From February 2020 onward, the impact of the fire can be seen as the fireground appears very dry.

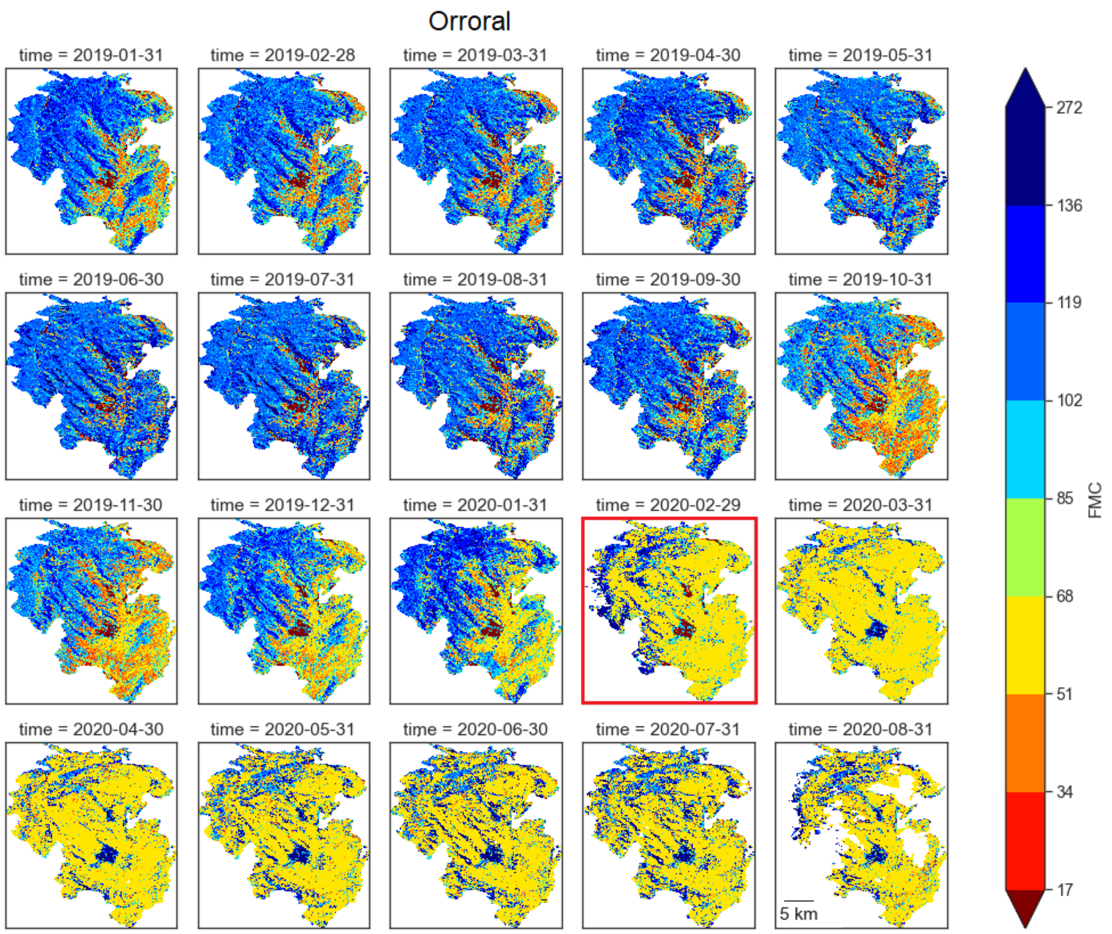


FIGURE 79: MAPS OF SPATIAL AND TEMPORAL VARIATION OF HIGH-RESOLUTION FMC (25M) OVER THE ORRORAL VALLEY BURN AREA FROM SENTINEL-2 SATELLITE DATA. FUEL MOISTURE CONTENT IS MEASURED IN PERCENT, WITH HIGH MOISTURE CONTENT IN BLUE AND LOW MOISTURE CONTENT IN YELLOW/RED. HIGHLIGHTED IN RED IS THE MAP CLOSEST TO THE DATE THAN THE FIRE STARTED.

In summary, extremes of temperature, precipitation and, at times, vapour pressure contributed to very low soil and fuel moisture content over the Orroral Valley fireground. Conditions were worse than in 2017 and 2018, with progressive decreases in fuel moisture content over the years immediately prior to the fire. Notably, however, fuel moisture content was recorded as being lower in 2003 during the Millennium drought.

ADDITIONAL FINDINGS

Antecedent conditions for the southern fire season of 2019-20 were extreme when measured against a number of metrics. We summarise this in Table 1, which presents the ranking of conditions over each fire area against all years for which data is available.

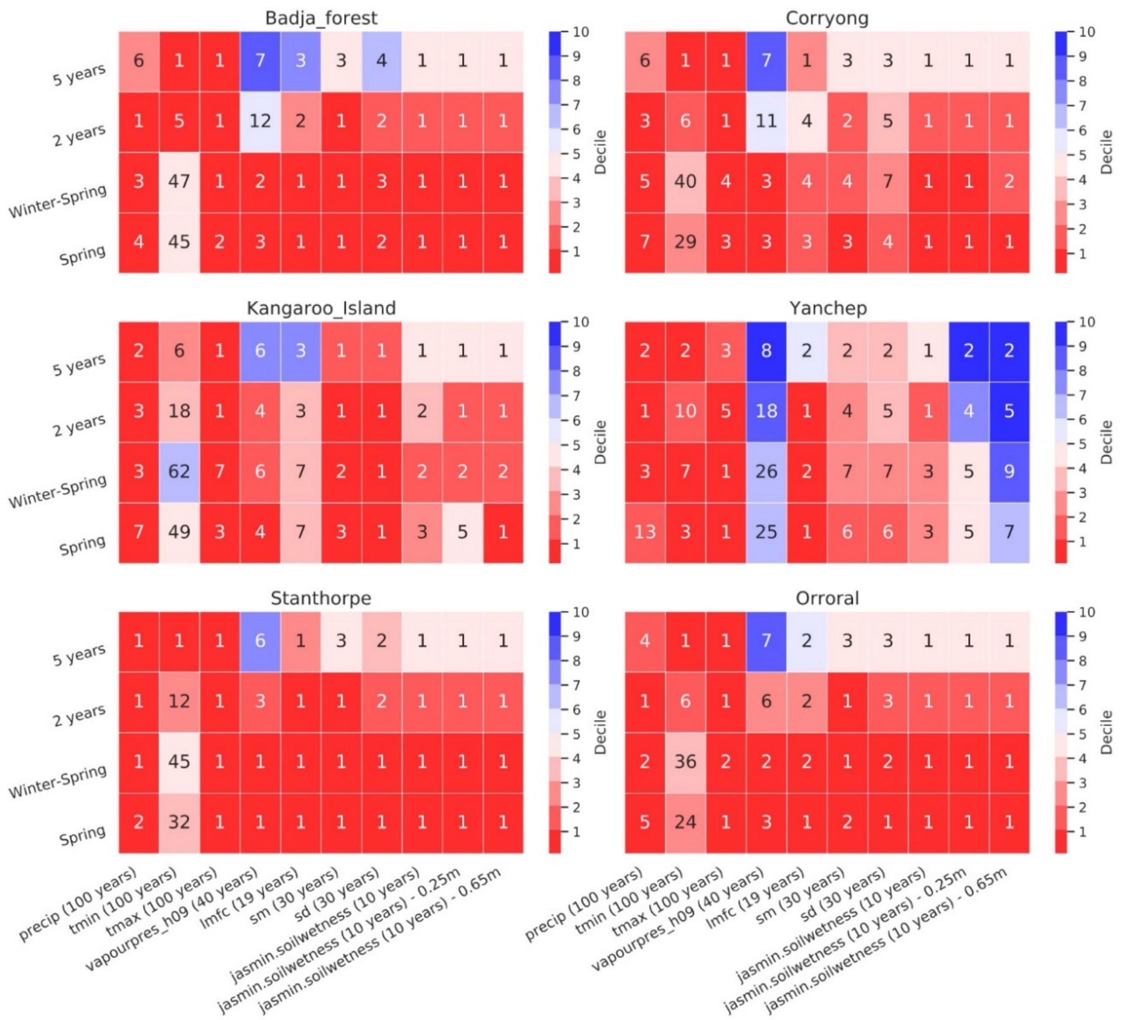


TABLE 1: SUMMARY OF DECILE VALUES OF METEOROLOGICAL PARAMETERS AND SOIL AND FUEL MOISTURE CONTENT FOR EACH OF THE SIX FIRES INVESTIGATED IN THIS REPORT.

The table cells are colored according to the decile of the corresponding data. Thus, decile one data is colored deep red, decile 10 as deep blue, for example. The numbers in each cell represent the ranking of the 2019-20 period against all existing data, with the number of years of data for each data type noted in parentheses in the table column descriptions. The table rows contain data averaged over a constant period: the top row of each fire sub-table contains data averaged over a five-year period, for example, for the bottom rows the averaging period is the Spring season.

Fields analysed are:

Precipitation (100 years of data available).

Minimum temperature (100 years).

Maximum temperature (100 years).

9am vapour pressure (40 years).

AWRA-L root-zone (0-1 m) soil moisture (30 years).

AWRA-L deep (1-6 m) soil moisture (30 years).

Satellite (lmfc output field) fuel moisture content (19 years)

Jasmin soil wetness for three soil layers, 0-0.1, 0.1-0.35 and 0.35-1 m (10 years)

For most cells for each fire, the dominant color is red, and the most common ranking (110 of 240 cells) is 1 – the most extreme period in the respective dataset.

Generally, longer term averaged (two and five year) maximum temperature was the field for which most fire areas experienced ranking 1 conditions. Yanchep was the only exception to this, where two and five year averaged maximum temperature was ranked 5th and third, respectively. For most fires, minimum temperature, particularly over shorter (three and six months) averaging periods, was least extreme.

For Yanchep, 0900 vapour pressure was not extreme, possibly reflecting its coastal location and the fact that the most difficult fire conditions occurred during the late afternoon and evening of the days when fire occurred. Interestingly, however, minimum temperature at Yanchep for those two averaging periods was closer to extreme than at other fire locations.

Satellite derived fuel moisture content and Jasmin soil moisture content were the shortest duration datasets of those contained in the table. Thus, it is less significant that it is those fields for which the most extreme rankings consistently occurred across fire areas and averaging times, with longer (two and five year) averaging periods recording ranking one for most with the exception of Yanchep, which was less extreme.

UTILISATION AND IMPACT

SUMMARY

End-user agencies from the jurisdictions affected by the 2019-20 fires have been briefed on progress of the project. The project team highlighted the efforts to integrate separate strands of information to provide a coherent assessment of the preconditioning of the landscape prior to fire ignition. Agencies will be able to adopt a corresponding approach in coming seasons to be better prepared for future fire events.

Given the tight timeframes of the project, there has not been time for further uptake of the extension project work. However, the antecedent projects have both been utilised in a number of ways as described below.

JASMIN data from the Land Dryness project and FMC data for the “Mapping Bushfire Hazards and Impacts” are available to agencies via the BoM and ANU THREDDS servers respectively, with several fields available to visualise courtesy of the AFMS website.

AFMS

Australian Flammability Monitoring System website

Australian Flammability Monitoring System is in use by agencies across Australia, including during the 2019-20 fire season, to better monitor the state of fuels. A major component of AFMS is the Live Fuel Moisture Content which provides, on a landscape scale, an ability to assess dryness of live vegetation and its capacity support fire.

Utilisation potential

The work in the current extension project further refines the importance of monitoring FMC, and the AFMS as a tool for that purpose, given the close relationship established between declines in FMC and subsequent fire ignitions.

Utilisation impact

This work has not yet had a direct utilisation impact, having not been implemented on account of the short-term nature of the extension projects. As noted elsewhere, however, the soil and fuel moisture projects separately have had impacts both in operational use and in fostering further research. The combination of the two projects, in particular, is having a far-reaching impact in the Australian Fire Danger Rating System implementation.

Curing estimates are required for the sub seasonal to seasonal module of the new service, due to commence operational trial later in 2021, as curing is an important variable in the calculation of fire danger for over 60% of the land area of Australia (grasslands plus woodlands). In the past, however, there has not been an accepted tool for estimating future curing. Research work done as part of the Land Dryness project, using results from the Live Fuel Moisture Content project has shown how vegetation moisture content (including curing) can be estimated from soil moisture values up to several weeks ahead.

This research is being implemented through the currently operational AWRA-L framework, making use of the high correlation between the JASMIN and AWRA-L systems, established in the Land Dryness project, and confirmed in the current extension project.

CONCLUSION

A number of key results were identified by the project team:

Most fire locations experienced extreme temperature and (low) precipitation extremes leading into the times of fire ignition.

Immediately antecedent seasons were also generally dry and hot, which contributed to cumulative vegetation stress, but not as extreme as 2019.

While cool season fuel moisture levels ahead of the 2019-20 fire season were comparable to previous corresponding periods, the decline of fuel moisture content was steeper during the early part of the season.

Characteristics of the land surface model strongly influenced the soil moisture over fire grounds.

As identified during the original Bushfire and Natural Hazards CRC Land dryness project, AWRA-L performs comparably to JASMIN despite the systems employing different approaches to modelling soil moisture. This supports the view that research findings from the Land Dryness project (such as the relationship between soil and fuel moisture content) may be applied to the AWRA-L data to provide operationally useful outputs. Such work is underway currently, in the context of the Australian Fire Danger Rating System.

The project afforded the opportunity to investigate the interaction between meteorological parameters and the resultant soil and fuel parameters. It was clear that the moisture parameters integrated the cumulative effects of temperature, precipitation and atmospheric moisture in a way that highlighted subtle instantaneous differences from normal of the meteorological parameters. In this way, the project outcomes reinforce the view that monitoring of soil and fuel moisture content is a valuable tool to identify potential fire activity.

Many of these points are not unexpected. It is, however, valuable to confirm that they were present and very likely contributed to fire activity within the specific regions in which the selected fires occurred. In addition, the combination of meteorological and soil and fuel moisture fields had not been examined in this fashion before. It is something that fire, and land managers have had to do in an intuitive and heuristic fashion, however. Having a scientific basis to continue this practice can only assist in refining an operational analysis of field and landscape-scale data for the assessment of fire potential.

Some immediate benefits for fire managers of this work include:

- AWRA-L provides comparably valuable root-zone soil moisture information to JASMIN. AWRA-L is currently available on a daily basis (e.g. at http://www.bom.gov.au/water/landscape/#/sm/Actual/day/-28.4/130.4/3/Point////2021/6/14/). In particular, relative values of AWRA-L soil moisture provide an historical context for values on several timescales, allowing a qualitative assessment of fire risk in the environment.
- On an annual and area-integrated basis, mean levels of fuel moisture content can change substantially, especially in forested areas of eastern Australia. By implication, successive years of dry conditions can lead to

dramatic downward changes in fuel moisture content, and thus heightened fire risk.

- Related to these points, and as noted in the Key Findings above: if soils are very dry in the cool season, even if fuel moisture content is close to normal at that time, the fuel moisture can rapidly decrease with the onset of warmer conditions. This observation can act as a useful warning indicator for fire managers of potential rapid onset of increased fire risk.
- Each of the meteorological and moisture variables investigated in this study contributed useful information to an understanding of increased fire risk at each site during the 2019-20 Australian summer. Fuel moisture content provided perhaps the most immediate indicator of present fire risk. Soil moisture content permitted an assessment of future changes in fuel moisture content. Both of these integrated changes in meteorological parameters. As such, the meteorological parameters (temperature, precipitation, atmospheric moisture represented by vapour pressure) contributed an understanding of why soil and fuel moisture changed in the ways that they did and offered information on how they would change in the future. Monitoring these quantities can help fire and land managers understand how and why fire risk changes across a landscape.

NEXT STEPS

The land surface model used in the ACCESS numerical weather prediction model doesn't include consideration of groundwater, i.e. that water below the bottom model level of 3 m in JULES/JASMIN and 6 m in AWRA-L. Preliminary analysis of GRACE (Gravity Recovery and Climate Experiment) datasets over these fire locations indeed showed a significant downward trend of soil water storage (primarily as ground water) prior to the fire season, suggesting an important contribution of ground water conditions to this fire season. Discussion within the project team during the course of the project identified an uncertainty about the extent to which particularly forest vegetation was able to access such water, and therefore influence the accuracy with which the land surface model soil moisture representation is able to reflect fuel moisture. This will be valuable to investigate in future, as part of the Bureau of Meteorology hydro-JULES coupled earth-system modelling framework. This may assist in explaining some results reported before that using JASMIN soil moisture to predict FMC is less successful for forest sites than other vegetated surfaces.

Similarly, it was outside the scope of the current project, but it would be valuable to investigate the optimal vertical resolution of the land surface models used in coupled earth-system models, for better modelling of the surface-atmosphere interaction, including representation of vegetation fluxes. At climate timescales, broader vertical resolution of the land surface seemed adequate, as there were generally similar trends through the JASMIN soil profile with time. At synoptic timescales (days to a week or more), greater, potentially important, differences could be seen to emerge.

Assimilation of Sentinel radiances into land surface models would likely prove useful to better constrain such fluxes.

Further effort to develop downscaling techniques for soil moisture modeling would be valuable. The high resolution of Sentinel-2 vegetation moisture content highlighted the differences in resolution between the two fields.

This points to a further area of useful research. While the project team were able to identify areas of higher fire severity via damage to vegetation, and link that to some degree with antecedent low fuel moisture (Supplement 2), it would be valuable to investigate the potential links between periods of enhanced fire weather and burn severity. This may be possible by tying in ACCESS-Fire simulations, a sister project, with this work. It would, however, require there to be sufficiently detailed fire behavior observations for any fire studied, a constraint that will not be universally met.

Again, at high spatial resolution, it would be valuable to re-examine variation of weather parameters within fire areas e.g., Badja final boundary includes maritime influenced locations, however the project averaged parameter values across the fire area, noting for future investigation that there would likely be substantial differences at times across the fireground.

All of these potential activities will improve measurement of soil and fuel moisture content across the Australian landscape. They would also enhance understanding of the interaction of weather and the flow of moisture through the environment and improve procedures for routine fire and land management and the management of bushfire events.

The project focused on interaction of atmospheric and land surface variables on live fuel moisture. In future, it would be valuable to adopt a similar spatially aware approach with dead fuel moisture (a variable ANU is generating under the frame of another Black Summer project), to develop a holistic approach to fuel availability, live or dead. This would be directly applicable to the AFDRS.

Ongoing verification and calibration of the soil moisture models will be important, given their value for numerical weather prediction in general, and fire weather forecasting in particular, both at the weather (0-7 days) and longer climate timescales.

The project team hopes to document aspects of the final report as a publication in the peer-reviewed literature.

TEAM MEMBERS

Team members were drawn from several groups within the Bureau of Meteorology Research Centre and from the Fenner School of Environment and Society at the Australian National University.

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Dr Paul Fox-Hughes (BoM)

Mr. Jeff Jones (BoM, Project Manager)

END-USERS

End-user organisation	End-user representative	Extent of engagement (Describe type of engagement)
NSW RFS	Laurence McCoy, David Field	Data supply, discussion of fire activity and underlying vegetation state
VIC DEWLP	Anthony Cheesman	
ACT Parks	Adam Leavesley	
SA DEW	Simeon Telfer	
WA DBCA	Lachie McCaw, Valerie Densmore	
WA DFES	Jackson Parker, Agnes Kristina	
QLD QFES	Ray Bott, Russell Stephens-Peacock	

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SUPPLEMENT 1: HIGH RESOLUTION FUEL MOISTURE CONTENT

Sentinel - 2 was used to investigate live Fuel Moisture Content (LFMC) change at high spatial resolution over the period of data availability (2015 to 2020) and the influence of FMC gradients on fire severity.

Sentinel 2 mission from the EU Copernicus Programme includes Sentinel 2A and Sentinel 2B satellites which were launched in 2015 and 2017, respectively Revel et al. 2019). Sentinel 2 provides global coverage with 5 days revisit frequency, 13 spectral bands and spatial resolution of 10m, 20m and 60m depending on the spectral band (Revel et al. 2019; Gascon et al. 2017). Sentinel 2 data were obtained from Digital Earth Australia (DEA) hosted at National Computing Infrastructure in Canberra, Australia (www.nci.org.au). DEA produces analysis ready data that went through several data processing steps that includes geometric and surface reflectance correction (https://docs.dea.ga.gov.au).

Yebra et al. (2018) algorithm was used to calculate LFMC from Sentinel-2 dataset. The methodology of the algorithm comprises of a physically based retrieval model to estimate LFMC from MODIS (Moderate Resolution Imaging Spectrometer) reflectance data using radiative transfer model inversion. Accuracy of the model was evaluated with 360 field observations at 32 locations across Australia. Average accuracy of all land cover classes (grassland, shrubland, and forest) was RMSE=40% with explained variance of r2=0.58 (Yebra et al. 2018). This algorithm was adapted to calculate LFMC from Sentinel 2 data (https://github.com/ANU-WALD/sentinel2_fmc).

Time-series of LFMC were calculated from all the good quality Sentinel-2 data for all sites to investigate how LFMC changed over time. Furthermore, LFMC values for each site were resampled to monthly and yearly averages and time-series plots were produced to represent LFMC trends. In addition, several LFMC maps were produced for each site which allow to visually compare pre and post fire LFMC values. To investigate the influence of vegetation types on LFMC, we use a Landsat based product of woody vegetation cover across Australia (Liao et al 2020) to classify the fuel in three fuel classes (grass, shrub, forest) and plotted LFMC change over time in accordance with those categories.

Fire severity was estimated using the relative differential normalised burn ratio (Relative dNBR) (Equation 1) calculated from Sentinel-2 dataset.

$$RdNBR = \frac{dNBR}{\sqrt{ABS(\frac{NBR_{pre-fire}}{1000})}}$$ (Equation 1)

Where dNBR = pre-fireNBR – post-fireNBR (Equation 2)

and pre-fire- or post-fire- are the before and immediately after the fire normalised burn ratio (Key and Benson 1999) (Equation 3)

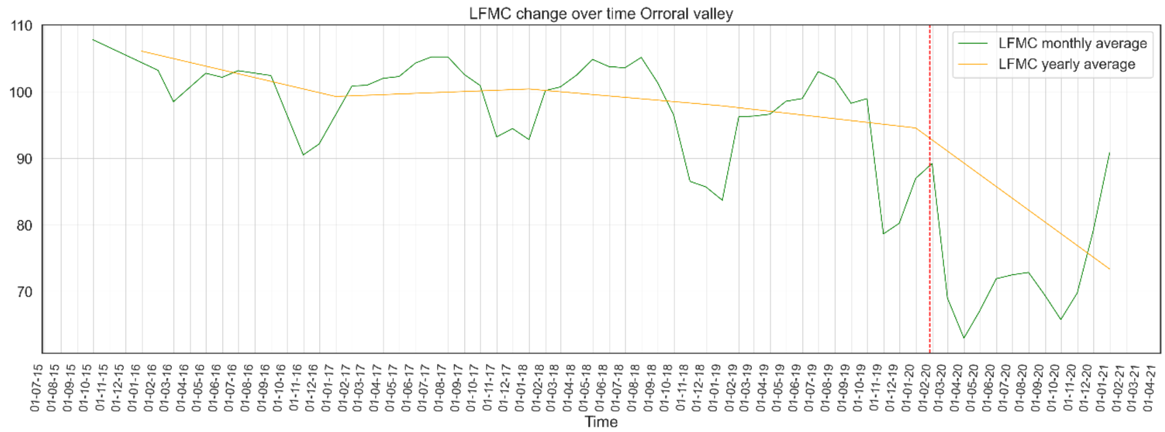
NBR = (NIR - SWIR) / (NIR + SWIR) (Equation 3)

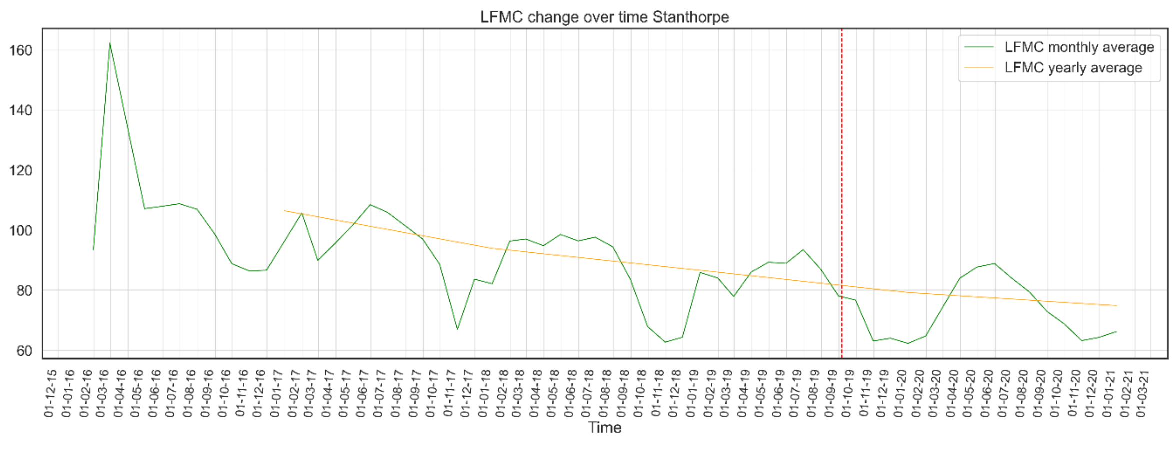
NBR uses near-infrared (NIR) and shortwave-infrared (SWIR) portions of the electromagnetic spectrum (Formula 1). NBR values range between –1 ad 1. Burn pixels have positive dNBR values while unburn pixels have negative or very close to zero dNBR values. Furthermore, dNBR values were classified into unburn (< 0.01), low burn (< 0.40) and high burn (> 0.40) to generate fire severity map.

Results

Time series analysis of LFMC change revealed patterns that are directly or indirectly related to 2019-2020 bushfires. Monthly LFMC averages demonstrate seasonal change with sharp decline and rapid increase of LFMC values between seasons. It also shows a trend toward lower values in 2019 in comparison to previous years. For example, the LFMC for Orroral valley and Stanthorpe averaged for the total burned extend gradually decreased since 2015 until before the respective fires started. However, for other fires (e.g., Badja) LFMC stayed more or less stable between years.

We can also see dramatic decline in post fire LFMC values (given the vegetation is either scorched or fully burned) and a gradual recovery in LFMC a few months after the fires across all sites, given precipitation events.





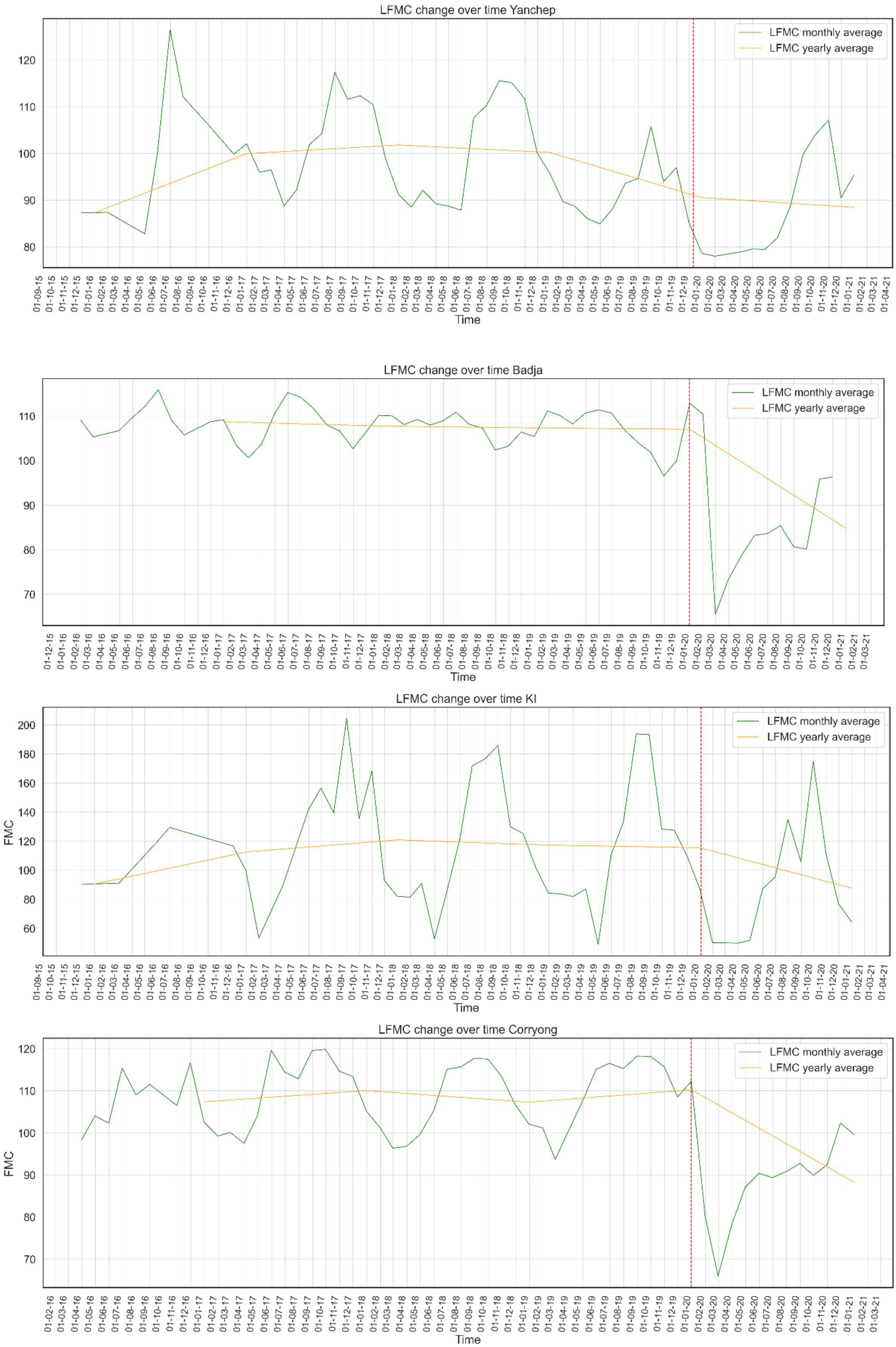


FIGURE 1. TIME-SERIES OF LFMC CHANGE AVERAGED OVER THE FIRE PERIMETERS OF EACH OF THE STUDIED FIRES BETWEEN 2015 AND 2020. GREEN AND ORANGE LINES SHOW MONTHLY AND YEARLY AVERAGES OF LFMC VALUES, RESPECTIVELY. VERTICAL RED DASHED LINE INDICATES THE DATE THAT FIRE STARTED.

Figure 2 shows the LFMC dynamics for different vegetation types and three fires as example. The forest (land cover dominating the study areas) LFMC has gradually decreased LFMC in the last 5 years whereas that decreased in not as evident for the other land cover types.

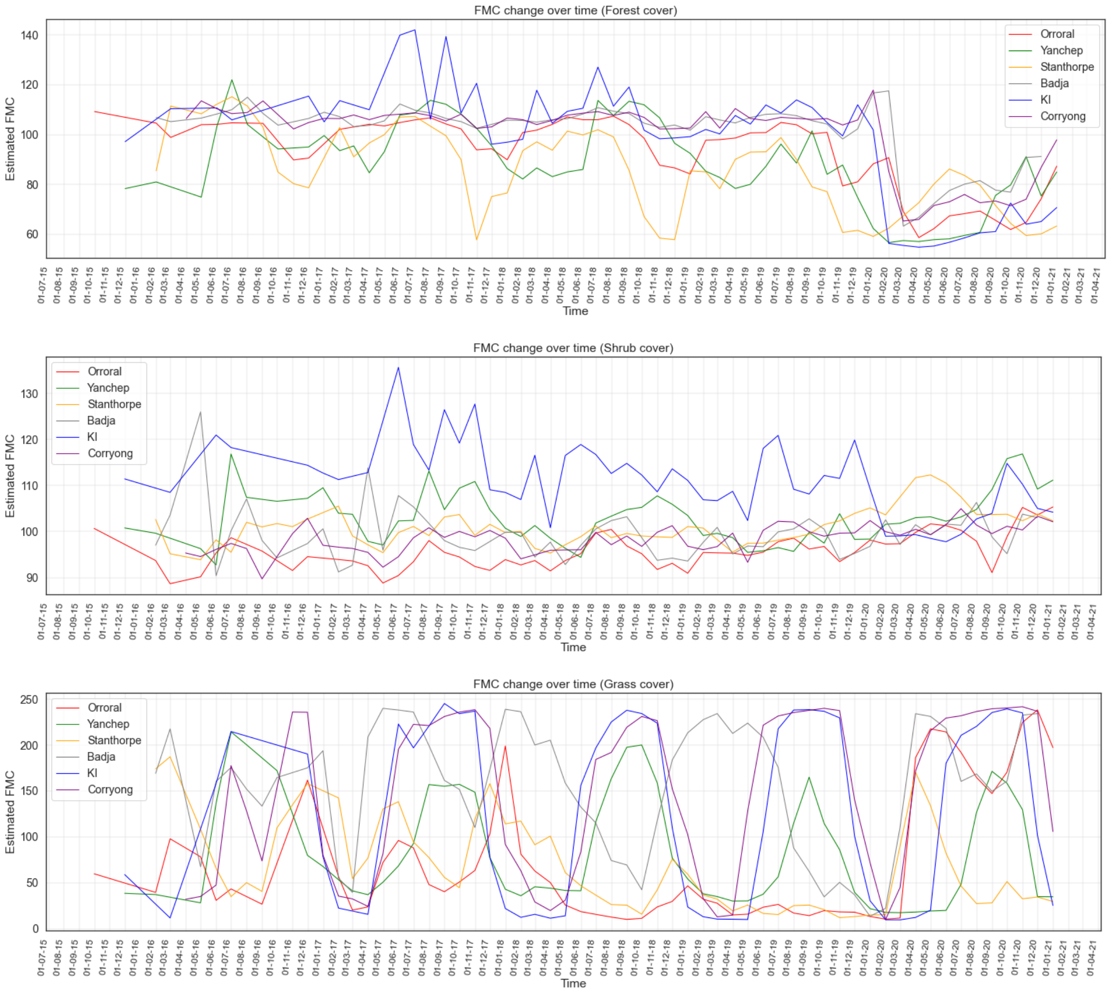
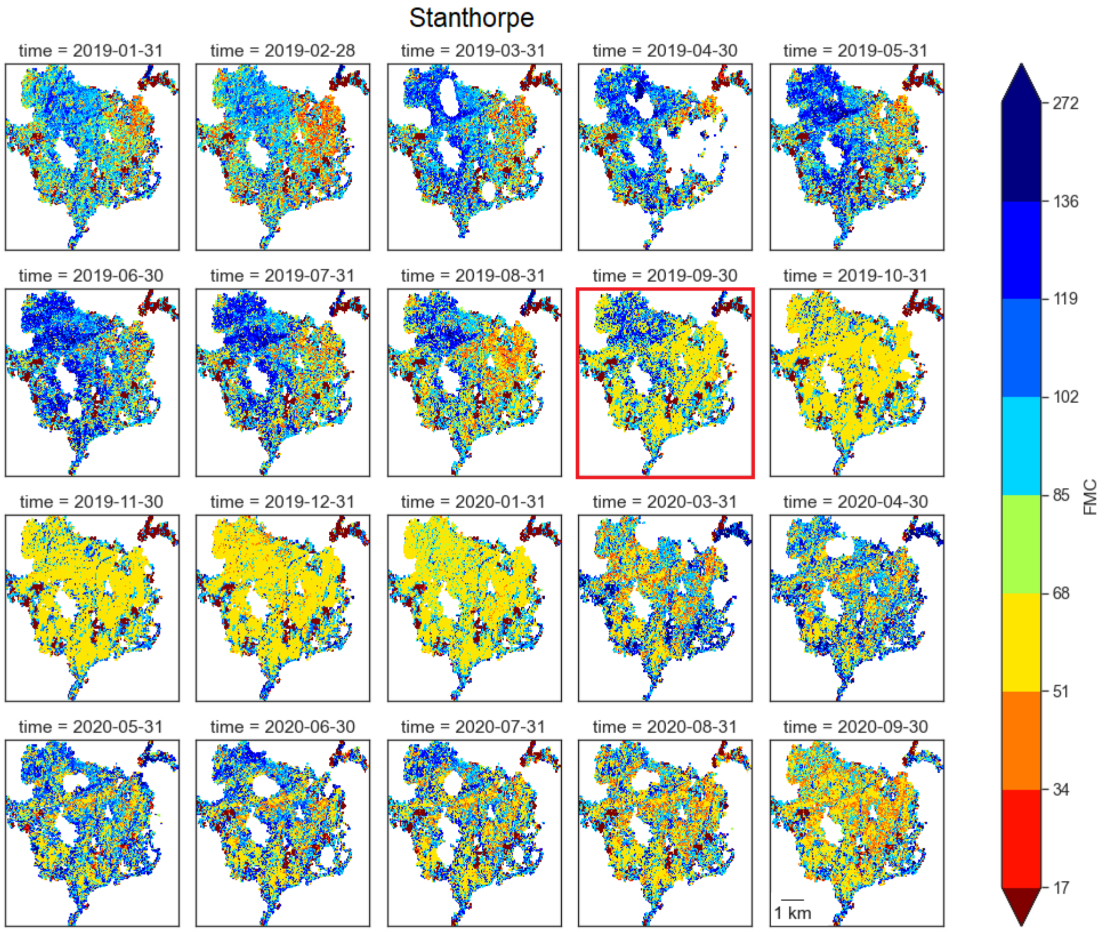


FIGURE 2 MONTHLY AVERAGE LFMC CHANGE BY VEGETATION TYPES: FOREST (TOP), SHRUB (MIDDLE) AND GRASS (BOTTOM). VERTICAL LINES INDICATE THE DATES THAT FIRE STARTED.

Time series maps were generated to visually represent LFMC change before and after fire (Fig 3) and investigate its relation with fire severity. Pre-fire LFMC had a strong seasonality for the Orroral Valley fire, especially in the south east corner that significantly dropped LFMC in the months leading to the fire. After the fire LFMC slowly increased with post fire rains (Fig 3) being that increment more evident after October 2020 (Fig. 1). These results align with the patterns of LFMC change that were described in Fig 1.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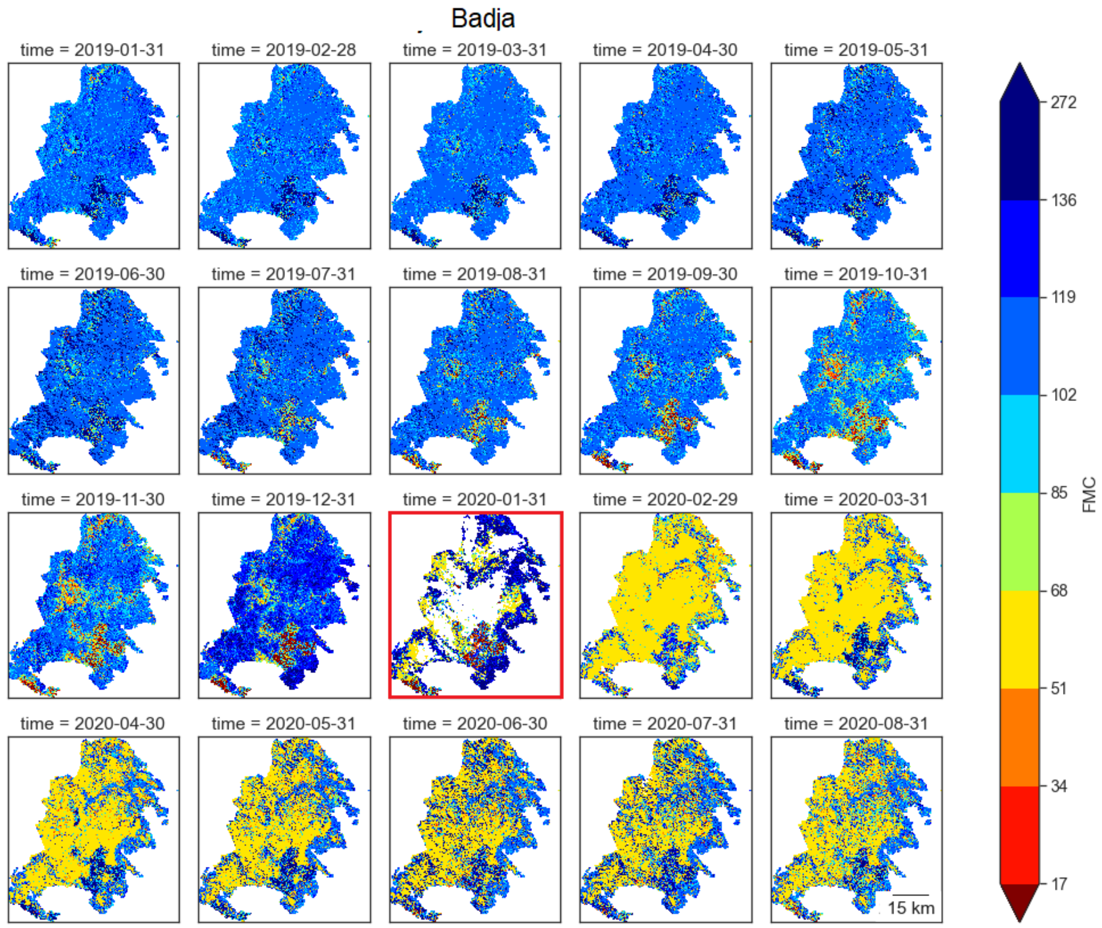
time = 2020-01-31
time = 2020-03-31
time = 2020-04-30
time = 2020-05-31
time = 2020-06-30
time = 2020-07-31
time = 2020-08-31
time = 2020-09-30
1 km
272
136
119
102
85
68
51
34
17
FMC


Badja
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time = 2019-11-30
time = 2019-12-31
time = 2020-01-31
time = 2020-02-29
time = 2020-03-31
time = 2020-04-30
time = 2020-05-31
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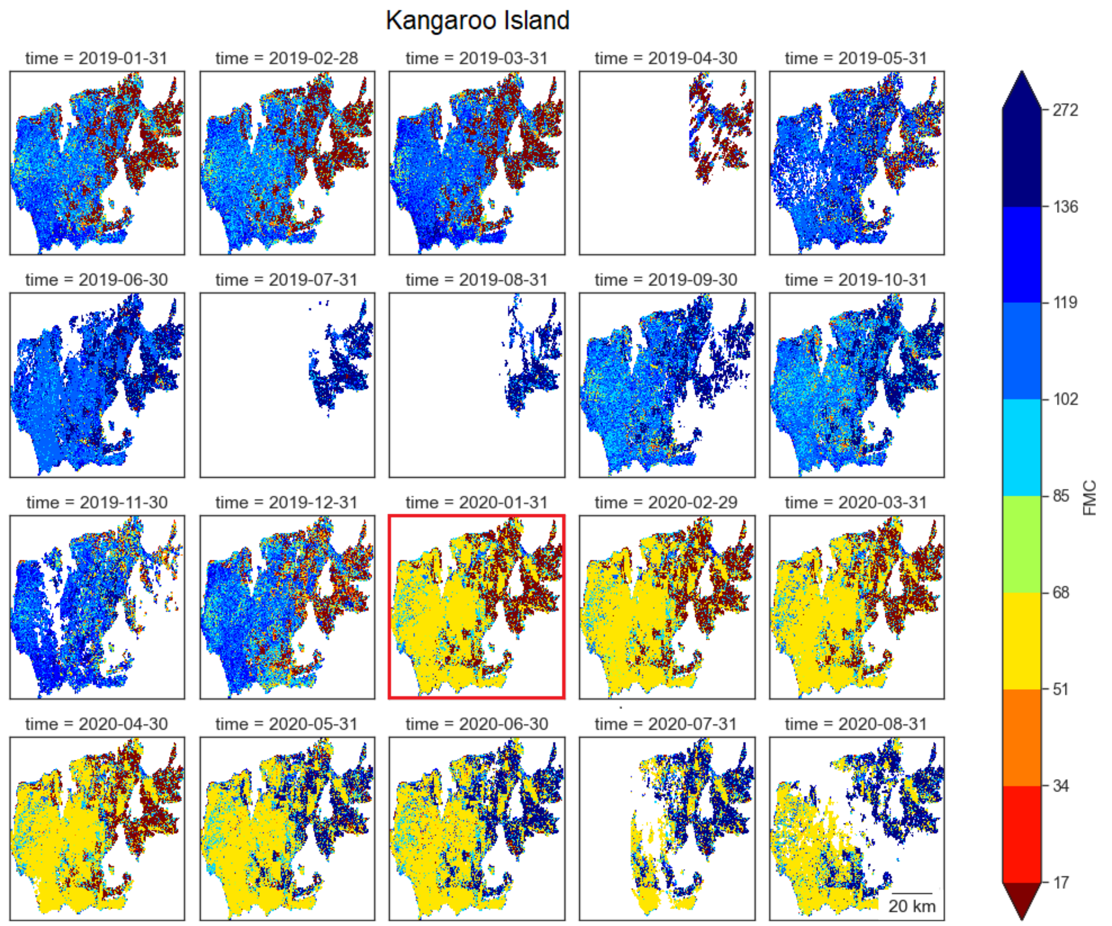
time = 2020-08-31
15 km
272
136
119
102
85
68
51
34
17
FMC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time = 2019-11-30
time = 2019-12-31
time = 2020-01-31
time = 2020-02-29
time = 2020-03-31
time = 2020-04-30
time = 2020-05-31
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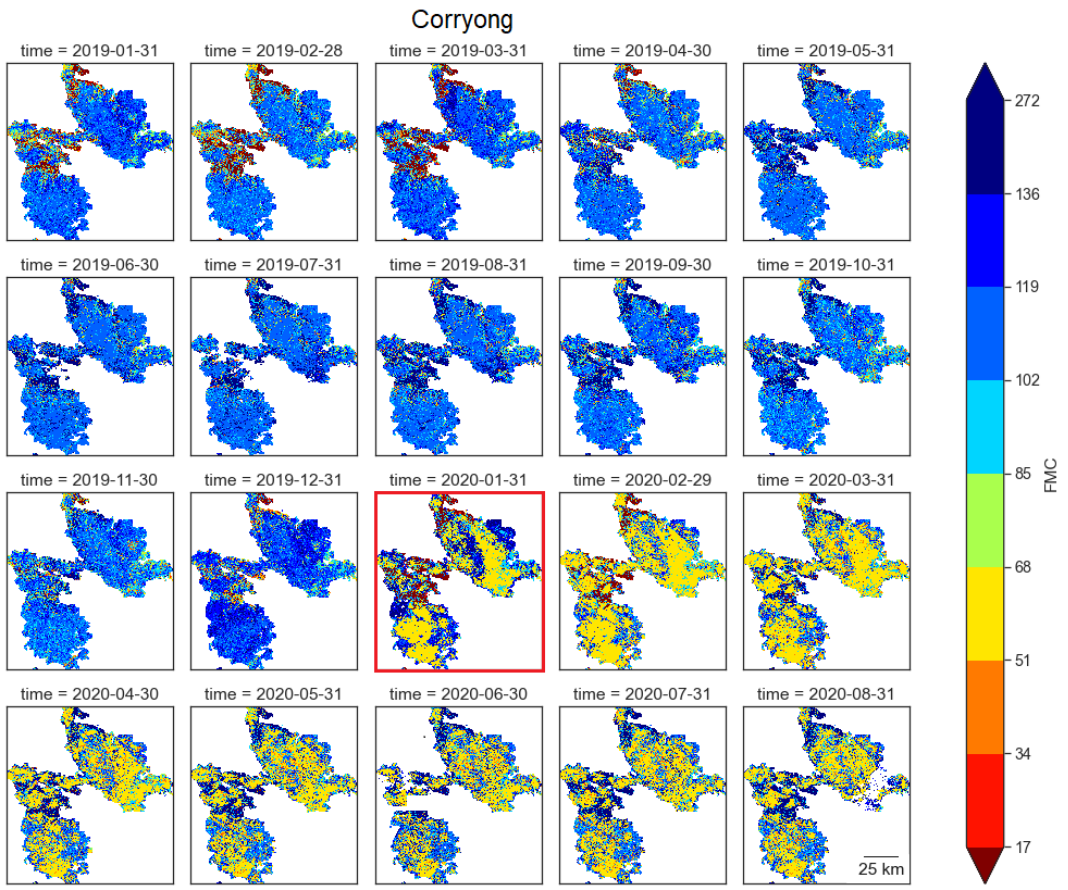
time = 2020-08-31
20 km
272
136
119
102
85
68
51
34
17
FMC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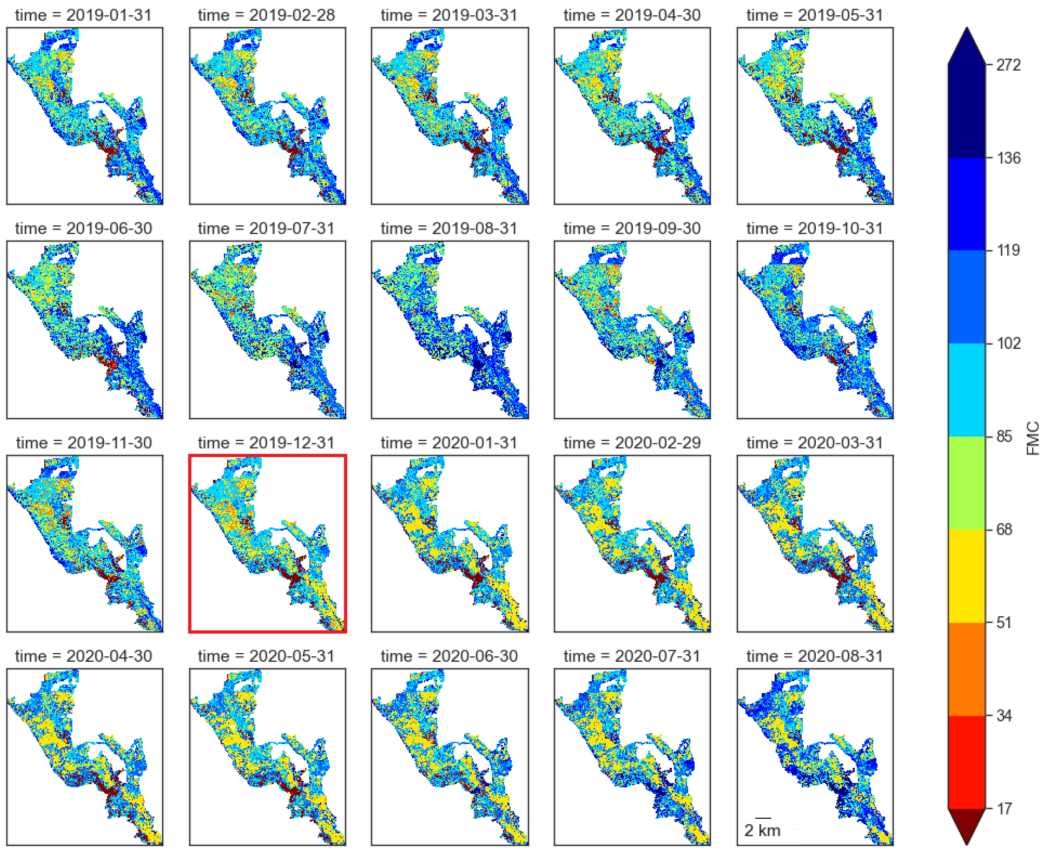
time = 2019-11-30
time = 2019-12-31
time = 2020-01-31
time = 2020-02-29
time = 2020-03-31
time = 2020-04-30
time = 2020-05-31
time = 2020-06-30
time = 2020-07-31
time = 2020-08-31
25 km
272
136
119
102
85
68
51
34
17
FMC

Yanchep



Orroral

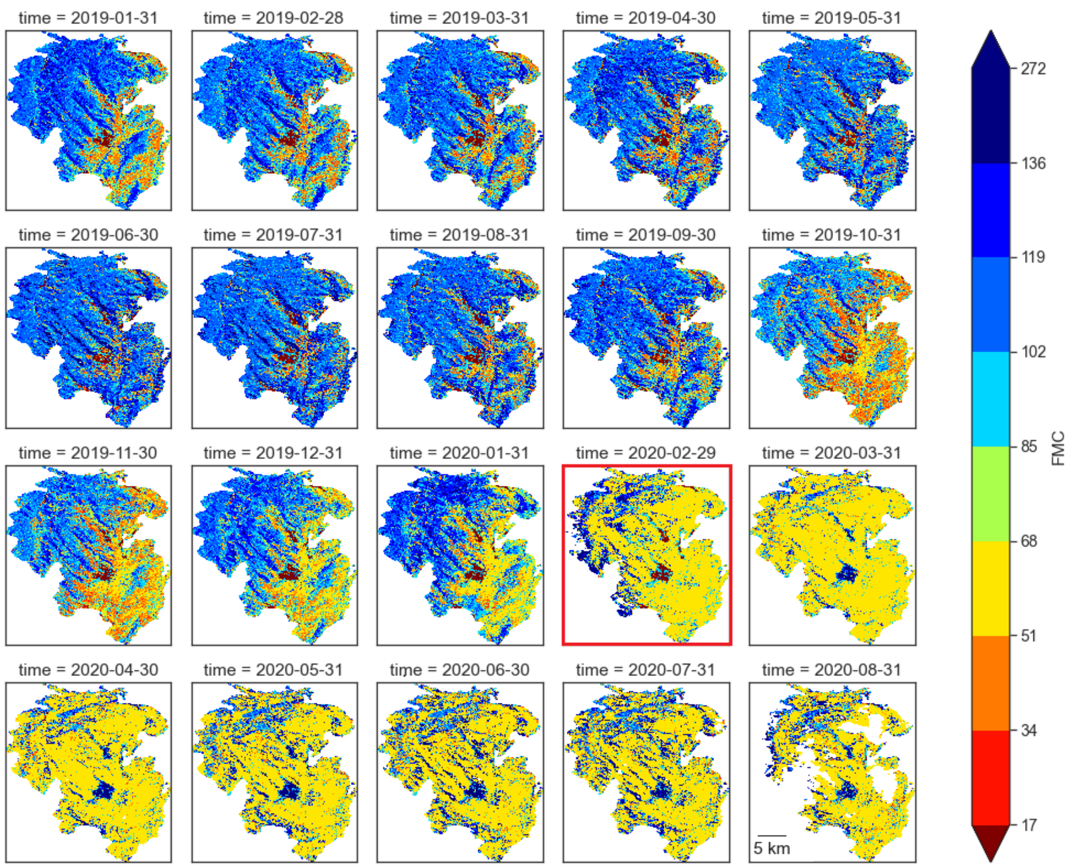
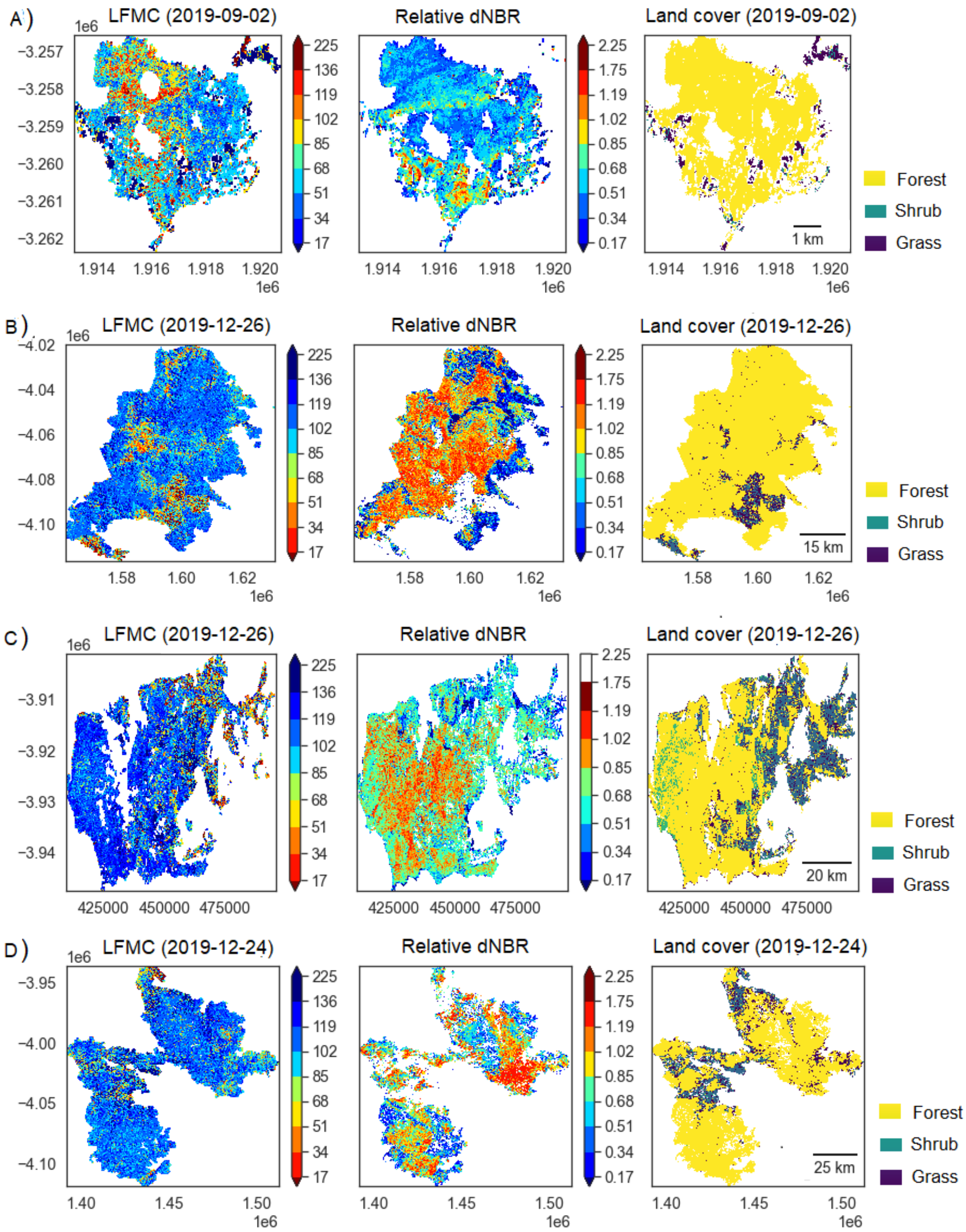


FIGURE 3. PRE AND POST FIRE MONTHLY AVERAGE LFMC MAPS FOR THE STUDIED FIRES. RED TO BLUE GRADIENT COLORS SHOW LOW TO HIGH LFMC VALUES. RED OUTLINED MAPS HIGHLIGHTS THE MONTH THAT FIRE STARTED.

Figure 4 shows pre fire LFMC, post fire burn severity map (based on the RdNBR) and vegetation cover maps. It should be noted that Orroral valley, Yanchep and Stanthorpe sites mostly covered by forest. Only small portion of sites covered by shrubland and/or grasslands. Overall, there seem to be better match between LFMC and fire severity for the Orroral Valley where the areas that were drier in the pre-fire scene seem to better correspond to areas with higher fire severity. This is not as evident for Yanchep and even less for Stanthorpe.



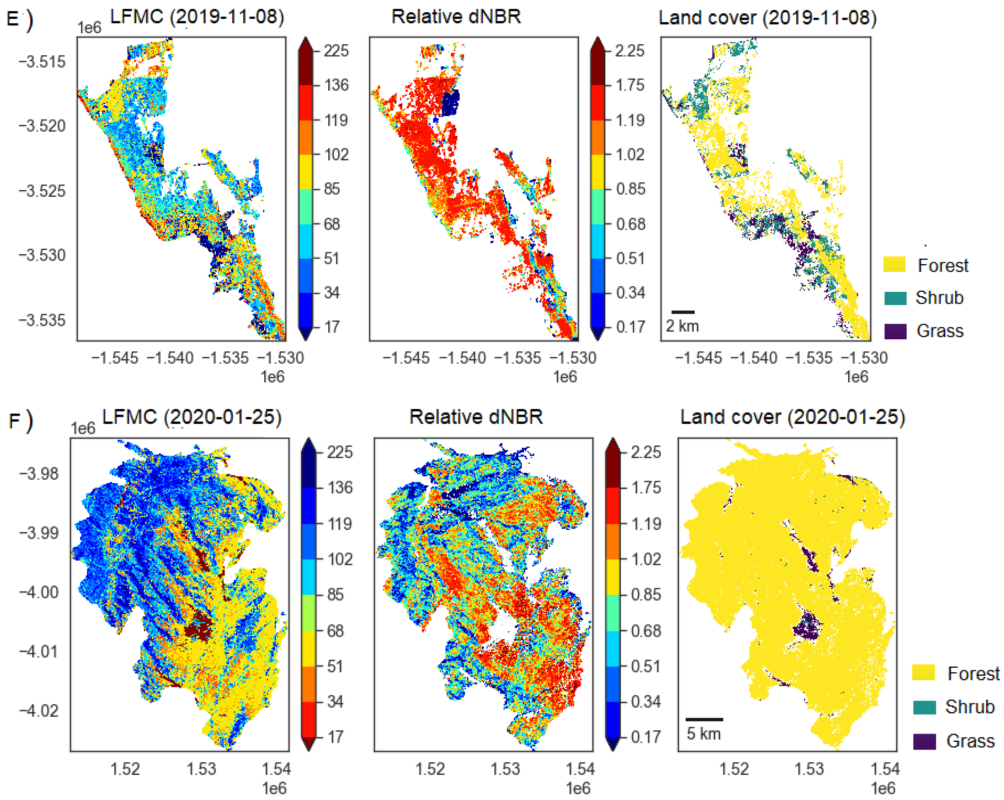


FIGURE 4 PRE FIRE LFMC (LEFT), FIRE SEVERITY MAP EXPRESED AS RDNBR (CENTER) AND VEGETATION MAP (RIGHT) F0R STANTHORPE (A), BADJA (B), KANGAROO ISLAND (C), CORRYONG (D), YANCHEP (E) AND ORRORAL VALLEY (F). GRASSLAND AREAS WERE MASKED OU.

Quantitatively pre-fire LFMC and RdNBR are negatively related to RdNBR for Orroral and Yanchep but there is not significant correlation for Stanthorpe nor the other fires except for Kangaroo Island that present a positive relation that should be further investigated (Figure 5).

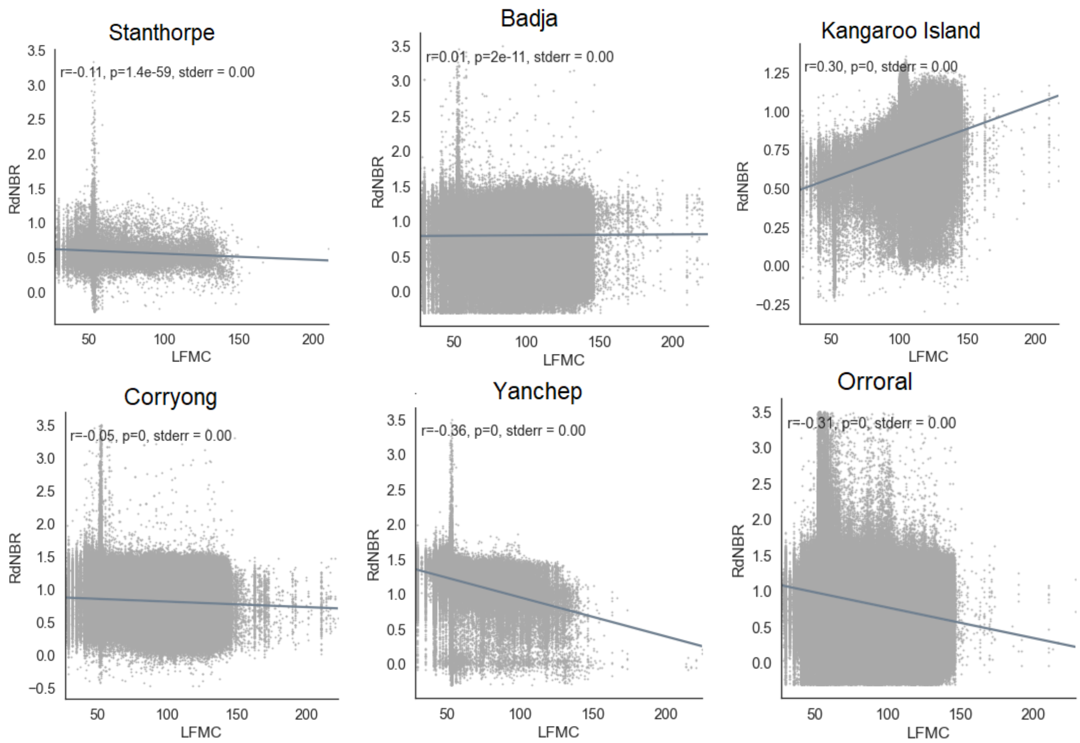


FIGURE 5. RELATIONSHIP BETWEEN RDNBR AND LFMC FOR THE DIFFERENT STUDIED FIRES.

1 Gascon, Ferran, Catherine Bouzinac, Olivier Thépaut, Mathieu Jung, Benjamin Francesconi, Jérôme Louis, Vincent Lonjou, et al. 2017. "Copernicus Sentinel-2A Calibration and Products Validation Status." Remote Sensing 9 (6):584.

2 Revel, Charlotte, Vincent Lonjou, Sébastien Marcq, Camille Desjardins, Bertrand Fougnie, Céline Coppolani-Delle Luche, Nicolas Guilleminot, et al. 2019. "Sentinel-2A and 2B absolute calibration monitoring." European Journal of Remote Sensing 52 (1):122-37. doi: 10.1080/22797254.2018.1562311.

3 Yebra, Marta, Xingwen Quan, David Riaño, Pablo Rozas Larraondo, Albert I. J. M. van Dijk, and Geoffrey J. Cary. 2018. "A fuel moisture content and flammability monitoring methodology for continental Australia based on optical remote sensing." Remote Sensing of Environment 212:260-72. doi: 10.1016/j.rse.2018.04.053.