BLACK SUMMER 2019–20 RESEARCH
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COUPLED FIRE-ATMOSPHERE SIMULATIONS OF FIVE BLACK SUMMER FIRES USING THE ACCESS-FIRE MODEL

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Cover: Fire generated vortex near Karumba (Victoria, Corryong fire) at 7.30pm 30 December 2019. Photo courtesy Ms Janice Newnham.

TABLE OF CONTENTS

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We are very grateful to all our end-user representatives and their agencies for their support of, and their input into this project. We would particularly like to thank those who have provided fire behaviour and other data and participated in valuable and enjoyable discussions with us as work on the case studies has progressed.

We would like to thank our Bureau custodians and sponsors Harald Richter, Bertrand Timbal and Gilbert Brunet for their support of this work and for affording us autonomy and flexibility while undertaking this project. We would particularly like to thank Dr Beth Ebert for her detailed reviews of our draft report and her ongoing support.

We are especially grateful to those sponsors who have supported our work with coupled fire atmosphere models since our first experiments in 2010, through the ACCESS-Fire CRC project which ran from 2016 to 2020 and then to this current work on the Black Summer fires. It has been a long pathway which started with a very small team that has expanded in response to the recognised value of this work in contributing to our future needs for fire prediction. We look forward to extending recent discussions on plans for operational application.

The authors are grateful to staff at the CRC for their ongoing support of the project and offer thanks to everyone at the CRC for the work administering our project, running events and promoting research, facilitating end-user engagement and supporting communication activities. We look forward to continuing to work with the team in the new centre.

Finally, we would like to acknowledge all those Australians whose lives were impacted by the Black Summer fires. We hope that this work goes some way in assisting the Australian community in understanding and reconciling the devastating fires that occurred. We are optimistic that this research will place us to respond better to inevitable fire events in the future.

EXECUTIVE SUMMARY

Context

This research builds on previous work completed during the *Coupled fire-atmosphere modelling ACCESS-Fire* project, by conducting case studies of five major bushfires that occurred across Australia during the 2019-20 summer. The previous work provided valuable insights into the drivers of periods of extreme fire behaviour associated with the Waroona fire in WA, and the Sir Ivan fire in NSW.

The main objectives of this project are: to investigate the meteorological drivers of extreme fire behaviour at five further fire events; to further test the reliability and stability of the model in different environments across Australia; and to support and share learnings from the events of the 2019-20 summer with partner agencies.

The fire events nominated by state jurisdictions for investigation were: *Badja* (New South Wales), *Stanthorpe* (Queensland), *Corryong* (Victoria), *Kangaroo Island* (South Australia); and *Yanchep* (Western Australia).

The case studies show that the local context for each fire is important. Each of the fires posed significant challenges in different ways. In the heavily forested areas of NSW and Victoria, the sheer size, intensity, and duration of the fires were distinctive. At other fires, the proximity of local communities and infrastructure posed serious challenges. All fires were active in the overnight period when conventional fire danger indices typically suggest a decrease in fire activity.

The marine boundary layer, local coastal effects and topography combined to generate complex wind flows that influenced the progression of the Kangaroo Island fire. We also studied the way in which the sea breeze circulation interacted with the Yanchep fire, and examined the impact of a prescribed burn on the rate and direction of spread of the Stanthorpe fire under extreme fire weather conditions.

This project has explored gaps in knowledge and understanding of the processes at play during these unusual events by using the Bureau's ACCESS-Fire model to examine the local three-dimensional interactions between the fires and the atmosphere. The learnings from this project may be applied to shape future fire weather products and services.

Method

Based on discussions with our partners in fire agencies, together with documents (including photographs and video) and information on fire spread, fuel types and fuel moisture and atypical fire behaviour, we have run a series of simulations and prepared case study chapters for each of the five fires.

The ACCESS-Fire model was initialised using information provided by fire agencies on ignition location or fire line perimeter and fuel type and availability. Several simulations were conducted for each of the fires, with a focus on different time periods of interest and using updated fire polygon boundaries based on available line scan imagery.

The model configuration does not permit the simulations to account for suppression activities by fire agencies, changes in fuel types on the urban interface, or the impact of roads or other fire breaks in reducing the rate of spread of the fire. Another limitation is that the simulations are a single realisation, when in reality, consideration of forecast uncertainty (for example through running an ensemble scheme) would capture a range of potential outcomes.

Learnings from the case studies reinforce and refine some previous learnings from historical fire events and uncover some new insights into the processes driving the periods of unusual fire behaviour that were observed during the 2019/20 season.

Key findings

The case study analyses have provided valuable insights into meteorological aspects of observed extreme fire behaviour during the 2019/20 summer. Key findings for each of the five case studies are included in the individual chapters for each fire and a synthesis is provided here.

The ACCESS-Fire simulations run at 300 m spatial resolution show that some of the most dangerous effects of the fires, in particular damaging and destructive winds, are fire driven and therefore very localised at a much finer scale than current fire weather products.

The depth, elevation and structure of low-level jets over topography was a critical driver of overnight fire activity. Given that these jets are driven by larger scale processes (typically synoptic scale), there is an opportunity to develop new tools based on numerical weather prediction output that highlight the location and intensity of these features. Such tools would provide additional information for meteorologists and FBANs on the strength and height of representative winds for input to two-dimensional fire spread models and could be used to alert fire managers to the risk of atypical fire spread in the overnight period.

A key theme that emerged from the case studies and discussions with stakeholders was the consistent occurrence of heatwaves and their influence on boundary layer structure overnight and on inhibiting fuel moisture recovery during the overnight period. Further research quantifying the effects of overnight heatwaves is required to appropriately plan for the increased risk to communities and fire crews in a changing climate, as the frequency of elevated overnight temperatures has increased over the last few decades and is projected to increase further (along with other factors influencing fire activity).

Deep moist pyroconvection producing pyrocumulus (pyroCu) or pyrocumulonimbus (pyroCb) clouds was a feature of the 2019-20 fire season and a record number of sustained outbreaks of pyroCbs occurred. However, the five fires examined here were not all associated with pyroCb, highlighting that it is not the sole weather phenomenon associated with extreme fire behaviour. In particular, no lightning was detected within the Green Valley Talmalmo fire (that subsequently became the Corryong fire when it burned into Victoria) as it burned through Green Valley, which shows that dangerous tornado-strength fire-generated winds can occur without pyroCb.

The simulations produced fire-generated extreme winds associated with both rotation and straight-line flow, which present a serious hazard. ACCESS-Fire simulated rotating winds in the updraft of the Green Valley Talmalmo/Corryong fire. More work is required to understand the mechanisms for these, they are likely related to the high intensity of the fire, coupled with topographic influences.

Spot fires were an important component in the observed rate of spread, particularly in the forest fires overnight. The extremely dry, drought-affected fuel beds meant that the ignition efficiency of spot fires was enhanced compared to an average season. Inclusion of a spotting parameterisation in ACCESS-Fire would accelerate the forwards fire spread and improve validation of the simulated fire perimeters.

Coastal processes were evident in the simulations of the Kangaroo Island and Yanchep fires. Localised wind effects in the simulations showed interactions between the fire and maritime airmass including sea breeze circulations can modify the updrafts associated with the fire as well as produce rapid transitions in fire intensity around a fire perimeter. Cooler moister air associated with a maritime airmass may not necessarily reduce fire intensity, depending on its depth and penetration inland.

Utilisation – where to from here?

The high level of engagement in this work from a range of stakeholders has demonstrated the value of this research and the appetite for operational application.

The learnings from this work should be incorporated into training packages tailored for fire meteorologists and FBANs that describe characteristics of the local meteorological environment favourable for extreme fire behaviour. Such training will complement other current research and training on fire behaviour aspects such as spotting and potential for pyroCb.

This work, which has been conducted in close collaboration with partners in fire agencies, has demonstrated that a comprehensive understanding of the mechanisms driving fire behaviour requires a multidisciplinary approach. Similarly, the successful application of fire behaviour and meteorology knowledge in operations requires locally connected specialised expertise, combined with tailored modelling tools to inform objective, evidence-based decisions.

The insights gathered from these five case studies have further demonstrated the value of this high resolution coupled modelling approach. In order to progress ACCESS-Fire to an effective operational tool, more robust testing of the model is required, in addition to the more subjective assessments that have been made through the case study work. This would include technical testing, additional sensitivity testing and routine verification.

This project has demonstrated that the Bureau's technology and simulation capability, scientific expertise and established relationships with fire agencies can meet the Australian community's need to understand the drivers of fire behaviour during the 2019-20 fire season. In doing so, we have further developed and validated our modelling systems and made progress towards their future operational use.

END-USER PROJECT IMPACT STATEMENT

John Bally, *Lead end-user, Fire Prediction Business Manager, AFAC*

The report describes an impressively large body of work, achieved over the past six months or so. It is very encouraging to see that the complex ACCESS-Fire system has proved robust enough to produce compelling simulations across this diverse set of sometimes quite extreme conditions. As the report points out, some of the simulated intense phenomena are small in scale, ephemeral and certainly highly sensitive to environmental conditions. They are not always to be taken literally, but the results presented here shed a very useful light into their structure and the larger scale and more reliably predictable conditions in which they form.

The work has been very enthusiastically received by the end user group and should be continued. Future operational use of ACCESS-Fire presents a host of technical, financial, data and organisational challenges. Some of these are particular to the very compute intensive nature of coupled fire models. Others are similar or even identical to the challenges of developing the Spark national operational bushfire simulator. In many ways, the two systems are complimentary, and development plans for both should be closely aligned. ACCESS-Fire is getting good enough to show up the limitations we get when not using more realistic fuel, full suite of fire behaviour models and not including spotting or suppression. As these are developed for Spark they should be incorporated.

PRODUCT USER TESTIMONIALS

Mike Wouters, *Manager, Fire Science & Mapping, Department for Environment and Water SA, Chair, AFAC Predictive Services (Bushfire) Practitioners' Network*

This study has progressed the state of coupled atmosphere-fire modelling significantly. The case studies have shown the benefit of this type of modelling over surface fire models in explaining/predicting fire behaviour, particularly in complex landscapes. This will push the desire of end-users and capability of BoM to progress this modelling closer to an operational state.

The case studies using this modelling have also highlighted the significant role upper atmosphere weather has on fire behaviour and End Users limited understanding of these effects. Coupled models, even if not operational yet, provide significant insights into the local effects and what may be causing them. These insights into what is driving extreme and unexpected fire behaviour are extremely valuable for future predictions, greatly enhancing firefighter and community safety.

Musa Kilinc, *Predictive Services Specialist, Bushfire Management – Predictive Services, CFA*

This project has developed sophisticated fire weather and fire spread reconstructions of major fires during Black Summer which traditional surface-based fire behaviour models were unable to reconcile adequately. This report provides us with better insights into fire generated vortices and merging fires, as well as the effects of low-level jets on fire behaviour. For many of us who were involved in the management of these fires, the work and effort put into this report provides context, sound science and reasoning to explain our observations. As a result, continued research, testing and application of predictive or risk-based modelling coupled with fire-atmosphere interactions could better inform fire management staff and activities in the future.

Dr Valerie Densmore, *Department of Biodiversity, Conservation & Attractions WA*

The five case studies evaluated using Access-Fire illustrate an important advance using coupled fire-atmosphere modelling to understand fire behaviour and review operational decisions. Classically, we have understood the critical roles that temperature, windspeed and direction, relative humidity and fuel dryness play to drive fire behaviour and the success of suppression efforts. This report crucially demonstrates how wind convergence and interactions with atmospheric and topographic features modified wind effects considerably from surface forecasts, producing spotting in contrary directions, significantly altered windspeeds and variable directions around the fires' perimeters. The reasonably accurate simulations also highlighted the potential benefits of fuel reduction burns to decrease fire spread and firepower. These key findings are centrally important to support appropriate media alerts and community warnings and the most beneficial structuring of operational resources and suppression efforts, both during the fire and the off-season hazard-reduction burning. The development of this tool into a real-time operational product would be a significant benefit to our organisation and other fire-fighting agencies across Australia.

Jackson Parker, *Director Bushfire Technical Services, Department of Fire and Emergency Services WA*

This project has demonstrated the benefits of coupled atmosphere modelling in the understanding of the effects of complex topography and the local meteorological environment on fire behaviour, during periods of elevated bushfire risk across five diverse case studies where unusually extreme fire behaviour was observed during the 2019-20 season. The Yanchep coupled fire-atmosphere simulations support the observations of the local fire agencies and when combined with the understanding of the preceding enhanced dryness of the landscape fuels, provides additional insight into the causes of the complex pattern of fire spread and fire behaviour changes that occurred over several days.

For the management of these fires the embedding of BoM Meteorologists into the incident management team to work alongside Fire Behaviour Analysists, has been invaluable in providing enhanced bushfire intelligence in regard to the potential variations in meteorological conditions around the fire perimeter and temporally. The potential of this collaboration to be enhanced by an operational version of ACCESS-Fire is demonstrated in the evidence of the effects of complex meteorology and topography on the fire behaviour within the case study bushfire reconstructions. These include new insights into known complexities that are only partially understood through previous learnings, however they cannot currently be adequately accounted for within current operational 2-dimensional bushfire simulators.

INTRODUCTION

The 2019-20 Australian bushfire season was extraordinary in many respects. Extended drought that led to dry, flammable fuels and anomalous hot, dry, westerly winds across eastern Australia during spring and early summer were key factors driving the broad spatial extent and prolonged nature of the multiple campaign fires that occurred.

The drought in eastern Australia that preceded the fire season was exceptional in terms of severity (extremely low rainfall compared to average), spatial extent and prolonged nature (multi-year low rainfall without relief). The drought coincided with the warmest period on record. The combination of hot and dry conditions led to very dry forest fuels across large areas of the country, which primed the landscape for intense, prolonged fires.

The season commenced very early with dangerous fire weather conditions experienced in south east Queensland and north east NSW in late winter and spring. These conditions extended to central eastern parts of NSW by late spring and early summer, then across south eastern parts of Australia in early to mid-summer, with a peak in fire extent and impacts around the New Year period before conditions abated in late summer.

The elevated fire dangers across eastern Australia were driven by unusually strong westerly winds during spring and early summer, which brought hot, dry air from inland areas to the coast.

Lightning strikes from thunderstorms that produced no significant rainfall (dry thunderstorms), were a significant source of fire ignition during the late spring and early summer period. Exceptionally dry fuel beds increased the likelihood of ignition due to lightning.

Heatwave conditions (defined as consecutive days and nights with unusually high maximum and minimum temperatures) were a significant feature of the fire season. *Severe* to *Extreme* heatwave events were recorded frequently across Australia during the months from November to early February. Intense drying of forest fuels, combined with record low relative humidity overnight, led to intense fire activity during these periods.

The interaction between intense fires burning in complex terrain and favourable atmospheric conditions led to localised pyro-convective hazards, including fire generated thunderstorms and fire generated vortices. Fire-generated thunderstorms were associated with several major fires in the forested areas of Queensland, NSW and eastern Victoria. A very destructive fire generated vortex was associated with the Green Valley Talmalmo (NSW) fire on 30 December 2019 and another intense vortex occurred overnight on 30 December to the north west of Cobargo with the Badja Forest fire.

The resources of fire and emergency management agencies across Australia were stretched by the demands of the season, due to numerous episodes of extreme fire behaviour on individual days and the prolonged multiple campaign events of the season. On several days during the season, the fire behaviour and spread did not reconcile with the standard application of fire behaviour models using surface-based inputs. Formal inquiry mechanisms and informal discussions have identified the need for a deeper understanding of the fire activity that occurred during these events, as well as exploring predictive techniques that may be implemented in the future.

The Bureau's coupled fire-atmosphere model ACCESS-Fire provides a tool to conduct case study analyses of impactful fires. Simulations of the Sir Ivan Dougherty and Waroona fires conducted during the Bushfire and Natural Hazards CRC *Coupled fire-atmosphere modelling* project provided valuable insights into fire and atmosphere interactions that contributed to the extreme fire behaviour during those events.

Simulations and analysis of a further five fires have been requested in the follow-up project that is reported on here. The five fire events from the 2019-20 fire season that were identified by fire agencies for detailed examination using ACCESS-Fire are:

1. Stanthorpe, Queensland, September 2019
2. Yanchep, Western Australia, December 2019
3. Corryong, Victoria, December 2019
4. Badja Forest, New South Wales, December 2019
5. Kangaroo Island, South Australia, January 2020

The locations of these fires are provided in Figure 1.

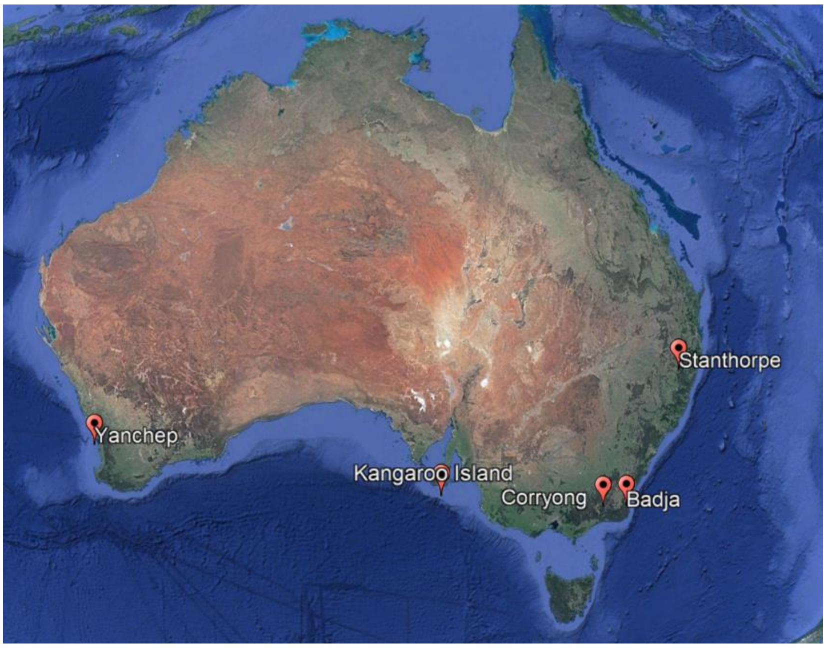


FIGURE 1: LOCATIONS OF THE FIVE FIRES STUDIED.

This report provides a description of each fire and of the simulations for each case. Based on discussions with partners in fire agencies, we have conducted a deeper analysis of periods of particularly unusual fire behaviour. Key findings for each of the fires have been identified and these include new insights derived from the simulations. In the final section, we explore how the findings can be applied to drive improvements in operational practices, including training that may be provided to FBANs and fire meteorologists in the future.

BACKGROUND

Australia has one of the most fire-prone landscapes in the world and, as with many other regions, is experiencing increased impacts of fire in a changing climate. The increasing risk presented by changing fire regimes is motivating development and use of new tools and techniques for understanding and predicting fire behaviour. Coupled fire-atmosphere models are one such tool, as they capture the interactions between the fire and surrounding atmosphere and thereby provide insights into some of the drivers of extreme fire behaviour.

ACCESS-Fire is the Australian coupled fire-atmosphere model. It uses the Bureau's climate and weather prediction model ACCESS, which links directly to Australia's operational and research meteorological computing capability.

This project builds upon the capability that was demonstrated through case studies of the Waroona and Sir Ivan Dougherty fires in the Bushfire and Natural Hazards CRC *Coupled fire Atmosphere modelling* project.

Coupled fire-atmosphere models are being used increasingly internationally in both research and operational spheres. The most progressive operational implementation is in the USA states of California and Colorado, where the WRF-SFire model is a component of a new capability for fire prediction.

Fire-atmosphere feedback is important because it often reflects a transition from steady-state fire spread to rapidly fluctuating, dynamic and more intense fire activity, which is inherently more difficult to predict.

In this project we extend the use of ACCESS-Fire to study another 5 cases of unusual fire behavior during the 2019/20 summer. This work increases the number of case studies that ACCESS-Fire has been run on; it provides more extensive testing on some of the code developments that were made in the original project; and supports the case for the potential operational application of the model in future so we are equipped to anticipate and respond to more challenging fire regimes in a changing climate.

RESEARCH APPROACH

ACCESS-Fire

ACCESS is the Australian Community Climate and Earth-System Simulator. It is the numerical weather prediction model used for climate and weather research and operational prediction in Australia. The ACCESS model framework is the Australian version of the UK Met Office Unified Model (UM).

The fire model runs in the 'nesting suite' of the ACCESS model. The fire component of the code is in the source tree for the land surface model (Joint U.K. Land Environment System – JULES).

The fire spread model used is the dry Eucalypt Forest (Vesta) rate of spread model developed by CSIRO for predicting fire spread rates in Eucalypt Forest.

The coupling of a fire spread model to the ACCESS model was a project conceived in a collaboration between the University of Melbourne and Monash University. The objective of that project was to simulate the Black Saturday Kilmore East fire (described in Toivanen et al., 2018). Section 2 of their paper describes the UM model and Section 3 has a detailed description of the fire code. A copy of the ACCESS-Fire code was provided to the Bureau in 2016 and was extensively modified and run for the Waroona and Sir Ivan fires during the Bushfire and Natural Hazards CRC *Coupled fire-atmosphere modelling* project.

ACCESS-Fire development

Substantial developments were made to the original ACCESS-Fire code and these are reported on in the CRC project report (Peace et al., 2021). The model configuration used for the final simulations of that project is very similar to the configuration used here. The simulations were run on the Gadi supercomputer on NCI. Two changes have been made to the model configuration since previous reporting:

1. Added capability to have multiple fire polygons at the start or multiple spot ignitions at any timestep.
2. Added capability to use fuel hazard score maps (instead of constants), when available.

The investment in the original project developing ACCESS-Fire has been leveraged during the case studies reported on here. The earlier development work has permitted the modelling framework to be re-configured and relocated to a further five case studies. Importantly, no issues were encountered with model numerical stability during the current simulations, indicating that the changes made during the original CRC project hold across a broad range of conditions.

ACCESS-Fire simulations and model configuration

Details of the base atmospheric model configuration used can be found in Peace et al., 2021.

The simulations used the standard Unified Model (UM) nesting suite with UM version 10.6, with 140 vertical levels through a height of 40 km with model levels on hybrid heights to produce smooth levels over topography. The vertical configuration is the same for all the nested limited area models. The lowest permitted time step of one second was used on the inner nest.

The current model configuration has a series of nested domains at 4 km (0.036°), 1.2 km (0.01°) and 300 m (0.0028°).

The fire model was switched on and coupled to the atmosphere model for Nest 3. The nests run to completion sequentially, so fire coupling only occurs on the innermost nest.

The two-dimensional fire spread occurs on the same horizontal grid resolution as the ACCESS output, at each time step, however the variables on the fire grid are output at more frequent intervals.

Fuel inputs

In most of the simulations for the five fires, a 'default' forest fuel amount of 20 t/ha was used in the CSIRO Forest ('Vesta') fire spread model. Based on advice from NSW RFS the fuel load for the Badja Forest fire was increased to 30 t/ha. For the Kangaroo Island fire, simulations were run using a combination of grass and forest fuel data from the Fuel Hazard Score database provided by the SA Department of Environment and Water (personal communication, Simeon Telfer).

The use of constant forest fuels is recognised as a limitation in the current simulations. It has not been in scope for this project to include variable fuel mapping as the timeframe has not permitted the significant code development and testing required. The national fuel grids for the AFDRS have recently been made available to the project team and planned activities for late 2021 include implementation of the national fuel grids so that future simulations can incorporate more accurate fuel information.

CASE STUDIES OF THE FIVE FIRES

THE STANTHORPE FIRE (QLD), (6-7 SEPTEMBER 2019)

Introduction

The Stanthorpe fire occurred following a period of record low rainfall in the region over timeframes ranging from months to years. 2019 was the driest year in more than 100 years of records. The monthly satellite derived Live Fuel Moisture Content (LFMC) had been extremely low in the preceding months.

The fire was reported at 14:35 local time (LT) on 6 September 2019, to the north west of Stanthorpe on the edge of the Broadwater State Forest. It ignited on the western flank of a north south oriented ridge with highest tops around 950 m and moved into the valley towards Stanthorpe (elevation around 800 m), burning through a region of mixed fuel comprising forest and farmland.

Driven by warm, dry north westerly winds, the fire spread to the south east and impacted the outskirts of Stanthorpe in the late afternoon. A strong, deep south west wind change around 21:00 LT spread the fire north eastward towards the community at Applethorpe while a second arm of the fire spread eastwards across the northern part of the Broadwater State Forest.

Queensland Fire and Emergency Services (QFES) provided information on fire activity and fire behaviour, including results from post-event modelling which indicated that a hazard reduction burn (HRB) conducted in the Broadwater State Forest in July had reduced the impact of the fire on the communities at Stanthorpe and Applethorpe. Four houses were lost in the fire, and the New England Highway was closed for a period in the early hours of 7 September. The total area burned was approximately 2000 ha.

This case study looks at the background climatic and synoptic setting for the event and uses the Bureau's ACCESS-Fire model to look at unusual aspects of the fire behaviour. The model is used to examine the vertical structure of the wind and temperature fields using transects along and across the fire to diagnose the factors which drove the fire before and after the wind change. We also assess the impact of the fire scar from the HRB on the extent and rate of spread of the fire.

Antecedent conditions

By the start of September south east Queensland and north east NSW were primed for dangerous fire conditions. Year to date maximum temperatures were very much above average to highest on record. The January to August rainfall was lowest on record in the region, soil moisture levels were very much below average and atmospheric humidity levels across the continent were at or near record lows.

Further information on the climatic setting for the fires and the historical context for the dangerous fire weather conditions in spring is provided in *Special Climate Statement 72 - dangerous fire weather in spring 2019*:

http://www.bom.gov.au/climate/current/statements/scs72.pdf.

Meteorological situation and observations

The synoptic weather pattern on 6 September 2019 (Figure 2) shows an unusually strong springtime fire weather pattern for north east NSW and south east Queensland. At 16:00 LT, a strong front/trough system associated with an elongated low-pressure system (extending from Bass Strait to the southern NSW coast) was approaching the Stanthorpe region from the west. The front marked the boundary between warm, dry, north westerly winds and a dry south westerly wind change. The front passed through Stanthorpe at around 21:00 LT. A strong westerly pressure gradient is evident along the southern Queensland and northern New South Wales coastlines.

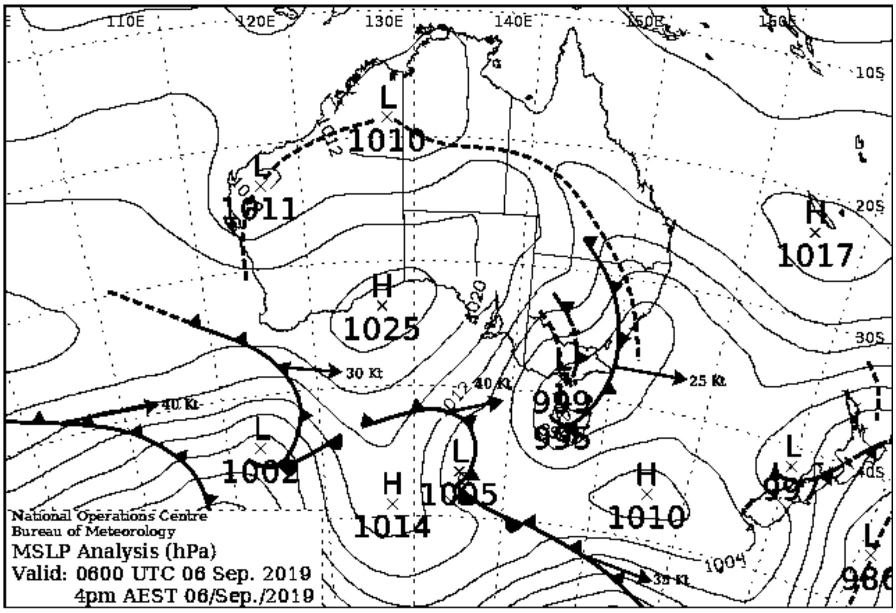


FIGURE 2: MEAN SEA LEVEL SYNOPTIC CHART AT 16:00 LT 6 SEPTEMBER 2019.

The closest surface weather observations to the fire were at the Bureau of Meteorology's Applethorpe Airport Automatic Weather Station, (Figure 3), located approximately 20 km to the east of the fire ignition point. A distinctive feature of weather on the day of the fire was the very dry atmosphere. Relative humidity (RH) dropped abruptly as the wind swung to the north around 06:00 LT. RH values were near 10% from around 09:00 LT until 21:00 LT in the evening, when the south westerly wind change arrived. The strongest winds, averaging nearly 30 km/h, occurred behind the change and persisted for several hours, which supported an extended time window for the fire to run in a north easterly direction.

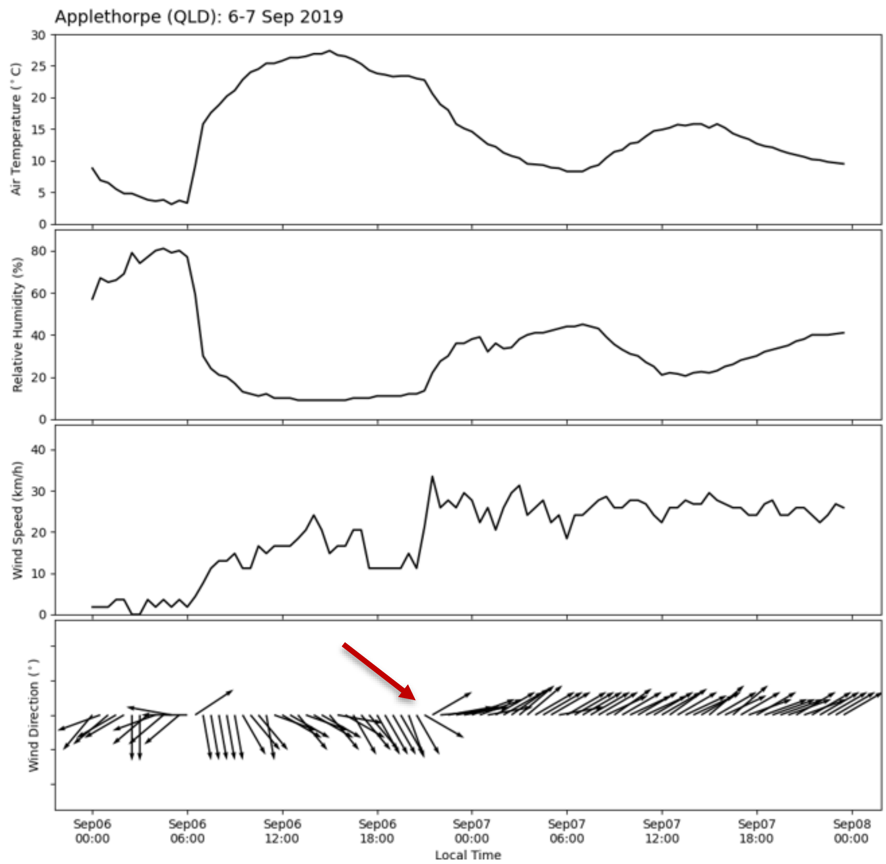


FIGURE 3: TIME SERIES OF TEMPERATURE, RELATIVE HUMIDITY WIND SPEED AND WIND DIRECTION AT APPLETHORPE FOR 6-7 SEPTEMBER 2019. RED ARROW SHOWS SOUTH WEST WIND CHANGE.

ACCESS-Fire model simulations

Two simulations using the ACCESS-Fire model were conducted. The first simulation was run without the HRB, the second took account of the fire scar from the HRB. Both runs assumed constant forest fuel amounts of 20 t/ha across the region where the fire occurred. The model was initialised at 07:00 LT and ignition time for the fire was at 14:30 LT 6 September. The model configuration does not permit the simulations to account for the impact of suppression activities on the fire, the urban interface outside Stanthorpe, or the impact of the other man-made fire breaks such as the New England Highway.

Simulation 1

Hourly isochrones of fire spread (Figure 4) show that the fire spread to the south east towards Stanthorpe along a narrow front in the afternoon. The fastest rate of spread to the south east was in the period immediately ahead of the wind change which occurred around 21:00 LT. Following the wind change, the fire spread to the north east towards Applethorpe. Information provided by QFES shows that the south east spread of the fire slowed on the outskirts of Stanthorpe in the late afternoon. This was most likely due to suppression activities and lower fuel amounts along the urban interface and the New England Highway that are not represented in the model. The wind change then turned fire spread towards the north east into a fuel regime more favourable for spread.

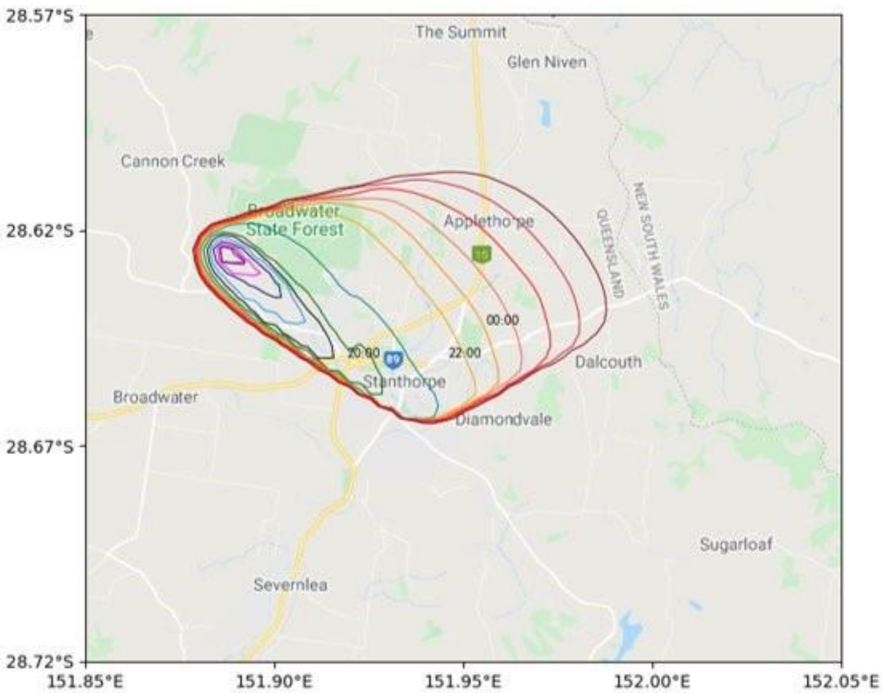


FIGURE 4: MAP SHOWING HOURLY ISOCHRONES OF THE FIRE PERIMETER FOR SIMULATION 1.

The vertical structure of the fire plume was examined along cross sections through Stanthorpe before and after the wind change. The potential temperature and wind profiles at 16:39 LT before the wind change (Figure 5, left panel), shows a well-mixed boundary layer up to around two kilometres above ground level. The tilted fire plume updraft (represented by the orange temperature shading) extends to a height of just under two kilometres above the ground. The vertical structure of the atmosphere behind the change at 21:09 LT (Figure 5, right panel), shortly after the change, shows cooler air from the south west extending up to a height of one kilometre above ground level.

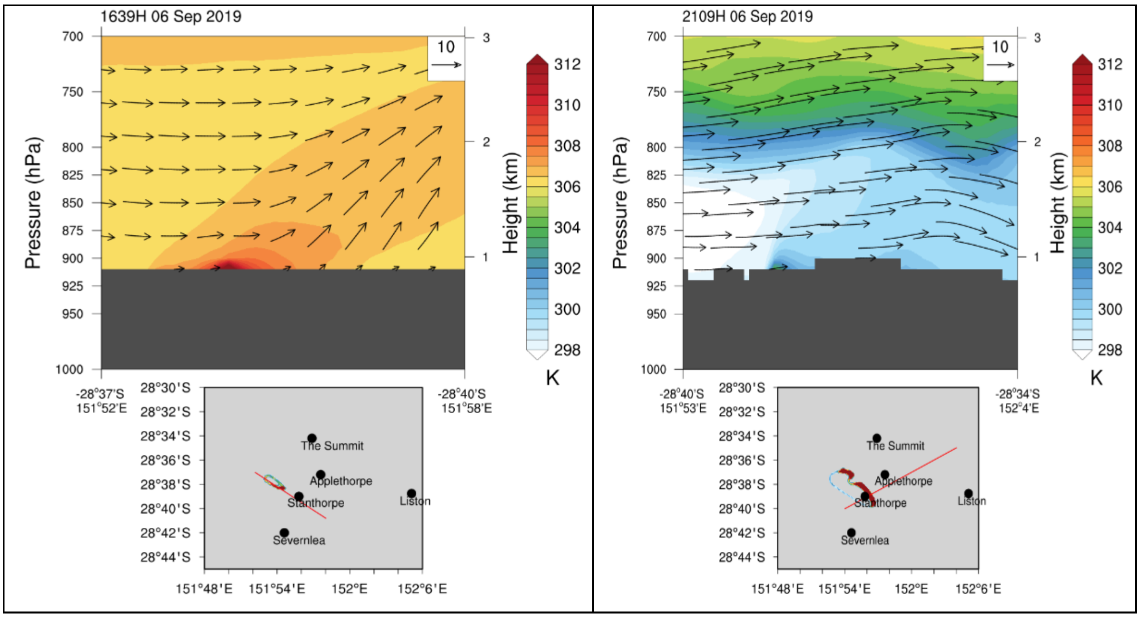


FIGURE 5: VERTICAL CROSS SECTIONS OF WIND (M/S) AND POTENTIAL TEMPERATURE (K) THROUGH STANTHORPE AT 16:39 LT (LEFT PANEL) AND 21:09 LT (RIGHT PANEL). HEIGHT ON THE VERTICAL AXIS IS KILOMETRES ABOVE SEA LEVEL. THE RED LINE SHOWS THE ORIENTATION AND THE HORIZONTAL EXTENT OF THE CROSS SECTION.

The time series plot of total fire power (Figure 6) shows that the maximum fire power of just over 200 GW occurred around the time of the wind change at 21:00 LT. The abrupt increase at this time resulted from broadening of the active fire front on the north east flank.

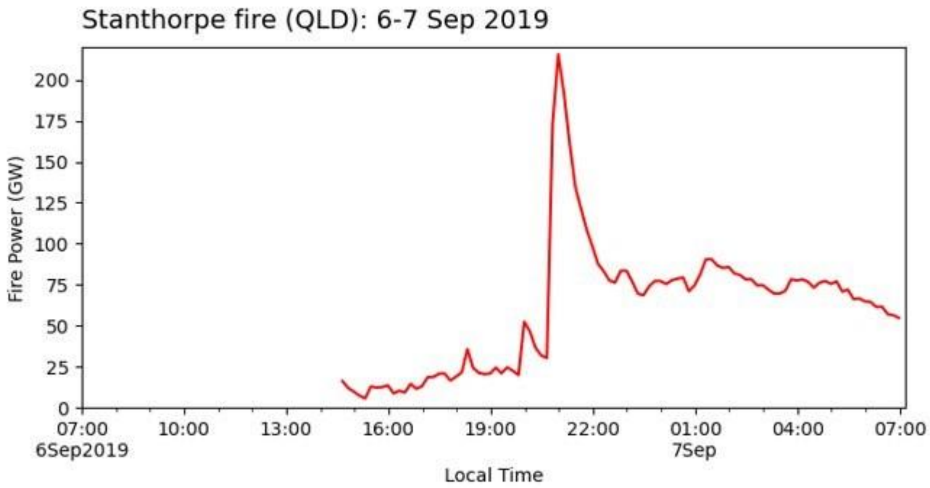


FIGURE 6: MODELLED TIMES SERIES OF TOTAL FIRE POWER FOR SIMULATION 1.

Simulation 2 (including fire scar of Hazard Reduction Burn)

The second simulation took account of the Queensland Parks and Wildfire Service hazard reduction burn conducted in July 2019, by setting fuel load to zero in this area.

Hourly isochrones of the fire spread (Figure 7) showed a similar, albeit slightly slower fire front moving to the south east. Following the wind change the fire front divided into two segments separated by the HRB, one moving towards Applethorpe with a second arm of the fire moving across the Broadwater State Forest.

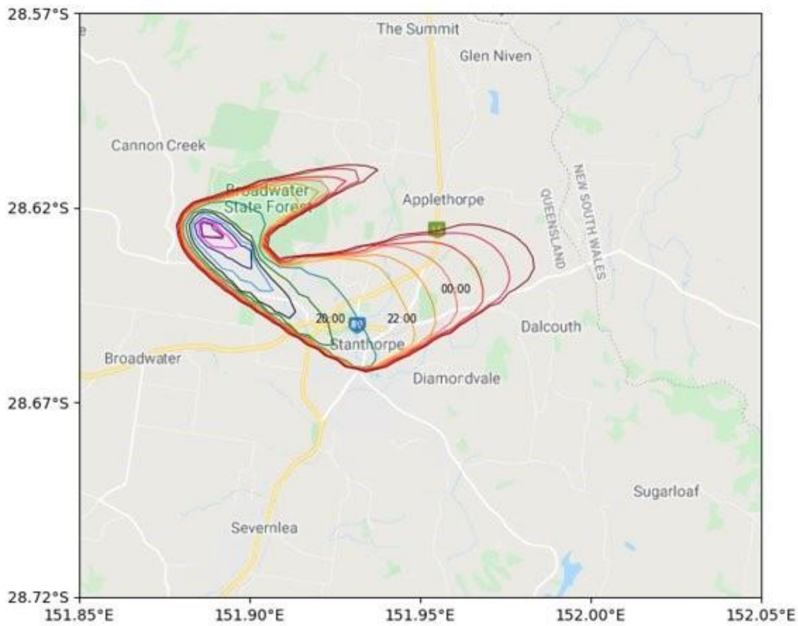


FIGURE 7: HOURLY ISOCHRONES OF FIRE SPREAD FOR SIMULATION 2.

The inclusion of the HRB in the simulations reduced the total area that burned and slightly reduced the size of the south eastward run of the fire in the north westerly winds. The length of the fire front on the north eastern side following the wind change was significantly reduced. There is broad agreement between the model fire simulation and the line scan image taken at 1030 LT on the 7 September 2019 showing the area burnt (Figure 8).

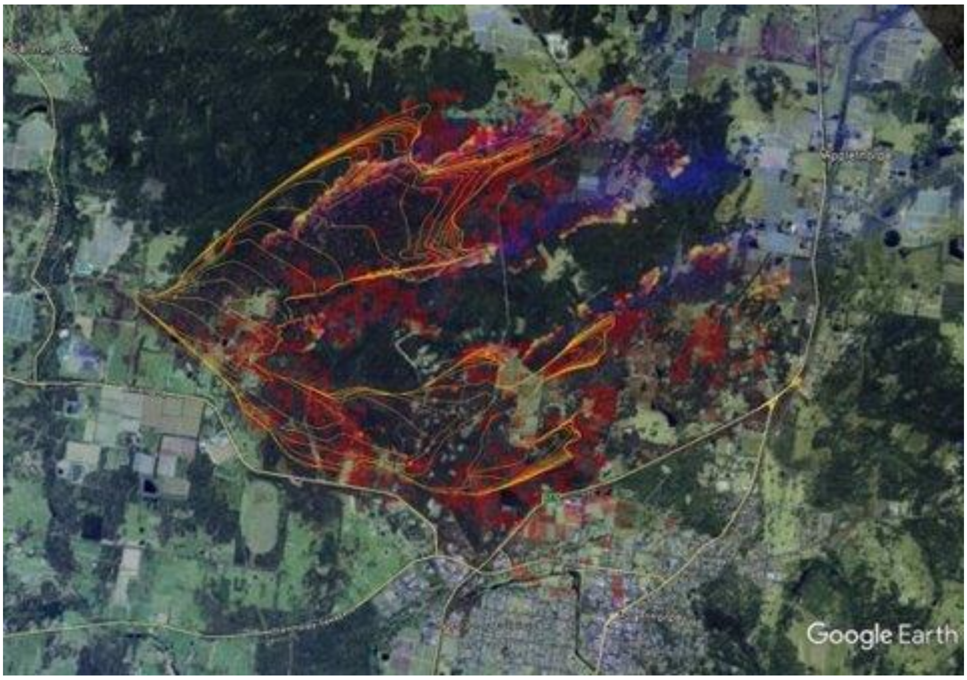


FIGURE 8: LINE SCAN AT 10:32 LT 7 SEPTEMBER (WITH SIMULATED FIRE SPREAD PREPARED BY QFES OVERLAIN IN ORANGE). IMAGE COURTESY QFES.

Total firepower (Figure 9) for the HRB simulation was around 150 GW, some 30 % lower than for simulation 1, broadly consistent with the reduction in length of the head fire.

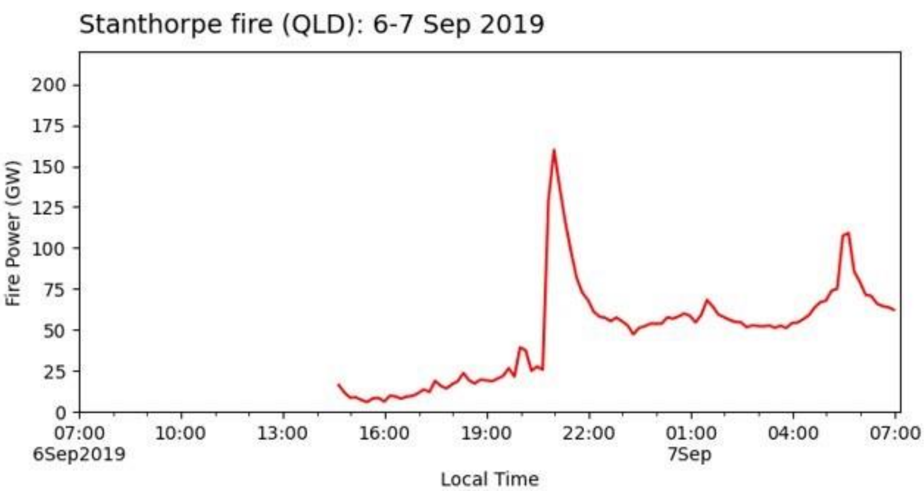


FIGURE 9: MODELLED TIMES SERIES OF TOTAL FIRE POWER FOR SIMULATION 2.

Key points

- The Stanthope fire occurred following a period of lowest on record rainfall in the area and the very dry antecedent conditions were a significant driver of fire activity.
- Warm, dry, north west winds ahead of a cooler, gusty but dry south west change during the late evening resulted in fire spread that was primarily wind driven for an extended time period. The simulated fire plume only reached 2 km elevation and was strongly tilted downstream from the surface fire.
- The exceptionally dry fuels and the very dry and windy conditions behind the change meant that the fire continued to run overnight, despite intensive suppression efforts.
- The simulations show that the maximum firepower (and therefore strongly elevated levels of hazard) peaked in the evening around the time of the wind change.
- Model simulations run with and without a hazard reduction burn (HRB) conducted in the Broadwater State Forest, showed that the HRB reduced the speed and intensity of the fire and the total area burned and resulted in two separate fire fronts after the wind change, consistent with observed line scan imagery.

THE YANCHEP FIRE (WA), (11-14 DECEMBER 2019)

Introduction

The Yanchep fire occurred on a gently sloping coastal plain in fuels comprised mostly of Tuart and Banksia woodlands with some Melaleuca forest on limestone ridges. The fire also ran through pine plantation on the second day. The fuel age ranged from 18 months to 15 years -there was little pasture growth due to recent very hot and dry conditions.

Some unusual aspects of the fire were highlighted during discussions with fire practitioners from WA Department of Fire and Emergency Services (DFES) and WA Department of Biodiversity, Conservation and Attractions (DBCA). Features of the fire activity included its longevity (4 days), the difficulty in suppression of the fire during the overnight periods and its proximity to the coastal villages, which were under threat from the fire for several days.

The spread of the fire was driven by the interplay between very hot and dry continental easterly winds in the overnight and morning periods, and cooler, shallow coastal sea breezes in the afternoons and evenings. These changing wind regimes resulted in the fire moving in a zigzag pattern up the coast, with westward fire spread in the easterlies overnight and in the mornings and north ward fire spread under the influence of the southerly sea breezes during the afternoon and evenings. Movement of the fire into the peri-urban environment slowed the rate of spread.

The fire was first reported in the Yanchep National Park at 14:16 LT on 11 December 2019. Under the influence of easterly winds, the fire moved towards the coastal town of Yanchep during the afternoon. On the eastern outskirts of Yanchep, the local service station and a house were destroyed due to ember attack from the fire around 17:00 LT. A southerly sea breeze turned the fire towards the north in the late afternoon.

Major suppression activities involving almost 180 firefighters were undertaken on the fire overnight on 11 December. By 14:00 LT on 12 December the fire was threatening the northern parts of Yanchep and the threat later extended to Two Rocks, a small coastal village some 5 km to the north of Yanchep. (Place locations are shown in Fig. 12). Significant aerial support was involved in the fire suppression. By 15:00 LT on 12 December 1680 ha had been burnt.

The return of the east to north easterly flow overnight on 12 December spread the fire to the west towards Two Rocks, which came under ember attack around 04:00 LT on 13 December. By 10:00 LT, 4400 ha had been burnt and by 06:00 LT on 14 December the area burnt had increased to 11000 ha.

Fire agencies reported that it was unusual for fires burning close to the coast to run overnight. In this case, where the fire was burning only 2-3 km from the coast, it is likely that the flammability of fuels due to the dry antecedent conditions, the limited moisture recovery overnight in the dry easterlies and the weak inland penetration of the moister sea breeze air were factors that limited the effectiveness of suppression activities. The recent prescribed burns (2-3 years old) did not hold up fire progression as much as expected.

In this case study, we examine the climatological conditions that prevailed in the months and weeks leading up to the event and look at the broadscale meteorological setting for the event. We then use the ACCESS-Fire model to explore the factors which contributed to the multi-day active fire, including the nature of the oscillating boundary between the continental easterly and sea breeze wind regimes, and the structure of the overlying atmosphere.

Antecedent conditions

The fire followed successive periods of extreme heat in November and the first half of December 2019. Pearce RAAF base (25 km to the east south east) recorded its hottest November on record and a record maximum temperature of 43.1°C on 16 November at the end of a 4-day heatwave. Intense heatwaves also occurred between 2-6 December and 10-16 December 2019. Perth city (50 km to the south) recorded five consecutive days above 35°C between 2-6 December and a further seven consecutive days above 35°C during the period 10-16 December. This latter period included three consecutive 40°C days from 13-15 December. The intense heat followed a year of very much below average rainfall over the region.

Meteorological situation and observations

The MSLP charts on 11 and 12 December 2019 (Figure 10) showed a classic extreme fire weather situation for the west coast.

The main features of the charts were a strong ridge of high pressure to the south of WA, with a high in the western Bight and a low over the inland Gascoyne extending a trough southward along the coast. The high-pressure system was slow-moving and directed a very hot east to north easterly airflow across the fire area. A southerly sea breeze was observed for a brief period along the coast in the late afternoon. This weather pattern persisted for several days, resulting in heatwave conditions. The strength of the easterlies decreased, and the airflow became more north easterly as the event unfolded.

In this synoptic situation, the peak fire danger typically occurs in the middle of the day before the easterly winds gradually weaken and turn more southerly in the afternoon. There is often a secondary peak in fire danger in the late afternoon due to stronger winds associated with the sea breeze.

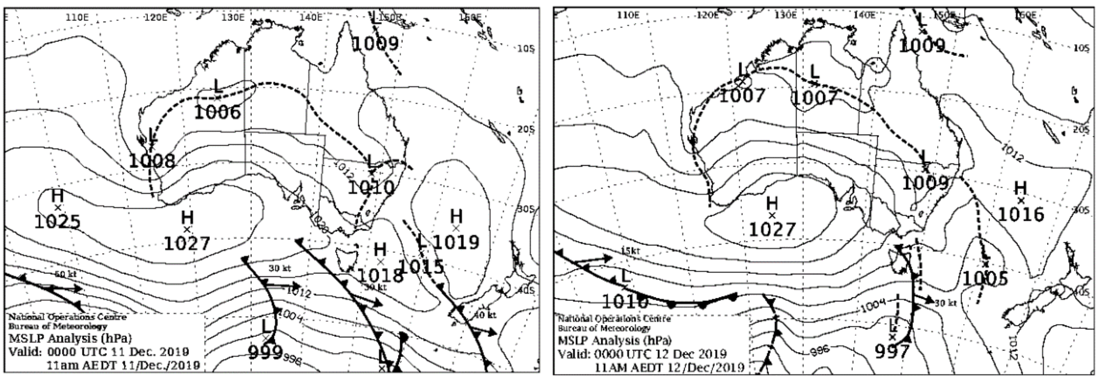


FIGURE 10: MSLP CHARTS AT 8:00 LT 11 DECEMBER 2019 (LEFT) AND 12 DECEMBER 2019 (RIGHT).

Wind observations from Ocean Reef from 11-14 December 2019 (a coastal 'wind only' station some 25 km to the south of the fire location, see Figure 10), show the abrupt daily wind shift during the afternoon associated with the sea breeze arrival. On the first day of the fire (11 December), the wind shifted very briefly from easterly through to southerly in the late afternoon before returning to easterly during the evening. The winds with an offshore component became more northerly and weakened over successive days, and the sea breeze arrival time was earlier.

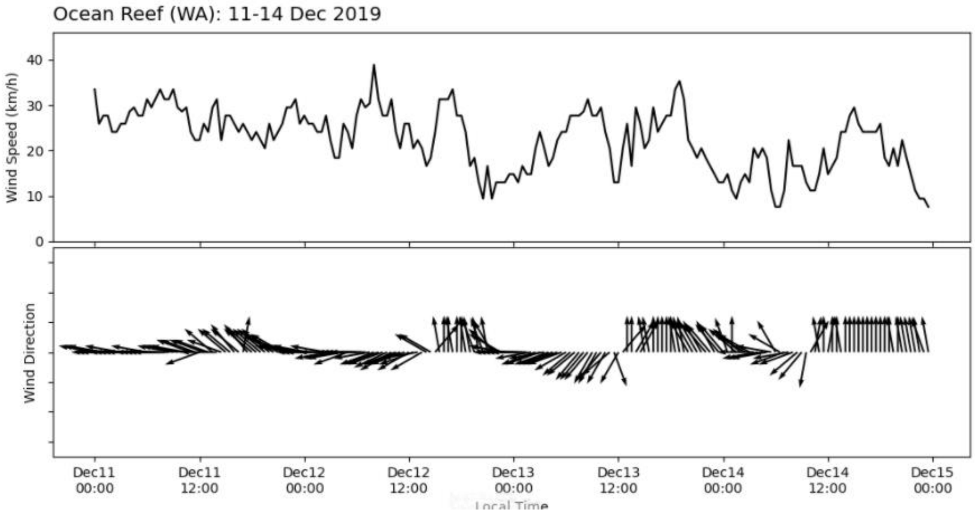


FIGURE 11: OCEAN REEF AWS WIND OBSERVATIONS (KM/H) FOR THE PERIOD 11-14 DECEMBER 2019. WIND DIRECTION ARROWS (BOTTOM PANEL) SHOW THE DIRECTION THE WIND IS BLOWING FROM. THE DAILY SEA BREEZE ARRIVAL TIME IS INDICATED BY THE RED ARROWS.

Observations from Pearce RAAF base some 25 km inland to the south east of Yanchep (Figure 12) show 4 days of heatwave conditions with temperatures near 40°C. Daytime relative humidity levels were near or below 10% each day and warm minimum temperatures resulted in lower relative humidity on the second and third nights. There is no evidence of a sea breeze this far inland until the third day.

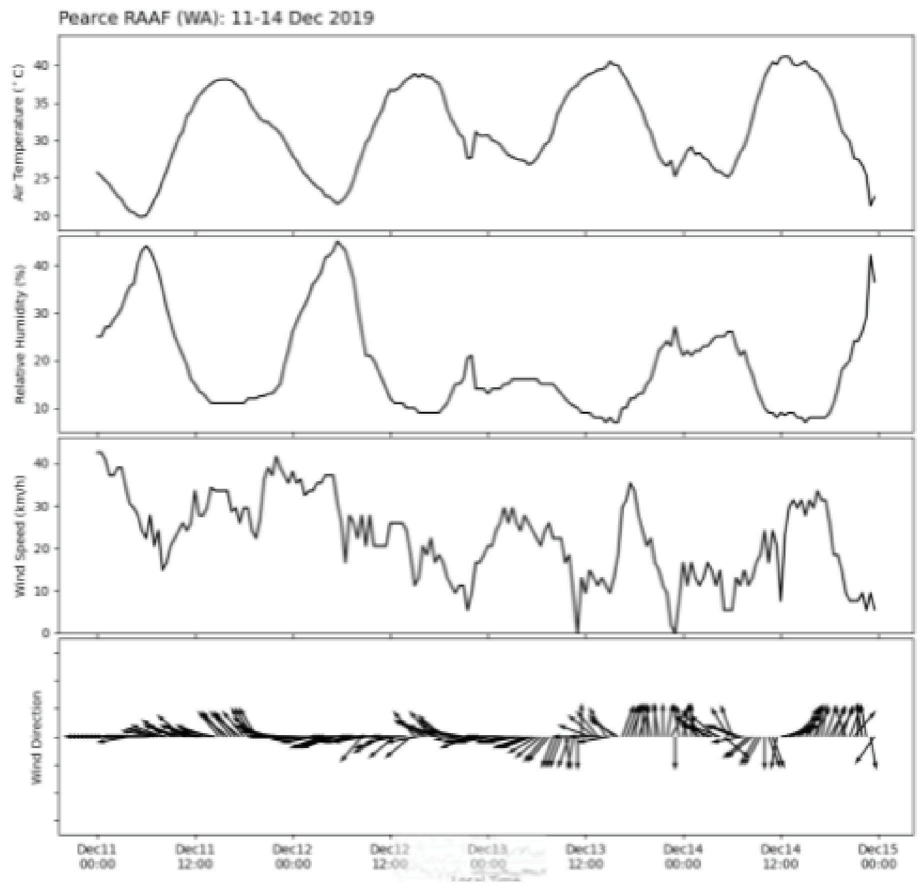


FIGURE 12: PEARCE RAAF AWS OBSERVATIONS FROM TOP TO BOTTOM PANEL: TEMPERATURE (°C), RELATIVE HUMIDITY (%), WIND SPEED (KM/H) AND WIND DIRECTION FOR THE PERIOD 11-14 DECEMBER 2019. WIND ARROWS SHOW THE DIRECTION THE WIND IS BLOWING FROM.

ACCESS-Fire simulations

Two simulations were run with the ACCESS-Fire model. The first simulation covered the afternoon and evening period on the 11th when the fire started and threatened Yanchep. The second simulation focussed on the evening and overnight period on the 12th when the fire threatened the community at Two Rocks.

In both runs forest fuels amounts of 20 t/ha were used. In reality, the amount of energy released by the burning of the coastal banksia heath would be less than the forest fuel used in the simulations. Experiments to calculate the difference in energy release and the influence on the coupling process could be carried out in future, once the AFDRS grids have been implemented in ACCESS-Fire.

Simulation 1 (afternoon-evening 11 December 2019)

The atmospheric model was initialised using data from 11:00 LT and the fire started at 14:15 LT on 11 December 2019.

Hourly isochrones of the simulated fire spread (Figure 13) show that the fire moved west north west towards Yanchep, before turning to the north north west under the influence of the sea breeze from around 17:30 LT. The fire slowed between 18:00 and 20:00 LT in the lighter wind region near the boundary between the sea breeze and the easterly winds. The rapid fire spread in the model between 20:00 and 22:00 LT resulted from a surge in the easterly flow.

Actual fire spread during this period was contained on a north south line inland of the coast, which appears to correspond to a reduction in fuel in the peri-urban environment.

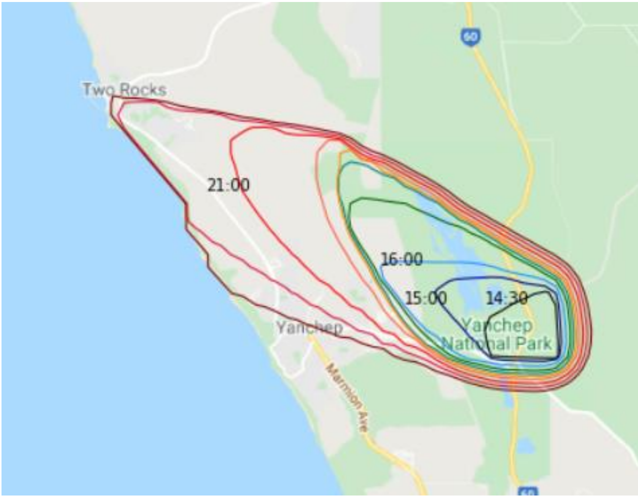


FIGURE 13: HOURLY ISOCHRONES OF FIRE SPREAD ON 11 DECEMBER 2019.

The evolution of the surface wind field during the late afternoon and early evening period is shown in Figure 14. Note the fire location is near the boundary of the southerly sea breeze and south easterly continental air at 17:30 LT, the lighter winds along the convergence boundary at 18:30 LT and the resurgence of the south easterly flow and retreat of the sea breeze by 20:30 LT. Also note that the eastern and western flanks of the fire experience differing wind regimes, this is particularly evident at 17:30 and 18:30 LT.

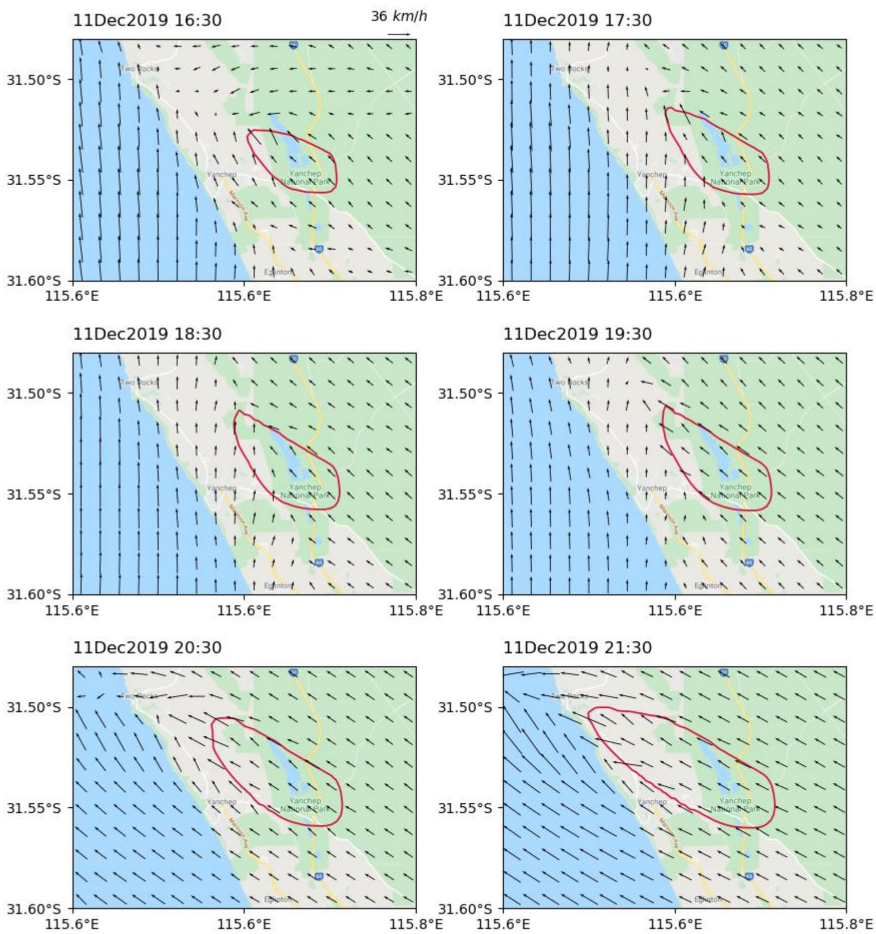


FIGURE 14: FIRE PERIMETER AND SURFACE WINDS AT: A) 14:30 B) 15:30 C) 16:30 D) 17:30 E) 1830, AND F) 1930 LT.

The sharp discontinuity in wind direction and relative humidity across the fire can be seen in Figure 15.

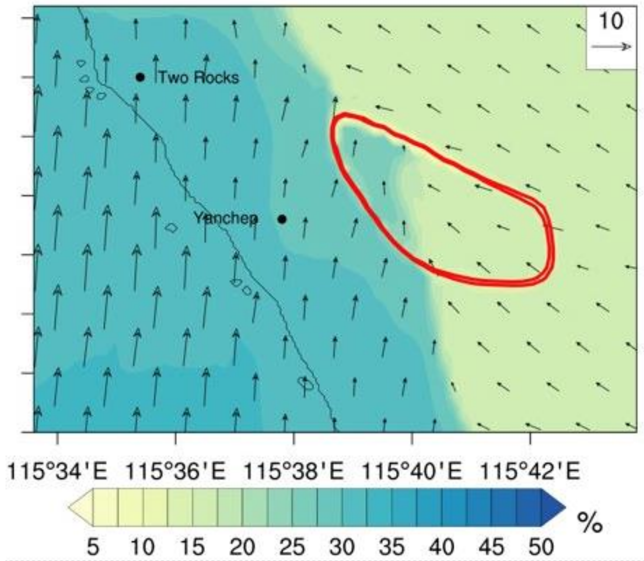


FIGURE 15: SURFACE RELATIVE HUMIDITY (%) AND WINDS (M/S) AT 18:00 LT 11 DECEMBER 2019 SHOWING THE SHARP BOUNDARY IN MOISTURE AND WIND DIRECTION ACROSS THE SEA BREEZE FRONT. THE DISTANCE FROM YANCHEP TO TWO ROCKS IS APPROXIMATELY 5 KM.

A vertical cross section of winds and potential temperature oriented south west to north east through Yanchep at 1619 LT on 11 December (Figure 16) shows strong updrafts within the fire plume extending to a height of 3 km above ground level. The updrafts reach higher in the atmosphere on the western side of the fire due to the convergence between the fire updraft and the shallow circulation associated with the leading edge of the cooler sea breeze air (yellow and orange shades on the bottom left of the figure). Lofting of embers in the enhanced updraft may have increased the potential for spotting during this period.

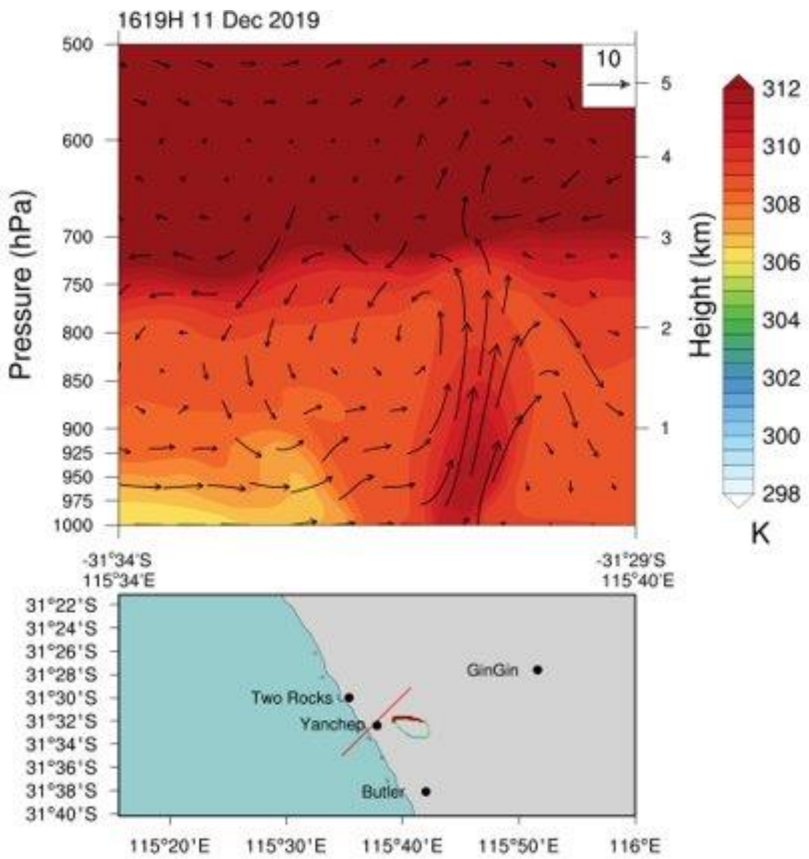


FIGURE 16: VERTICAL CROSS-SECTION OF WINDS (M/S) AND POTENTIAL TEMPERATURE (K) FROM SW TO NE THROUGH YANCHEP AT 16:19 LT 11 DECEMBER 2019. THE COOLER, SHALLOW SEA BREEZE AIR CAN BE SEEN AT THE BOTTOM LEFT OF THE IMAGE.

A time series plot of total fire power (Figure 17) shows oscillations in the intensity of the fire during the afternoon, a minimum in fire power in the evening in response to the lighter winds and then a significant increase in fire power due to the surge in the easterly winds in the late evening. As discussed earlier, the fire run to the north west was not observed on the fireground, most likely due to containment activities and changes in fuel type and amount, which are not included in the model configuration.

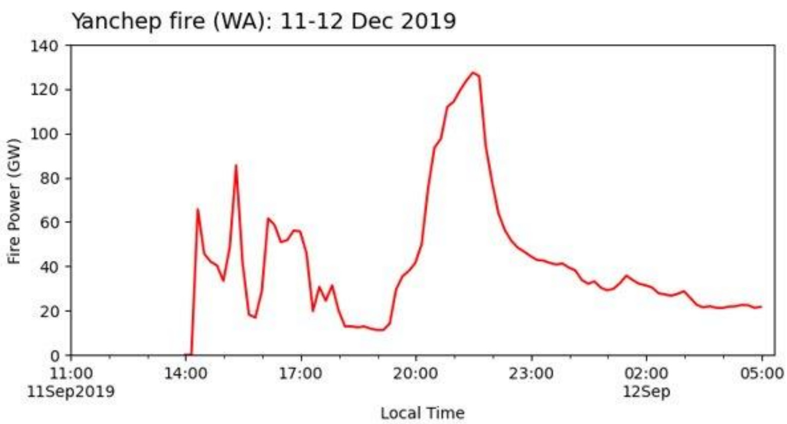


FIGURE 17: MODELLED TIME SERIES OF TOTAL FIRE POWER (GW) FOR SIMULATION 1.

There was no significant pyro-convective cloud associated with the fire, most likely because the heat output from the fire was insufficient to overcome stability in the mid-levels of the atmosphere. It is probable that the shrubland fuel (rather than forest), the discontinuity of fuel types, and the reduction of fuel load due to previous prescribed burns had a limiting influence on the heat output of the fire.

Simulation 2 – early evening and overnight fire spread 12 December 2019

The atmospheric model was initialised at 17:00 LT and the fire was ignited at 20:25 LT 12 December using a narrow rectangular fire area.

Hourly isochrones of the simulated fire spread (Figure 18) show that the fire spread to the west south west overnight, reaching the coast just north of Two Rocks by mid-morning. The fastest rate of spread was associated with a maximum in the low-level wind field around this time.

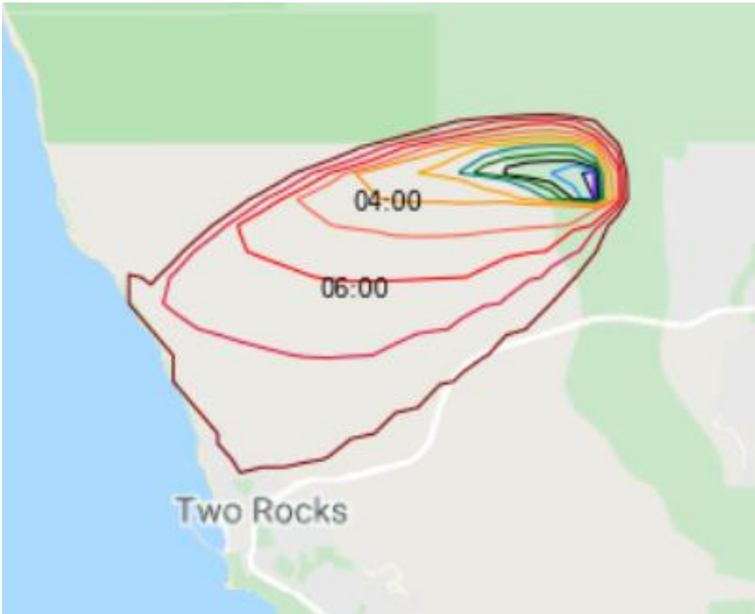


FIGURE 18: HOURLY ISOCHRONES OF FIRE SPREAD OVERNIGHT AND EARLY MORNING ON 12 DECEMBER 2019. THE ISOCHRONES ARE LABELLED WITH LOCAL TIME.

The evolution of the surface wind field during the overnight period is shown in Figure 19. Note the broad easterly flow driving the fire early in the period, then a shift to north easterly winds by the morning.

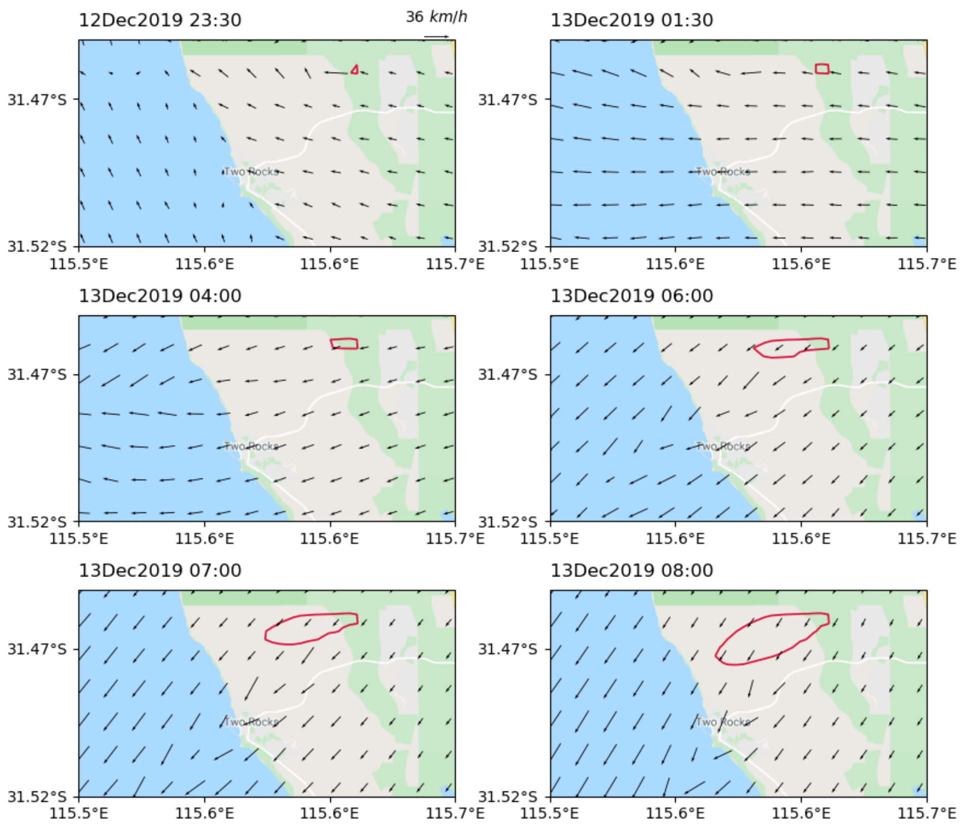


FIGURE 19: FIRE PERIMETER AND SURFACE WINDS FOR SIMULATION 2 AT: (TOP LEFT) 23:30 LT 12 DECEMBER, (TOP RIGHT) 01:30 LT 13 DECEMBER, (MIDDLE LEFT) 04:00 LT (MIDDLE RIGHT) 06:00 (LT BOTTOM LEFT) 07:00 LT, AND (BOTTOM RIGHT) 08:00 LT 13 DECEMBER.

A vertical cross-section through the fire (not shown here) showed that the fire circulation was much shallower (extending only a few hundred metres above the ground) than that simulated during the first afternoon, when the fire interacted with the sea breeze.

A comparison between the fire power in Figure 17 and Figure 20 shows that the simulated energy release was much larger on the first afternoon of the fire than during this period with the effect that the reduced heat output would have further limited plume rise.

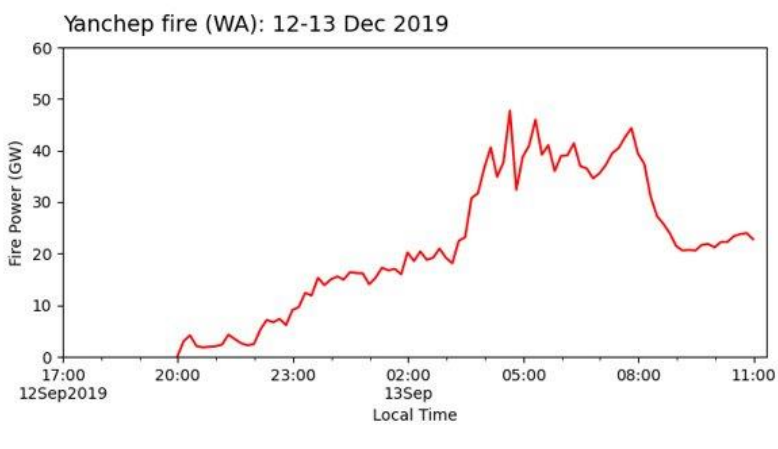


FIGURE 20: MODELLED TIME SERIES OF TOTAL FIRE POWER (GW) FOR THE OVERNIGHT AND MORNING PERIOD ON 12 DECEMBER 2019.

Key points

- The fire occurred during an intense heatwave (the third heatwave event within 4 weeks) and followed record heat in November 2019.
- The fire occurred near the coast, close to communities and within the afternoon sea breeze convergence zone.
- Hot, dry, continental easterly wind flow was the main driver of fire spread overnight and for much of the day. In the late afternoon and evening, the fire temporarily experienced the cooler, moister, southerly winds associated with the sea breeze. This daily variation posed challenges for fire suppression activities.
- The simulations show that the fire spread slowed during the evening period when the fire was located on the sea breeze convergence boundary but then became more active overnight as the dry easterly flow returned.
- The simulations showed that the interaction between the sea breeze and fire plume initially enhanced the upward motion to an elevation of almost 4 km.
- The relatively brief period of the sea breeze incursion each day meant that there was limited fuel moisture recovery overnight, and the fire remained active, despite suppression efforts by firefighters.
- The simulations produced temporal fluctuations and strong spatial variability in fire intensity around the fire perimeter in response to the temporal and spatial variation in wind direction in the sea breeze convergence zone. This highlights the requirement for careful interpretation of the influence of mesoscale wind changes on fire behaviour, particularly around a complex fire perimeter.

THE CORRYONG (VICTORIA)/GREEN VALLEY TALMALMO (NSW) FIRE, (30-31 DECEMBER 2019)

Introduction

Very dry and flammable fuels primed the landscape of southern NSW and northern Victoria for intense fire activity by the end of December 2019. These conditions, which were the culmination of a long-term severe drought, were further exacerbated by consecutive days and nights of heatwave conditions.

The Green Valley Talmalmo/Corryong[1] fire burned at the end of a very hot and dry period in the region. In the four months from September to December 2019, rainfall over the Eastern Riverina/Southern Slopes area of NSW was very much below average, while maximum temperatures were near to the highest on record. A severe heatwave occurred from 19-21 December 2019, when the nearby Khancoban weather station exceeded 40°C on three consecutive days.

A comprehensive observational and analysis dataset of the fire was provided by the Victorian Department of Environment, Land, Water and Planning (DEWLP). Observations provided by DELWP at Mount Elliott (50 km south east of the ignition site) showed surface fuel moisture readings of between 4 and 7%, and sub-surface fuel moisture readings between 2.5 and 6%. By the end of December, the Keetch-Byram Drought Index (KBDI) for the Upper Murray region was in the range 100-150

The Green Valley Talmalmo fire bushfire was ignited by a lightning strike in the Woomargama National Park in NSW on 29 December 2019. On 30 December the fire spread rapidly from north west to south east across Green Valley during the late afternoon before crossing the Murray River into Victoria. It was named the Green Valley Talmalmo fire in NSW and subsequently renamed the Corryong fire in Victoria.

The fire burned through Green Valley, near the township of Jingellic in southern NSW on 30 December 2019 during the late afternoon before crossing the Murray River into Victoria. During the period from early afternoon on 30 December to the early morning of 1 January, almost 110,000 ha of forest and farming land was burnt, with an extended period of dangerous fire behaviour and fast rate of spread in the late afternoon of 30 December in southern NSW that continued into the Upper Murray region of Victoria overnight through to the middle of the day on 31 December. The fire burnt in a strip from north west to south east and impacted NSW communities along the Murray River between Jingellic and Talmalmo, and Victorian communities at Walwa, Cudjewa and Corryong. The fire occurred in rugged topography with forests in the mountainous regions and grass farmland across the valleys.

The line scan imagery shown in Figure 21 (provided by DEWLP) shows the area burnt at 05:26 LT on 1 January. At 1830 AEDT on 30 December the area of the fire was around 4500 ha. Extreme fire behaviour occurred through the overnight period and, based on a line scan image at 1130 on 31 December, it was

[1] The fire was named Green Valley Talmalmo on the NSW side of the border and Corryong on the Victorian side, the names Green Valley Talmalmo and Corryong are used interchangeably here depending on the fire location at the time.

estimated to have burnt around 100,000 ha in less than 24 hours. Significant plume driven fire behaviour occurred overnight with extensive downwind spotting. Fire crews reported that they had not observed such extreme fire behaviour before.

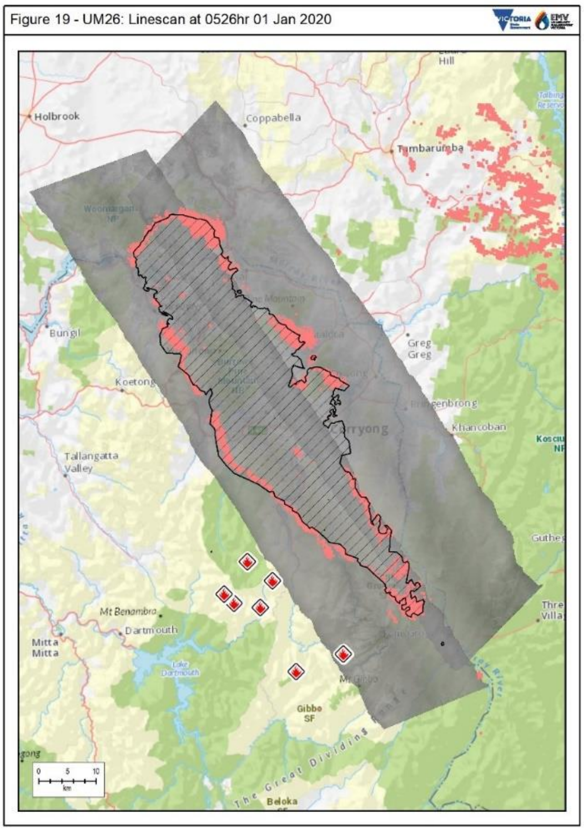


FIGURE 21: LINE SCAN IMAGE AT 0526 LT 1 JANUARY 2020 SHOWING THE AREA BURNT (PROVIDED BY DELWP).

In this study we begin by looking at the broadscale meteorological pattern on the days of the fire. The ACCESS-Fire model is used to examine the characteristics of the environment in which destructive fire-generated vortices formed. We then look at key drivers for the exceptional fire behaviour during the overnight period on 30 December using vertical cross sections to diagnose the important processes.

Meteorological situation

Weather conditions on 30 December 2019 were very hot and dry, with north westerly winds averaging 30 to 40 km/h in the early afternoon. Maximum temperatures in the area were near 40°C and the relative humidity dropped below 10% in the late afternoon.

The synoptic weather chart at 11:00 LT on 30 December (Figure 22, left panel) showed a sharply defined trough of low pressure ahead of a cold front through Tasmania and western Victoria. By 11:00 LT on 31 December (Figure 22: right panel) the cold front was located off the far south coast of NSW and the trough was located through north eastern Victoria. The trough marked the boundary between a very hot, dry airmass on its eastern side, and a milder, south westerly wind flow to its west.

The cooler wind change reached Dorchap Range, some 60 kilometres to the south west of Corryong at around 18:00 LT on 31 December. Cooler, more humid air behind the change led to a rapid reduction in fire activity overnight.

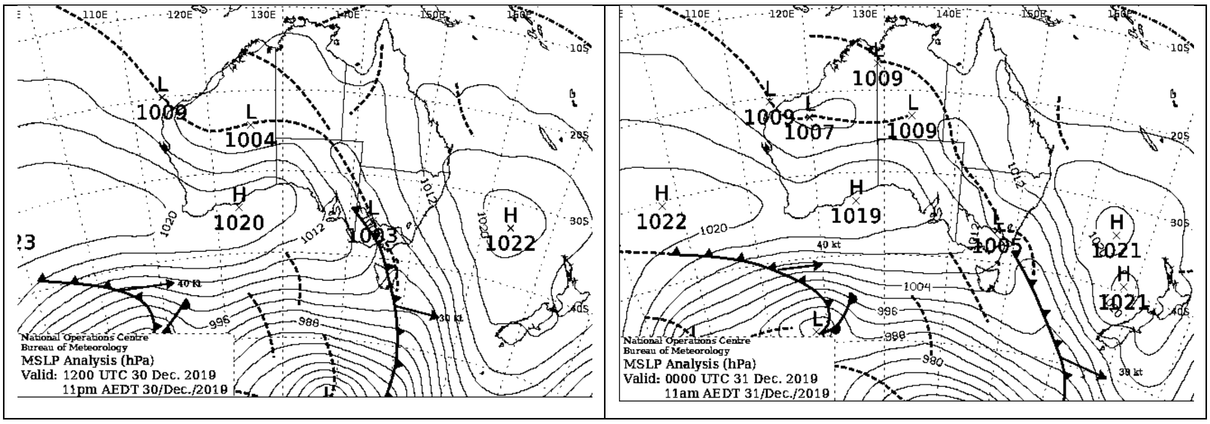


FIGURE 22: MSLP CHART AT 11:00 LT 30 DECEMBER 2019 (LEFT) AND 11:00 LT 31 DECEMBER 2019.

ACCESS-Fire simulations

The ACCESS-Fire model was used to explore factors which were important in driving the exceptional fire behaviour observed during the late afternoon and overnight period of 30/31 December 2019.

Of particular interest were the atmospheric conditions which drove extreme fire behaviour during the overnight period on 30 December; the presence of pyro convection and possible influence on fire behaviour; the impact of topography on the intensity and rate of spread of the fire; and the impact of coalescence of two fires in the early hours of 30 December.

To explore these aspects, several model simulations were conducted, covering the period from late afternoon on 30 December 2019 through until the evening of 31 December 2019 (Table 1). The simulations used constant forest fuel amounts of 20t/ha. It is likely that fuel loads were higher in some of the forested areas and lower in the valleys. No adjustment has been made for grass fuels in valleys.

	Fire perimeter	Model start time	Fuel type/amount
Simulation 1 Green Valley Talmalmo	Based on RFS 16:15 LT line scan image	14:00 LT 30 December 2019	Forest 20 t/ha
Simulation 2 Green Valley Talmalmo/Mount Alfred	As per simulation 1 except spot fire near Mt Alfred ignited at 17:30 LT	14:00 LT 30 December 2019	Forest 20 t/ha
Simulation 3 Corryong fire coalescence	Based on 21:30 LT line scan	20:00 LT 30 December 2019	Forest 20 t/ha

TABLE 1: CONFIGURATION OF THE THREE MODEL SIMULATIONS CONDUCTED.

For each of the simulations, several diagnostic fields were generated. These included hourly isochrones of fire spread, total firepower, surface wind fields, transects of vertical motion and wind speed, and plots of vorticity (a measure of rotation in the atmosphere) at various vertical levels.

Simulated fire spread from Green Valley Talmalmo/Mount Alfred run

Hourly isochrones of fire spread from simulation 2 (which includes the Mount Alfred spot fire) are shown in Fig 23. The model captured the south south east spread of the fire in the overnight period well (see line scan in Figure 21 above). The model rate of spread was less than the observed spread, shown by the line scan image. The slower simulated spread is most likely related to spotting ahead of the fire, which is currently not included in the model. The eastward spread of the fire in the last few hours of the simulation is faster than that observed, most likely due to a shallow wind change in the model, which was observed at Hunters Hill (location in Fig 23) but was not observed to cross the fire front.

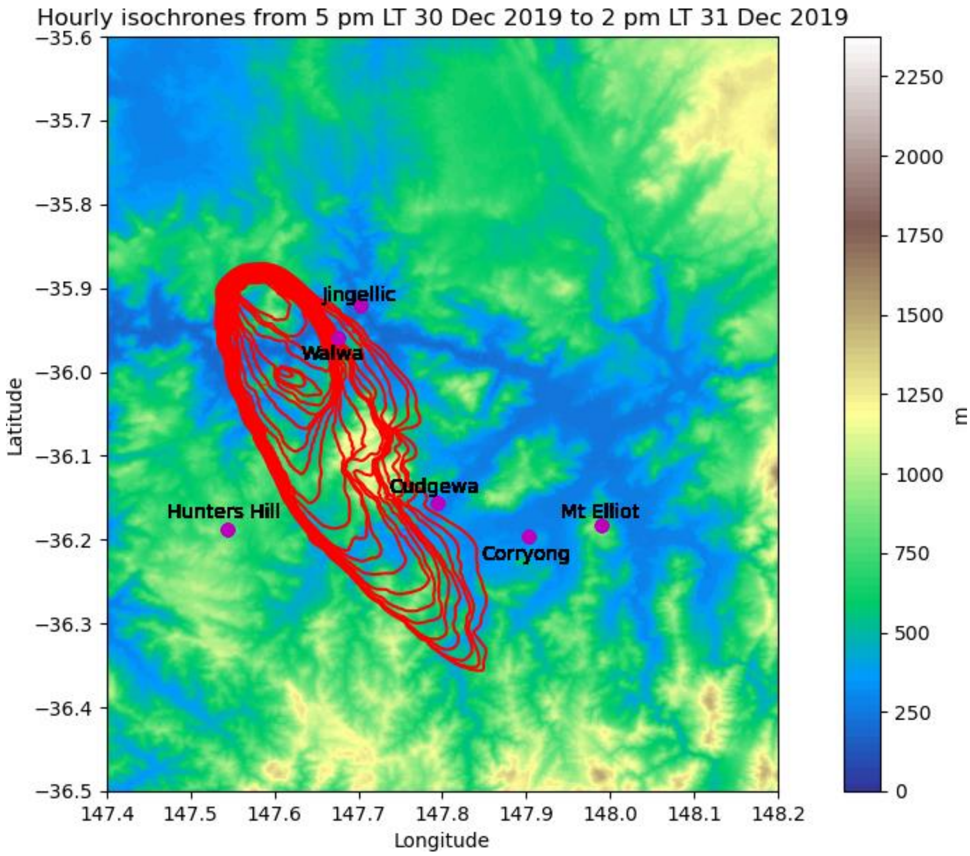


FIGURE 23: ISOCHRONES OF THE FIRE SPREAD (RED CONTOURS) AT HOURLY INTERVALS FROM SIMULATION 2, WITH MOUNT ALFRED SPOT FIRE INCLUDED JUST SOUTH WEST OF WALWA. COLOUR SHADING SHOWS THE ELEVATION ABOVE SEA LEVEL (M), AND KEY LOCATIONS ARE INDICATED.

Rotating fire plume and fire-generated vortices

Photographic and video footage of the fire at around 1730 LT (Figure 24) showed that the fire's convection column was rotating in a clockwise direction as it moved across the ridgetop into Green Valley. The Green Valley Talmalmo fire is known to have spawned at least two fire-generated vortices (FGVs) accompanied by tornado strength winds. Photographic evidence suggests that the first FGV formed within, or on the periphery of the rotating plume, and then moved to the south east downwind from the main fire front (Figure 25, left). A second FGV was observed around 19:30 LT near Karumba in Victoria, some 10 kilometres to the south east (Figure 25, right).

FIGURE 24: IMAGES SHOWING THE FIRE ENTERING GREEN VALLEY (NSW) AT 17:25 LT, 30 DECEMBER 2019.

LEFT ; PHOTOGRAPH FROM RECONNAISSANCE AIRCRAFT AT 17:25 LT LOOKING NORTH WEST ACROSS GREEN VALLEY.

RIGHT: VIDEO STILL IMAGE OF THE ROTATING FIRE PLUME ON THE NORTH WEST SLOPES OF GREEN VALLEY. THE FOOTAGE WAS TAKEN AT 17:30 LT APPROXIMATELY 1500 M TO THE SOUTH EAST OF THE FIRE [IMAGE COURTESY MR ASHLEY DRUMMOND]. [IMAGE NOT TO BE USED WITHOUT PERMISSION].

FIGURE 25: FIRE GENERATED VORTICES IN GREEN VALLEY (NSW) AT 17:30 LT 30 DECEMBER (LEFT) AND NEAR KARUMBA (VIC) AT 19:30 LT (RIGHT). BOTH PRODUCED VERY DESTRUCTIVE TORNADO STRENGTH WINDS.

[PHOTO (LEFT), COURTESY MR SCOTT ANDERSON. PHOTO (RIGHT), COURTESY MS JANICE NEWNHAM]. [PHOTOS NOT TO BE USED WITHOUT PERMISSION].

To assess the potential for rotation within the fire plume, surface winds and vorticity (a measure of rotation in the atmosphere) were analysed. The surface wind and vorticity fields between 17:30 and 17:45 LT (Figure 26) show a region of northerly winds just ahead of the fire in Green Valley indicative of turning of the winds into a meso-scale cyclonic circulation, as highlighted by the yellow ellipse in the bottom left image. The vorticity fields (blue and red shaded regions in Figure 26) show a region of cyclonic vorticity (positive blue shaded region) just to the north west of where the destructive FGV (marked by the black dot) was observed.

Radar observations of intense fires in the United States (pers. comm. Dr Neil Lareau) show that the area within the rotating updraft, and beneath the plume in the wake region downwind from the fire, are favoured areas for intense vortices to form. The lee side of a ridgeline in a crossflow wind is also a favoured location for FGV formation.

While the model results in Figure 26 show the potential of very high-resolution fire-coupled numerical weather prediction to resolve micro-scale processes, we caution that features of this small scale normally have very limited predictability in the atmosphere. Moreover, there are other occasions and locations within the simulation with similarly strong vorticity signatures, but where vortices were not observed in reality. A substantial amount of work, most likely within a probabilistic framework, would be needed before such features in the model could be confidently used in real-time fire management, even once the computer power is sufficient to deliver in a timely fashion.

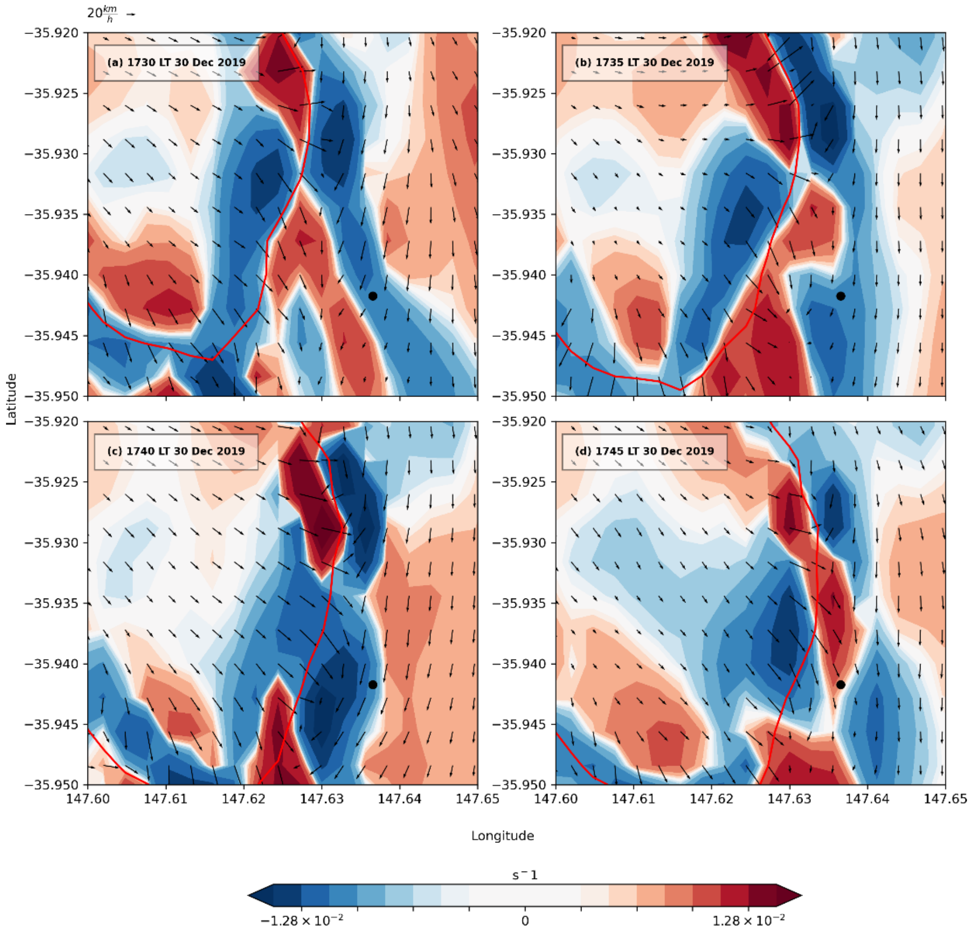


FIGURE 26: PLOTS OF SURFACE WINDS AND VORTICITY IN THE AREA SURROUNDING GREEN VALLEY, AT:

A) 1730, B) 1735, C) 1740, D) 1745 LT ON 30 DECEMBER. BLACK DOT SHOWS THE LOCATION AT WHICH A DESTRUCTIVE FIRE-GENERATED VORTEX OCCURRED. BLUE SHADES REPRESENT REGIONS OF CYCLONIC VORTICITY (CLOCKWISE ROTATION). RED SHADES SHOW REGIONS OF ANTICYCLONIC VORTICITY (ANTICLOCKWISE ROTATION). THE RED LINE IS THE FIRE PERIMETER. THE DOMAIN SIZE IS APPROXIMATELY 10 KM SQUARE.

Vertical structure of the fire plume in Green Valley

Cross-sections of vertical motion and potential temperature through Green Valley between 17:20 and 17:50 LT are shown in Figure 27. The solid black line in Figure 28 shows the location of the cross section. In Figure 27, the fire plume is a deep region of upward motion (red shading) that extends to a height of around 8 km above ground level. There was weaker compensating down motion to the rear of the fire (blue shading). The top of the well-mixed boundary layer is visible as the level where the tightly spaced potential temperature isotherms commence. Figure 28 shows strong modification of the wind fields near the active fire front where the destructive FGV formed.

Interpretation of this figure requires some caution. It is apparent that the plume is a highly dynamic feature, with substantial variation in time. It is unclear how much of this variability is due to variations in the heat input into the plume, and how much is the internal dynamics of a turbulent plume responding to the surrounding atmosphere, itself unsteady. Note also that at least some of the vertical motion apparent in the figure is likely due to mountain wave activity. Nevertheless, it is notable that the simulations produced an intense and relatively vertical plume near the time that the FGV occurred.

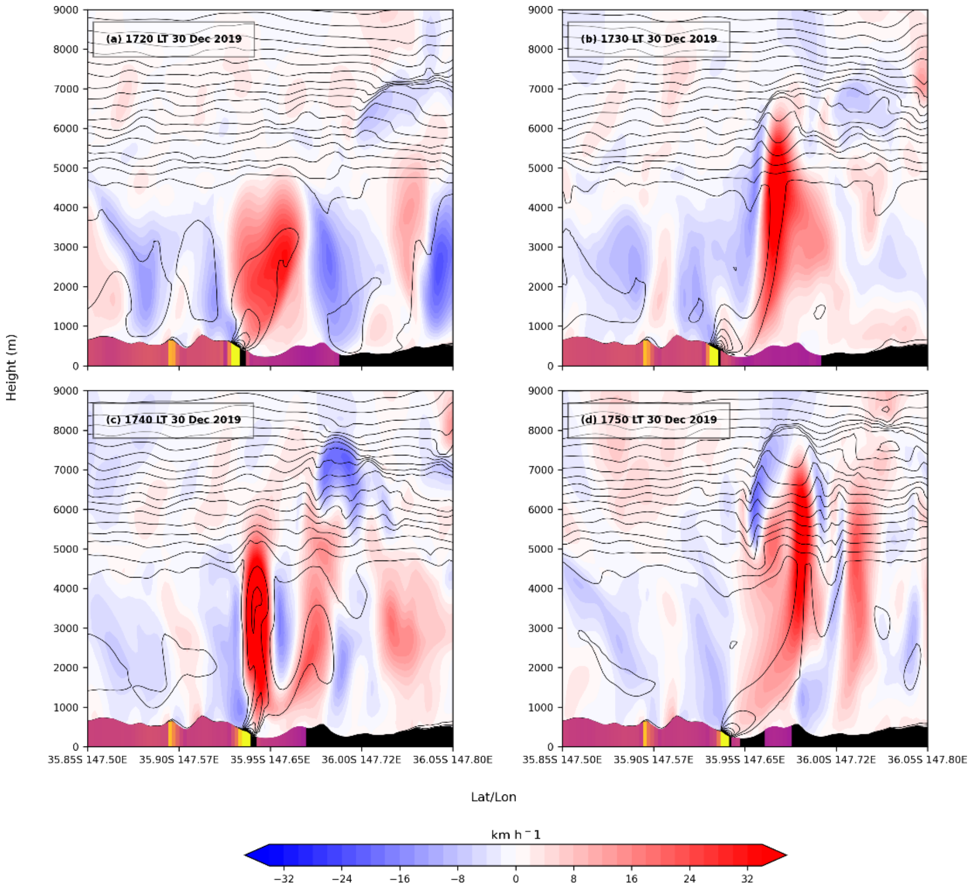


FIGURE 27: NW/SE CROSS SECTION THROUGH GREEN VALLEY AT: TOP LEFT) 1720, TOP RIGHT) 1730, BOTTOM LEFT) 1740 AND BOTTOM RIGHT) 1750 LT ON 30 DECEMBER. RED SHADING REPRESENTS UPWARD MOTION, BLUE SHADING DOWNWARD MOTION. CONTOURS ARE LINES OF POTENTIAL TEMPERATURE (°K). THE UP MOTION ASSOCIATED WITH THE FIRE EXTENDS TO A HEIGHT OF AROUND 8KM ABOVE THE GROUND AND SLOPES DOWNWIND TOWARDS THE SOUTH EAST. THE ORANGE AND YELLOW COLOUR SHADING ON THE TOPOGRAPHY INDICATES THE ACTIVE FIRE. THE HORIZONTAL SCALE IS APPROXIMATELY 30 KM.

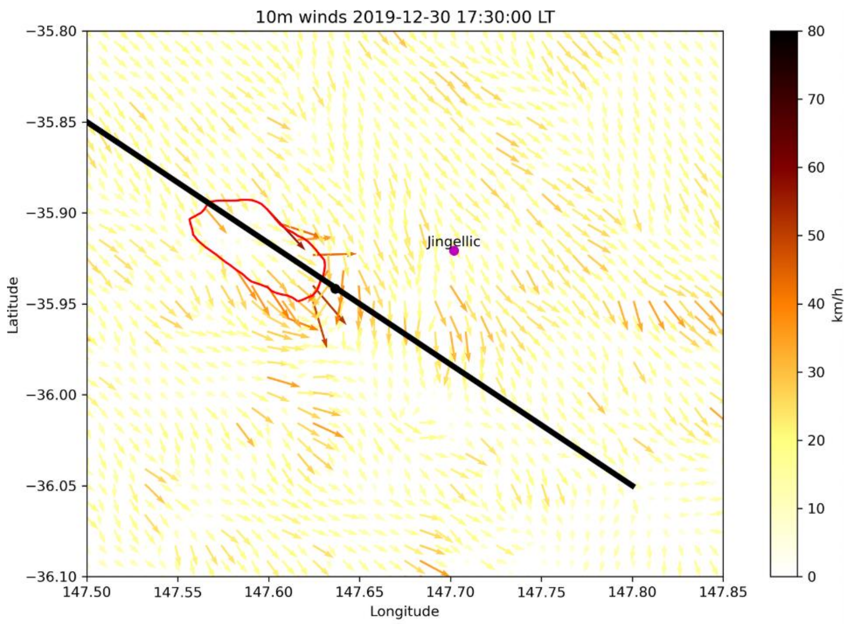


FIGURE 28: 10 M WINDS AND FIRE PERIMETER AT 17:30 LT. BLACK LINE SHOWS LOCATION OF CROSS SECTION IN FIGURE 27.

The Himawari-8 visible satellite image at 17:35 LT 30 December (Figure 29) shows that the updrafts associated with the fire resulted in formation of pyrocumulus clouds. Due to the downwind tilt of the convection column the highest cloud tops (whitest shading) are located across the border in Victoria.

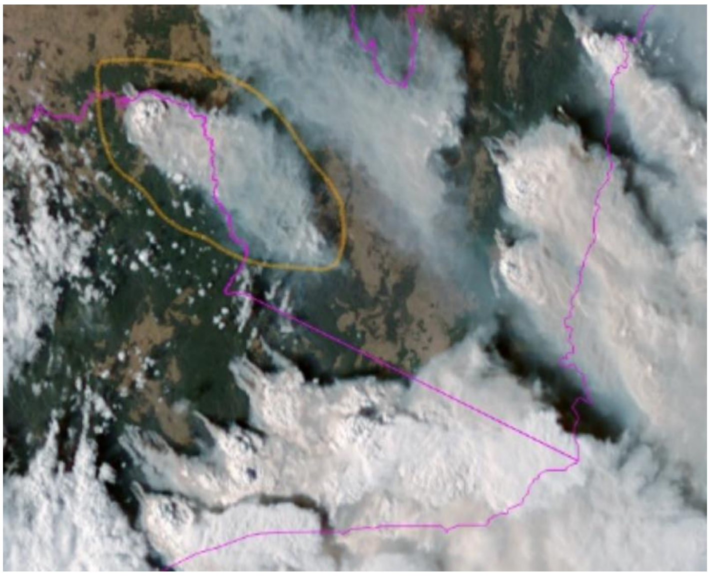


FIGURE 29: HIMAWARI-8 VISIBLE SATELLITE IMAGE FOR 17:35 LT ON 30 DECEMBER 2019. THE YELLOW ELLIPSE HIGHLIGHTS THE PLUME FROM THE GREEN VALLEY TALMALMO FIRE. THE AUSTRALIAN COASTLINE AND STATE/TERRITORY BORDERS ARE SHOWN IN MAGENTA.

The 18:30 LT high resolution infra-red satellite image (not shown) had the coldest cloud top temperature (CTT) in the sequence of images around the time of the incident. This coldest CTT of -20°C corresponds to a cloud top height of around 7 km above ground level, in reasonable agreement with the plume penetration height shown in Fig 27.

Mount Alfred spot fire

The vertical cross sections of wind from 1720 to 1750 LT (Figure 30) show that the strong updraft was collocated with a core of strong horizontal winds ascending to a height of around 4 km above ground level (Figure 30 a and b) which then descended onto the lee slopes of the Victorian mountains. While the strong ascending winds provided a favourable environment for lofting of embers, it is difficult to discern their likely path in such a complex and varying three-dimensional flow. It is plausible that the location of the spot fire that started at Mount Alfred around 17:30 LT, which is not aligned with the prevailing winds, but towards the south, resulted from the rotation in the convection column.

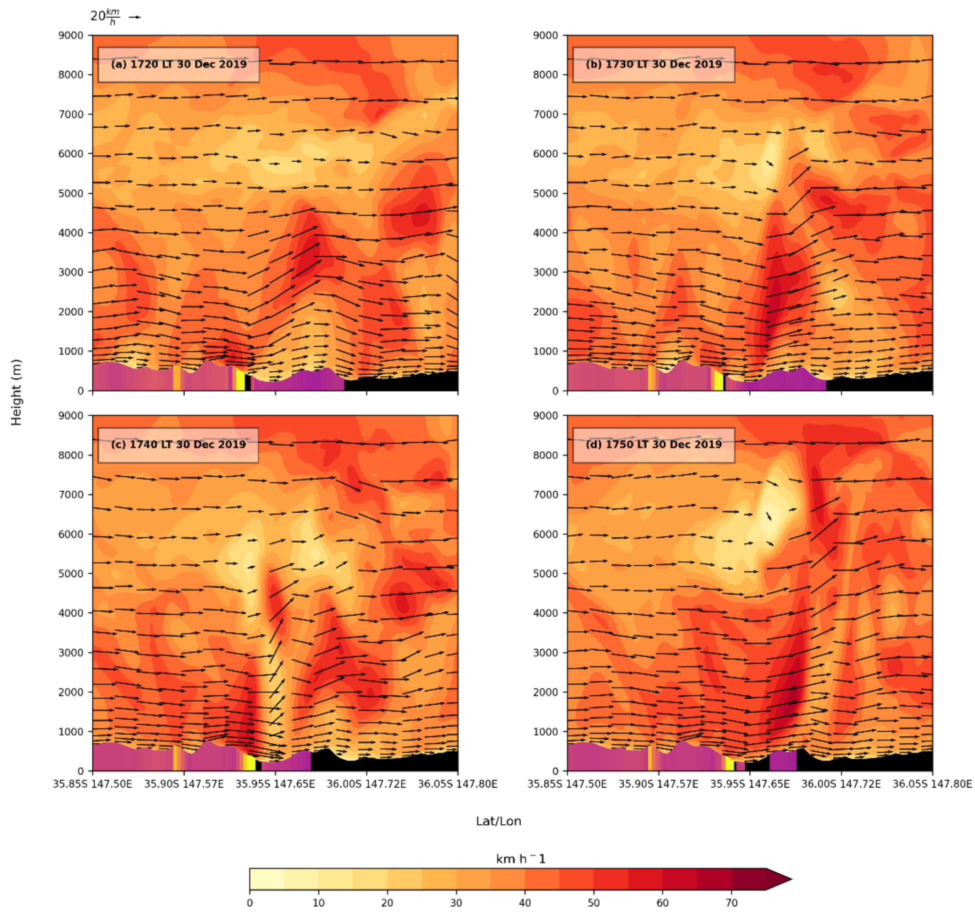


FIGURE 30: NW TO SE CROSS SECTION THROUGH GREEN VALLEY SHOWING VERTICAL PROFILE OF WIND SPEED (SHADED YELLOW TO RED). THE TIMES AND LOCATIONS OF THE CROSS-SECTION ARE THE SAME AS IN FIGURE 27. ARROW LENGTHS ARE PROPORTIONAL TO THE WIND SPEED (KM/H) AND THE DIRECTION OF THE ARROWS INDICATE UP AND DOWN MOTION. THE ORANGE AND YELLOW COLOUR SHADING ON THE TOPOGRAPHY INDICATES THE ACTIVE FIRE.

Simulated strong outflow winds ahead of the fire

Downbursts from convective clouds can be associated with sudden changes in surface wind direction and an increase in wind speed. The classic wind signature of downbursts on the ground shows radial outflow of winds from a central core region. Downbursts are typically short-lived with lifecycles of tens of minutes and are localised within a few kilometres in an outward direction from the descending central core.

Such a divergent pattern of surface winds was seen downstream from the Green Valley Talmalmo fire in the model simulation at different time intervals in the period between 17:30 and 20:00 LT on 30 December. A striking example can be seen at 19:24 LT (Figure 31).

There were no direct observations from the Mount Elliot area to verify the strong winds. Therefore, it cannot be stated with confidence that the simulated outflow represents a downburst from pyro-convective cloud. However, deeper analysis would be worthwhile, including comparison with uncoupled simulations, in order to fully understand the processes in the model that produced these winds, given their potential to produce unexpected hazardous conditions down-wind of the fire.

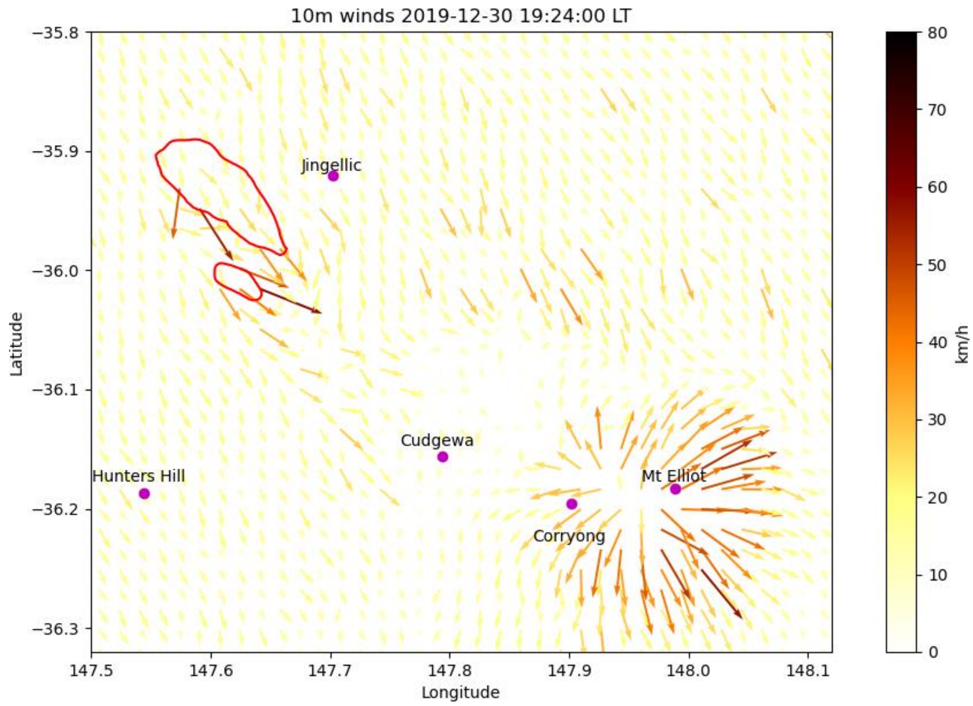


FIGURE 31: 10 METRE WINDS (KM/H) AT 19:24 LT 30 DECEMBER 2019 SHOWING: STRONG WINDS ALONG THE PERIMETER (RED LINE) OF THE GREEN VALLEY TALMALMO FIRE AND THE MOUNT ALFRED SPOT FIRE IN THE NW OF THE IMAGE, AND STRONG OUTFLOW WINDS NEAR MOUNT ELLIOT POSSIBLY CAUSED BY A DOWNBURST FROM THE PYRO-CUMULUS CLOUD THAT EXTENDED DOWNWIND OF THE MAIN FIRE. (THE DOMAIN SIZE IS APPROXIMATELY 55KM SQUARE).

Coalescence of the Mount Alfred spot fire with the Green Valley Talmalmo/Corryong fire

During the period between 21:00 and 23:00 LT on 30 December 2019 the Mount Alfred spot fire coalesced with the Green Valley Talmalmo/Corryong fire. The simulations allowed us to examine the evolution of the wind fields as the flow between the two fires interacted (Figure 32). A feature of the coalescence was the strength of the fire driven winds during the period of merging (Figure 32, top right panel). Near-surface winds exceeding 70 km/h were generated along the merging fire perimeters. After the two fires had merged, the strong winds eased and became confined to the head fire region (Figure 32, bottom left). The extreme and erratic winds that were simulated as the fires merged indicates the potential for very dangerous fire behaviour, which is consistent with anecdotal evidence from practitioners at numerous fire grounds.

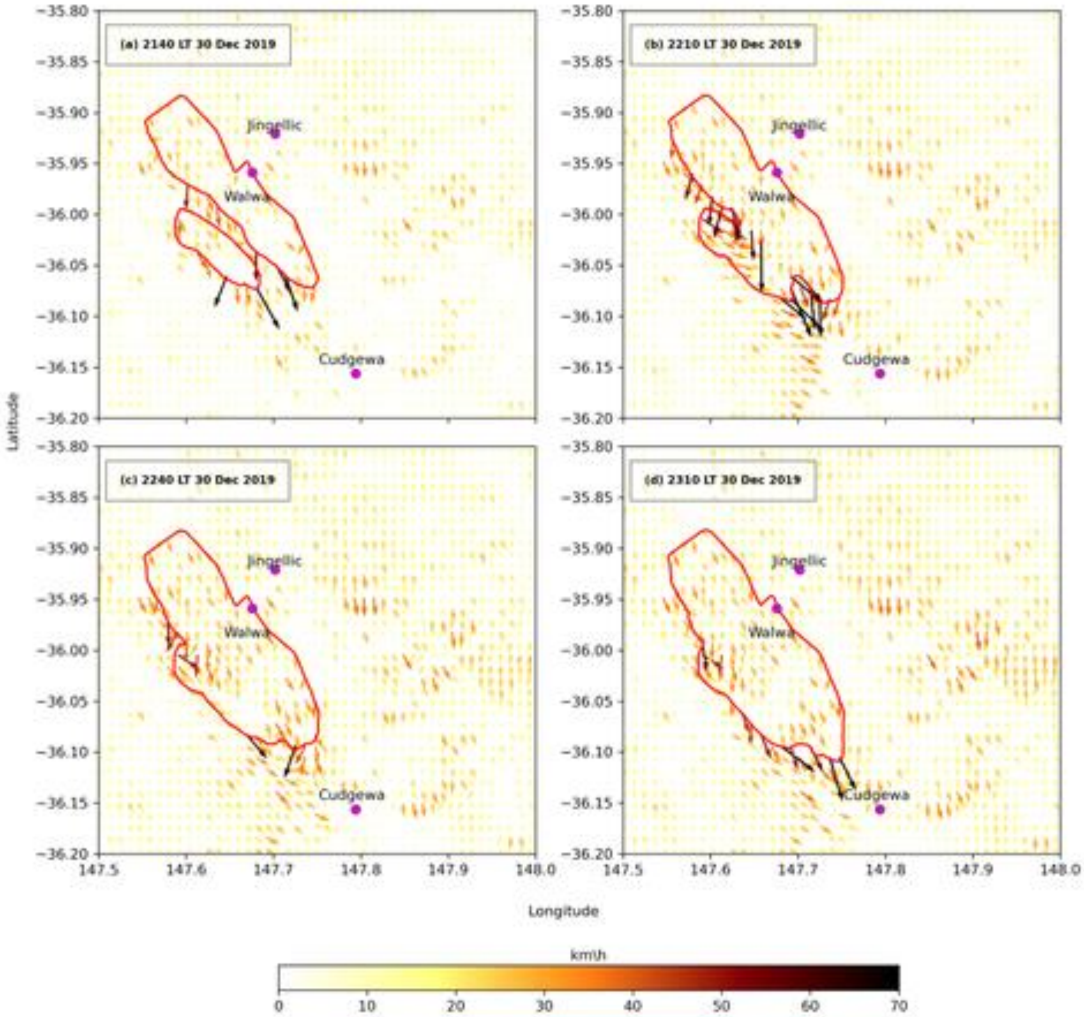


FIGURE 32: SURFACE WINDS (KM/H) COLOUR CODED ACCORDING TO WIND SPEED DURING THE PERIOD 21:40 (TOP LEFT) TO 23:10 (BOTTOM RIGHT) LT 30 DECEMBER 2019. NOTE THE VERY STRONG WINDS (MORE THAN 70 KM/H) AT THE TIME WHEN THE FIRES JOINED AROUND 22:10 LT (TOP RIGHT).

Destructive fire front winds

Some of the strongest fire-generated winds were produced during fire coalescence, however the surface wind fields showed other periods of localised destructive winds near the fire front. An example is shown in the period around 05:00 LT on 31 December in Figure 33, with the strongest winds highlighted by the black arrows.

A time series plot of the simulated maximum winds over the domain of the model for the 24 hours until 03:00 LT on 31 December (Figure 34) showed that 10-minute average winds approaching 130 km/h were generated, and that the peak wind seldom dropped below 80 km/hr. While the driving mechanisms and verification of these winds requires further study, they appear to be related to an increase in intensity of the fire and the slope and orientation of topography to the prevailing wind flow.

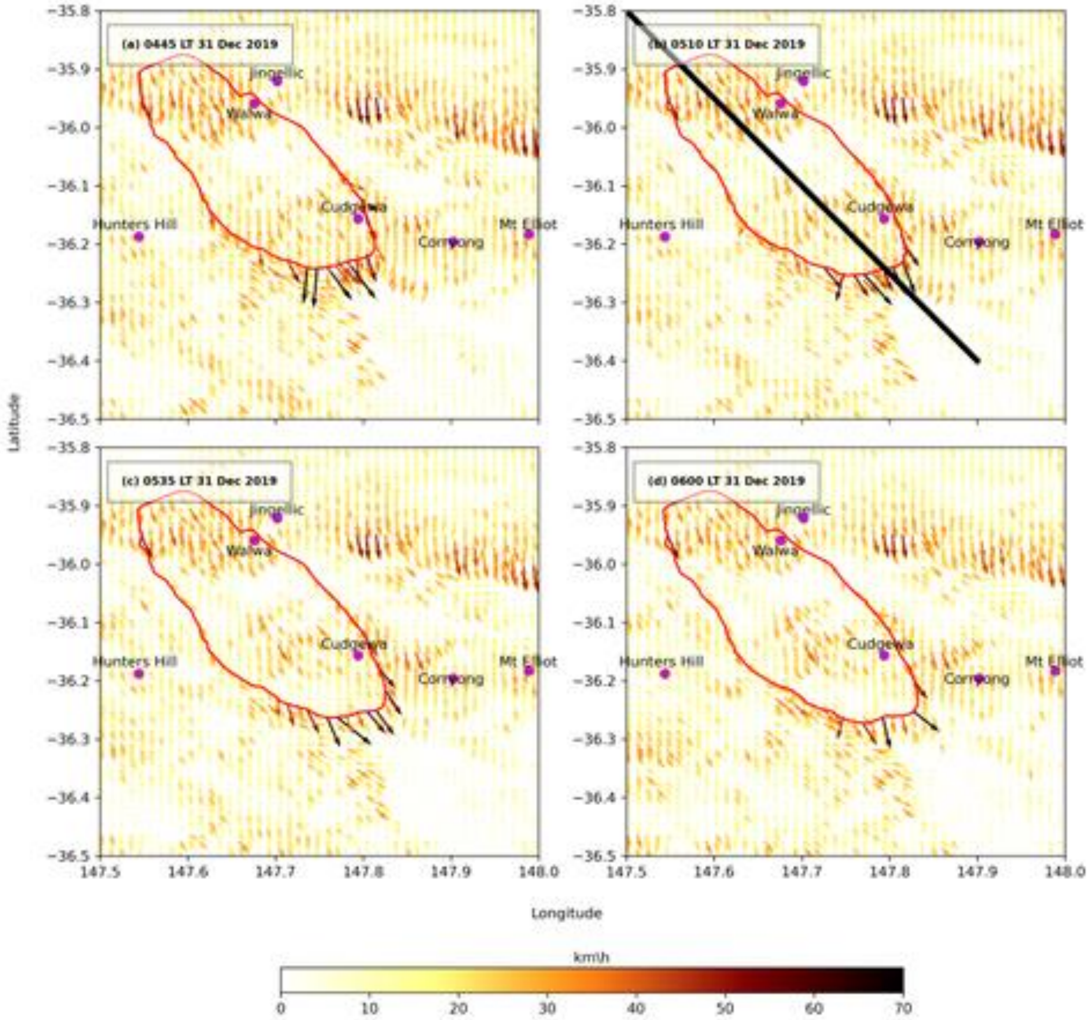


FIGURE 33: PLOT OF 10 METRE WINDS AT 04:45 LT (TOP LEFT), 05:10 LT (TOP RIGHT), 0535 (BOTTOM LEFT) AND 06:00 31 DECEMBER 2019. SHADED WIND VECTORS SHOW THE WIND SPEED IN KM/H. SOLID BLACK LINE (TOP RIGHT) SHOWS THE ORIENTATION OF THE VERTICAL TRANSECTS IN FIGURE 35.

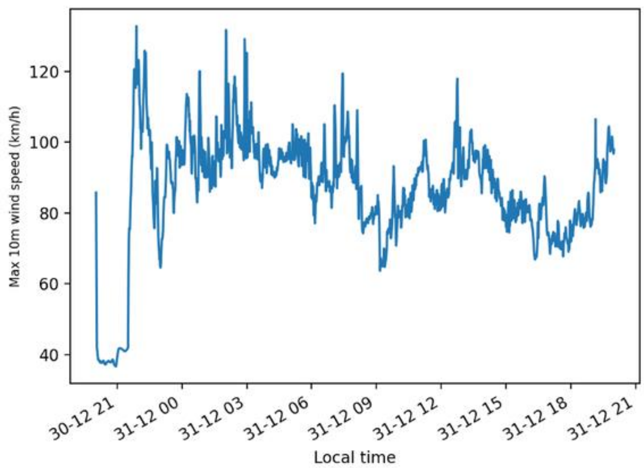


FIGURE 34: TIME SERIES PLOT OF DOMAIN MAXIMUM 10-MINUTE WIND SPEEDS ASSOCIATED WITH THE FIRE DURING THE PERIOD FROM 20:00 LT 30 DECEMBER TO 20:00 LT 31 DECEMBER 2019.

Role of a low-level nocturnal jet on fire spread in the overnight period

The development of a nocturnal low-level jet can be seen in Figure 35, which shows vertical cross-sections of the wind speed between 0010 and 0510 LT 31

December. The time evolution shows the jet core intensifying significantly over the six-hour period to be around 70 km/h at 05:00 LT. The high-resolution cross sections show that the elevation of the narrow jet core varies in response to the topography. Figure 35 bottom left in particular shows the jet core interacting with the fire, with the core being deflected downwards close to the surface near the rear of the fire, then shooting upwards in the convection column, to reach a height of around 3 km downstream of the fire.

There is significant variation in the speed of the near-surface winds along the cross section due to deflection of the low-level jet by the mountain peaks and the fire's convective column. These interactions highlight the complexity of topographic and fire-atmosphere interactions.

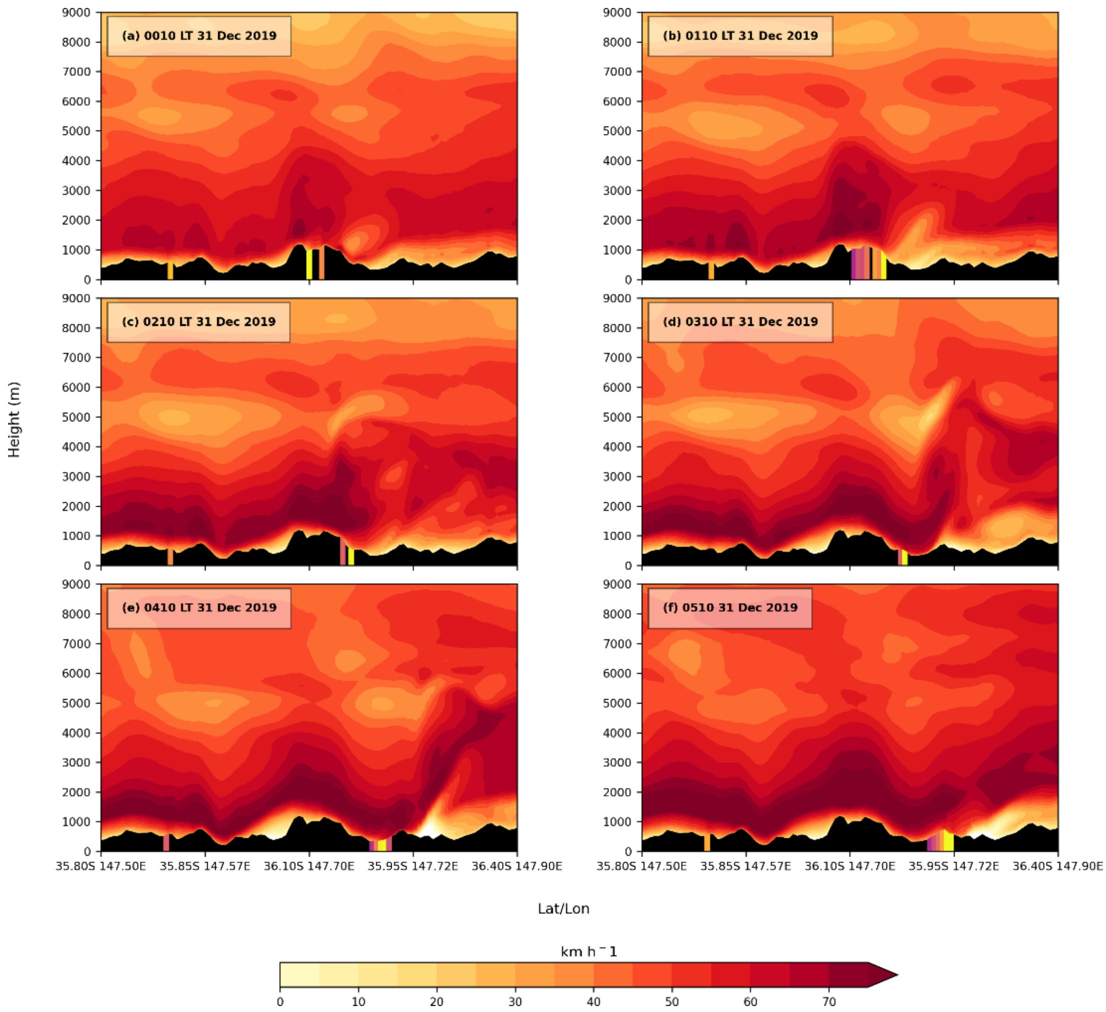


FIGURE 35: VERTICAL CROSS-SECTION ALONG THE TRANSECT FROM NORTH WEST TO SOUTH EAST IN FIGURE 33 (TOP RIGHT) OF WIND SPEED COLOURED ACCORDING TO WIND STRENGTH (KM/H) BETWEEN 00:10 LT (TOP LEFT) AND 05:10 LT 31 DECEMBER 2019 (BOTTOM RIGHT). THE MEANDERING JET OF STRONGER WINDS BETWEEN 1000 AND 3000 METRES CAN BE SEEN CLEARLY ABOVE THE SURFACE TOPOGRAPHY. THE HEIGHT SCALE ON THE VERTICAL AXIS EXTENDS FROM THE SURFACE TO 9000M. THE DISTANCE ACROSS THE HORIZONTAL AXIS IS APPROXIMATELY 40 KM. THE PINK AND YELLOW BARS OVER THE TOPOGRAPHY INDICATE THE LOCATION OF THE FIRE.

Key points

- Extreme heatwaves occurred in November and December and the fire ignition and major run occurred at the end of a heatwave. Record low rainfall had been recorded in the area over the previous months, leading to extremely low fuel and soil moisture.

- By late afternoon on 30 December, the fire had developed a deep convective plume. Vertical cross sections from the simulations show deep vertical motion within the fire plume, with high intensity updraft winds extending up to 8 km, that is consistent with the pyro-convective cloud heights observed on radar and satellite images.
- An intense fire-generated vortex was observed in Green Valley at around 17:30 LT on 30 December. Rotation on two spatial scales was recorded in photographic and video images, that of the vortex and larger-scale rotation of the fire's convection column. The simulations are consistent with the observations; showing an upright fire plume with strong updrafts and surface wind fields indicative of rotation as the fire moved into Green Valley.
- A distinctive wind signature consistent with convectively driven downburst winds was produced in the simulations at around 19:30 LT 30 December some 30 km south east of the fire.
- The ignition of a spot fire ignition near Mount Alfred with a southerly trajectory that was inconsistent with the prevailing winds was likely associated with lofting of embers in the strong rotating updrafts above the fire.
- Simulations capturing the coalescence period between the main fire and the Mount Alfred spot fire, shows surface wind speeds exceeding 100 km/h near the interface of the two fire perimeters.
- In the overnight period the fire behaviour and spread were driven by a strong low-level jet that that was drawn downwards into the rear of the fire. The model showed that the core of this jet was within 1 km of the surface upwind of and over the fire but ascended to up to 5 km in the plume.

THE BADJA FOREST ROAD FIRE, COUNTEGANY (NSW), (30-31 DECEMBER 2019)

Impact of the fire and description of fire behaviour

The *Badja Forest Road, Countegany, NSW* ('Badja Forest') fire was most likely ignited by lightning on the afternoon of 27 December 2019 in the Badja State Forest.

It occurred in heavy forest fuels in rugged mountainous terrain and burnt a swathe of forest and farmland from north west to south east from the Badja State Forest to Cobargo. On average, the fire front was around 8 km wide, but it reached up to 15 km wide across the flanks. Between late evening on 30 December and the early hours of 31 December, the fire spread 36 km to the south east, a forward speed of around 6 km/h. Four other fires in the vicinity, including the *Big Belimbla Creek, Dampier State Forest* fire ('*Big Belimbla Creek*') fire and the *Bumbo Creek* fire, grew rapidly on the evening of 30 December and merged with the *Badja Forest* fire on 31 December 2019.

Damage reports from a farm in the Wandella Valley (north west of Cobargo) indicate suggest that very destructive winds, associated with a possible fire-generated vortex occurred during the period between 03:00 and 05:00 LT on 31 December.

(See [https://www.canberratimes.com.au/story/6571353/the-night-the-beast-came-to-the-farm/)](https://www.canberratimes.com.au/story/6571353/the-night-the-beast-came-to-the-farm/)

Meteorological situation and surface observations

The mean sea level pressure (MSLP) charts for the overnight and morning period of 30/31 December 2019 (Figure 36) show a front and pre-frontal trough approaching the fire from the west in the overnight period. The front marked the boundary between very hot and dry north to north westerly winds and a cooler, moister southerly change. The southerly change (shown as a dashed line in the right panel) reached the fireground around mid-morning on 31 December.

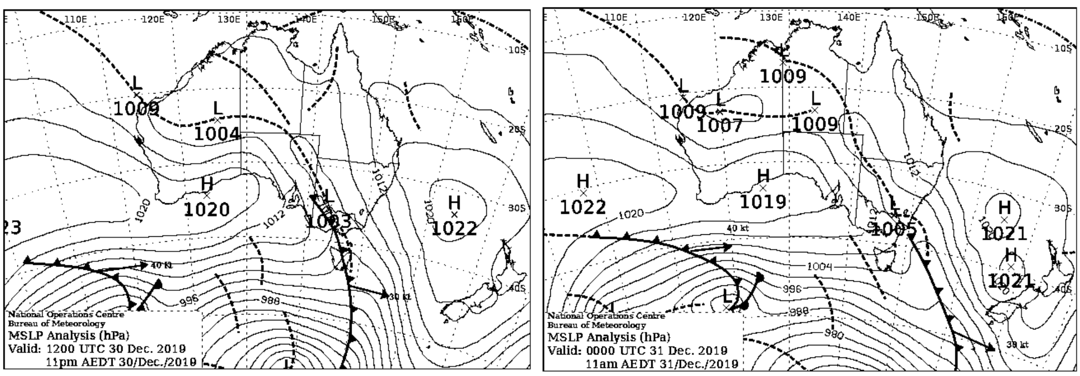


FIGURE 36: MSLP CHART FOR 23:00 LT 30 DECEMBER 2019 (LEFT PANEL) AND 11:00 LT 31 DECEMBER 2019 (RIGHT PANEL.

Information on the local meteorological conditions near the fire in the overnight period was provided by the NSW Rural Fire Service. A NSW National Parks and Wildlife Service portable Automatic Weather Station (AWS) at an elevation of around 1000 m ASL was overrun by the fire near Belowra (see location in Figure 37 below) at around 06:00 LT 31 December. At midnight on 30 December, the station recorded calm conditions, temperature near 20°C and RH 70%, then by 02:00 LT the RH had dropped rapidly to less than 10% while the temperature increased from the low 20°Cs to the mid 30°Cs. By 04:00 LT the wind had increased to WNW 50 km/h, gusting to 70 km/h. 'Catastrophic' Forest Fire Danger Index was observed at the station for a 1.5-hour period between 04:00 and 05:30 LT, a remarkable fire danger rating in the overnight period.

Observations from a private AWS at Eagles Rest to the south of the fire showed that the temperature rose from the mid 20°Cs around midnight 30 December to the mid 30°Cs by 01:00 LT 31 December, with the RH dropping below 10%. An infra-red video looking north from Eagles Rest showed intense fire activity on the lee side slopes at around 04:30 LT and airflow being drawn upslope towards the main fire to the west. The images also capture what appears to be a fire generated vortex travelling from west to east, away from the main fire front.

The convection column associated with the *Badja Forest* fire was observed on the outer limits of the Bureau of Meteorology Wollongong radar. It first became visible on the radar during the afternoon of 30 December, when the maximum plume height reached around 11 km height and the fire was about 240 km south west of the radar. The plume continued to be visible on radar through the evening of 30 December, re-intensifying around midnight and peaking at 13.8 km height in the next hour. The plume was visible on radar through the night, with occasional evidence of another plume some distance to the north north east.

ACCESS-Fire simulations

The ACCESS-Fire model was used to explore factors which were important in driving the exceptional fire behaviour observed during the overnight fire run on 30/31 December 2019.

Of particular interest were the atmospheric conditions which drove the extreme fire behaviour during the overnight period on 30 December, including the role of a nocturnal jet, the impact of topography on the intensity and rate of spread of the fire, and the effect of the two fires to the north east.

To explore these aspects, four model simulations were conducted covering the period from late on 30 December through until the afternoon of 31 December.

The configuration of the model simulations is summarised in Table 2.

	Fire ignition specification	Model start time	Fuel type/amount
Simulation 1	Based on RFS line scan image. Ignition at18:00 LT Main fire area polygon plus two small spot fire polygons to the south	14:00 LT 30 December 2019	Forest 20 t/ha
Simulation 2	As per simulation 1	14:00 LT 30 December 2019	Forest 30 t/ha (Based on advice from RFS that the higher fuel load is more realistic)

Simulation 3	As per simulation 1 plus *Big Belimbla Creek* and *Bumbo Creek* fire polygons added.	14:00 LT 30 December 2019	Forest 30 t/ha
Simulation 4	As per simulation 3 but with fire coupling off.	14:00 LT 30 December 2019	Forest 30 t/ha

TABLE 2: CONFIGURATION OF THE MODEL SIMULATIONS FOR THE *BADJA FOREST* FIRE.

For each of the simulations several plots were generated, these included hourly isochrones of fire spread, total firepower, surface wind fields and transects of vertical motion and wind speed.

Isochrones of fire spread

Fire spread isochrones of simulations 1- 4 (Figure 37) show the differences in the rate of spread of the fire under the different scenarios. The increase in fuel load from 20 t/ha to 30 t/ha in Simulation 2 (as suggested by NSW RFS) increased the rate of spread (ROS) of the *Badja Forest* fire and the total area burnt. The inclusion of the *Big Belimbla Creek* and the *Bumbo Creek* fire (also suggested by RFS) further increased the ROS and area burnt. More detailed investigation will be required to understand how the growth and interaction of the two smaller fires affected the growth of the *Badja Forest* fire to such an extent. The ROS of the fire in the uncoupled run (simulation 4) is around half that in simulation 3, highlighting that fire-atmosphere coupling played a critical role in the wind modification and interaction processes that drove the spread of the fire.

The average forward speed of the *Badja Forest* fire is estimated at around 6 km/h in the period between 20:00 LT 30 December and 02:00 LT 31 December, compared to a speed of just under 1 km/h for the *Big Belimbla Creek* fire to its north east. The difference in rate of spread may be attributed to factors such as the extent of spotting in the fires, the size of the fires and the interaction with the low-level nocturnal jet.

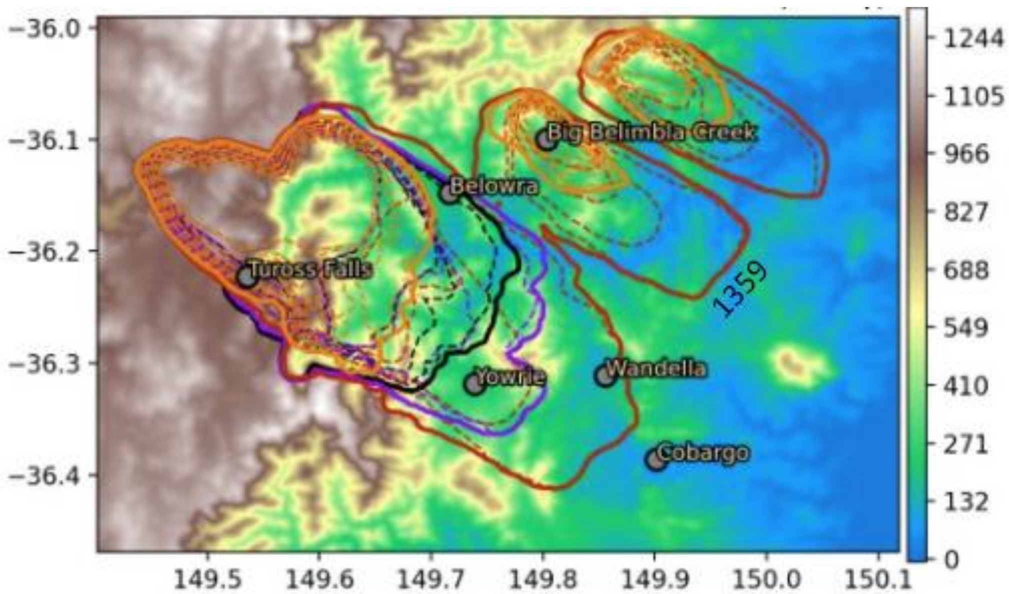


FIGURE 37: ISOCHRONES OF FIRE SPREAD FOR THE 4 SIMULATIONS- SOLID BLACK CONTOUR (SIMULATION 1), SOLID PURPLE CONTOUR (SIMULATION 2), SOLID DARK ORANGE CONTOUR (SIMULATION 3) LIGHT ORANGE CONTOUR (SIMULATION 4). DASHED CONTOURS SHOW 4-HOURLY FIRE SPREAD FOR EACH OF THE SIMULATIONS. COLOUR BACKGROUND SHOWS THE HEIGHT OF THE TOPOGRAPHY (IN METRES ABOVE SEA LEVEL).

While the overall shape and orientation of the simulated fires matched the observed characteristics, the ROS in simulation 3, (which is the fastest of the four simulations) was still slower than the observed fire spread speed. The observed fire edge was located approximately 2 km south west of Yowrie at around 01:40 LT 31 December and entered Cobargo around 05:00 LT. By comparison, the fastest simulated fire front reached Yowrie at around 05:00 LT but did not reach Cobargo due to the arrival of the southerly change around 09:00 LT (see Figure 38). (Cobargo is situated approximately 15 km south east of Yowrie).

RFS reports during the overnight period confirm there was significant spotting activity ahead of the fire (spotting was also seen in line scan images and video). The growth and coalescence of the spot fires and eventual merger with the main *Badja Forest* fire front are likely to have had a significant impact on the forward spread of the fire.

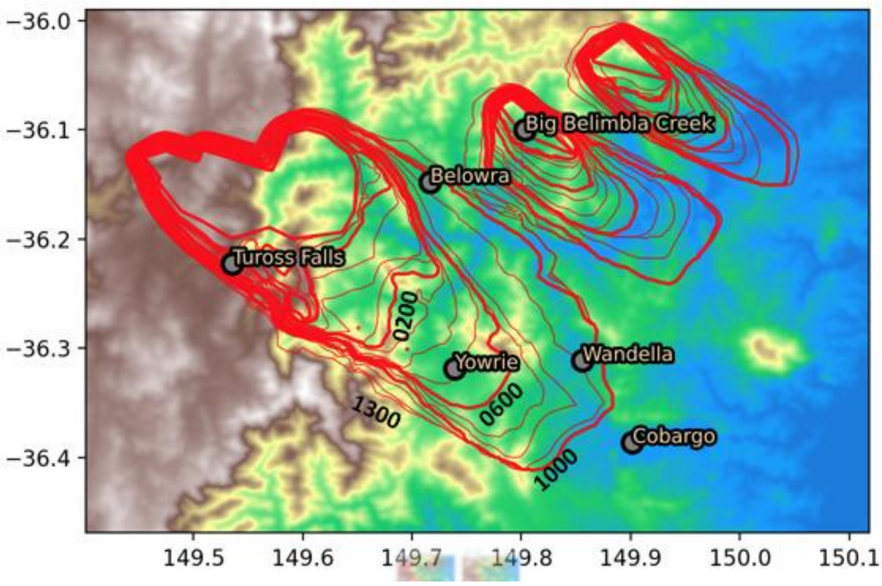


FIGURE 38: HOURLY ISOCHRONES OF FIRE SPREAD FOR MODEL SIMULATION 3. TIMES MARKED ARE LOCAL TIME ON 31 DECEMBER 2019.

The surface wind vectors and the growth of the fires in run 3 can be seen in Figure 39 for the period 21:02 LT 30 December (top left) until 13:57 LT 31 December (bottom right). Note the growth and south east spread of the fires overnight and the eventual merger of the fires following the wind change on the morning of 31 December.

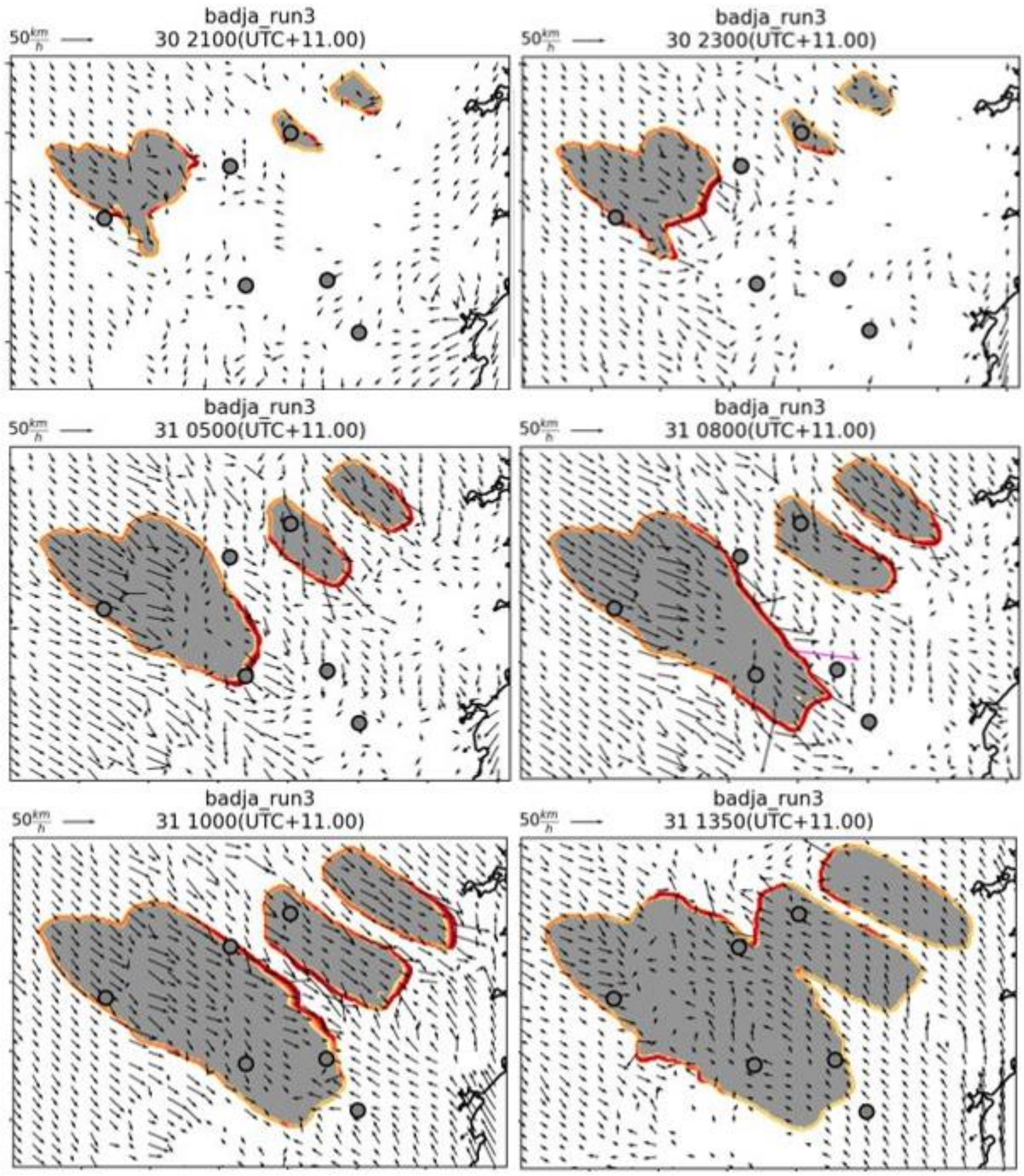


FIGURE 39: SURFACE WIND VECTORS, FIRE HEAT FLUX (WM^{-2}) AND FIRE AREAS FROM SIMULATION 3 AT: 21:02 AND 23:02 LT 30 DECEMBER (TOP), 04:47 AND 07:52 LT 31 DECEMBER (MIDDLE PANELS), AND 10:02 AND 13:57 LT 31 DECEMBER (BOTTOM PANELS). GREY DOTS MARK THE LOCATIONS ANNOTATED IN FIGURE 38.

Total fire power and extreme fire generated winds for simulation 3

Plots of the time series of total fire power (GW) and the maximum surface winds across the model domain at each time step are shown in Figure 40. In the period from 18:00 LT 30 December to 20:00 LT, the strongest winds were in the range 120-170 km/h with brief periods of winds exceeding 200 km/h. The destructive winds are mostly from the west to north west and are directed into the rear of the fire updraft. These exceptional winds occurred during the period when the main Badja fire was coalescing with two spot fires to the south, suggesting that the release of additional heat energy when the fire fronts merged may have been a contributing factor.

Another period of extreme fire-generated winds occurred with the peak in firepower around 10:00 LT 31December when the southerly wind change led to intense fire activity along the northern flank of the fire.

There is ample anecdotal evidence from past fires (e.g. the Dwellingup, WA fires in 1961 and the Black Saturday fires in 2009) of destruction of forest and buildings in broad swathes not related to the occurrence of fire generated vortices. While the magnitude of the simulated model winds cannot be validated at present, their occurrence is consistent with dynamic processes along the fire front resulting from intense localised heat energy release.

Destructive winds along a fire front have significant consequences for fire behaviour, fire management and community safety. More detailed investigation into the physical processes that drive this phenomenon is required.

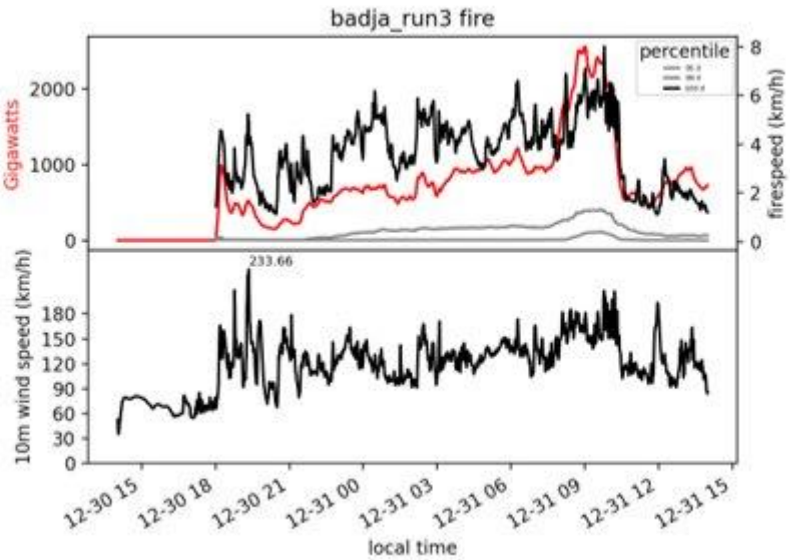


FIGURE 40: SIMULATED TIME SERIES PLOT OF TOTAL FIREPOWER (TOP) AND 10-MINUTE, 10 METRE HEIGHT WINDS IN KM/H (BOTTOM). TIMES ARE SHOWN AS MONTH-DAY-HOUR.

Interaction of the fire with a nocturnal low-level jet (simulation 3)

Time-evolving transects of the vertical wind profile above the fire during the overnight period show the formation of a low-level north westerly jet at around 1500 m elevation above sea level. The jet formation and strengthening can be clearly seen in the transects running north west to south east through Yowrie (see location in Figure 39). Between 23:00 LT 30 December and 00:00 LT 31 December (Figure 41, top panels) the band of strong elevated winds to the west of the ranges can be seen gradually descending to reach the western slopes of the ranges by midnight. A broad swath of ascending motion extending to a height of around 4000 m can be seen to the east of the ridge and extending downstream over the valley.

By 01:00 LT 31 December (Figure 41, middle left panel) the fire can be seen on the upwind slope of the ranges (orange/yellow shading) and the strength and height of the ascending motion has increased. Note the very strong wind shear between the low-level jet flowing across the top of the ridge and the light winds in the lee of the ranges near the valley floor. The fire progresses downslope into the valley between 02:00 LT 31 December and 04:00 LT 31 December (Figure 41, middle right and bottom panels) while the core of the low-level jet descends into the valley floor by 31 04:00 LT.

The hot, dry windy conditions observed at Belowra and Eagles Rest overnight were likely caused by the strengthening and descent of the low-level jet to ground level.

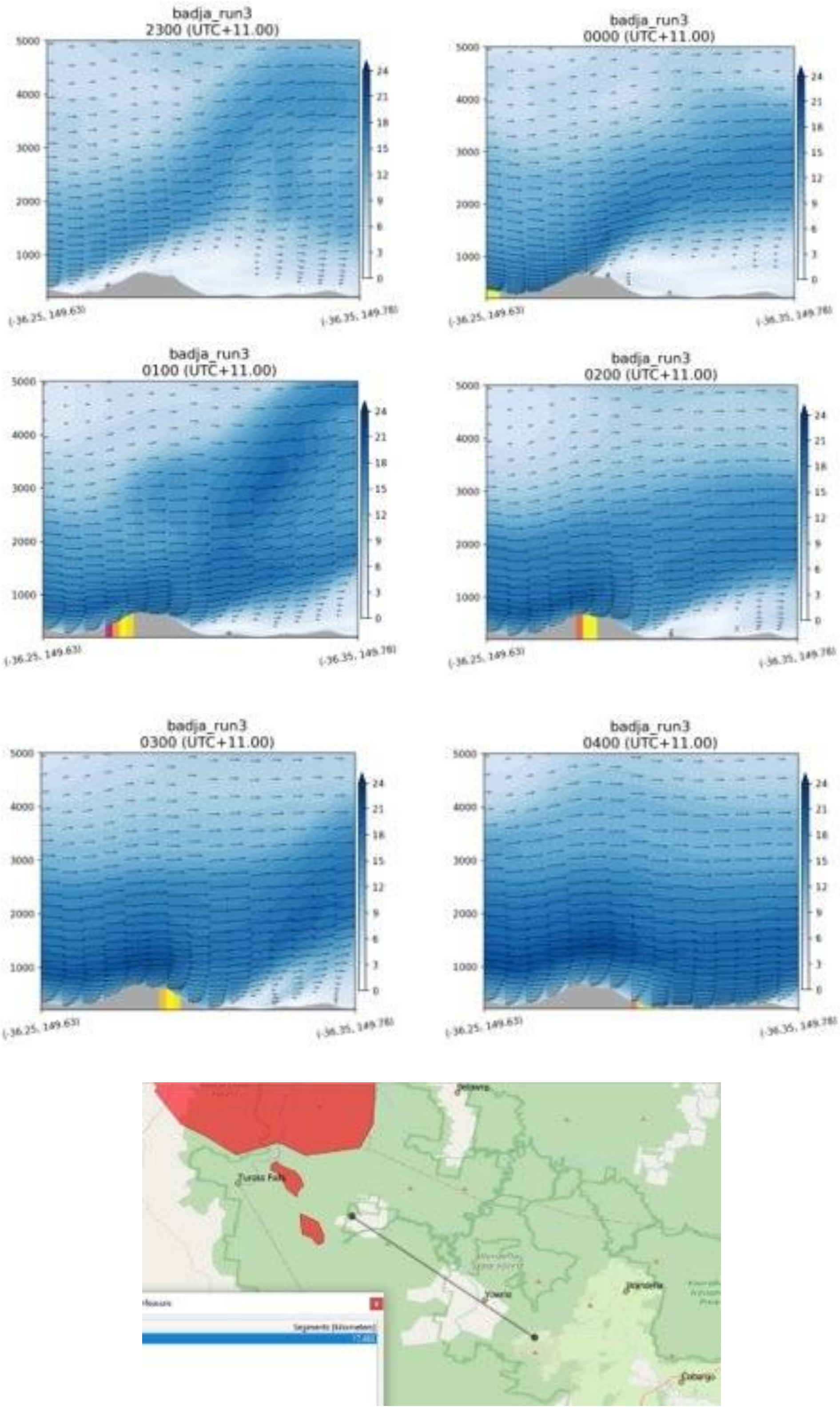


FIGURE 41: VERTICAL CROSS SECTIONS OF WIND VELOCITY (M/S) AT HOURLY INTERVALS BETWEEN 23:00 LT 30 DECEMBER AND 04:00 LT 31 DECEMBER 2019 ALONG A 17 KM TRANSECT RUNNING NW TO SE THROUGH YOWRIE, SHOWING THE STRENGTHENING AND DESCENT OF THE LOW-LEVEL JET TO GROUND LEVEL BY 04:00 LT. YELLOW, ORANGE AND PINK SHADING OVER GREY TOPOGRAPHY SHOWS THE LOCATION OF ACTIVE FIRE. RED ARROW SHOWS THE LOCATION OF YOWRIE.

Wind reversal on lee side slopes

A distinctive feature of the wind cross sections in the early hours of the morning was the low wind speeds in the valleys in the lee of the ranges. The model also showed periods when the wind direction reversed towards the west near the ground as seen at 00:20 LT 31 December (Figure 42). Note the westerly upslope flow in the lee of the ranges, most likely due to the transient formation of a lee rotor beneath the turbulent westerly flow above.

This process is consistent with descriptions of upslope fire spread against the direction of the prevailing winds, for example, in the Adelaide Hills during the Ash Wednesday fires in February 1983 and at the Stirling Ranges (WA) fire in January 2020. This strong wind shear provides a rich source of horizontal vorticity which can be tilted into the vertical by the updrafts associated with a fire, causing the convection column to rotate and the upward motion to increase. In the case where there is spotting into a valley this sets up a potentially dangerous situation for rapidly escalating fire danger (Simpson et al, 2013). In effect, the process results in fires burning vigorously upslope on both sides of the ridge, broadening the fire near the ridgetop where the fires merge and generating a rapid increase in fire power.

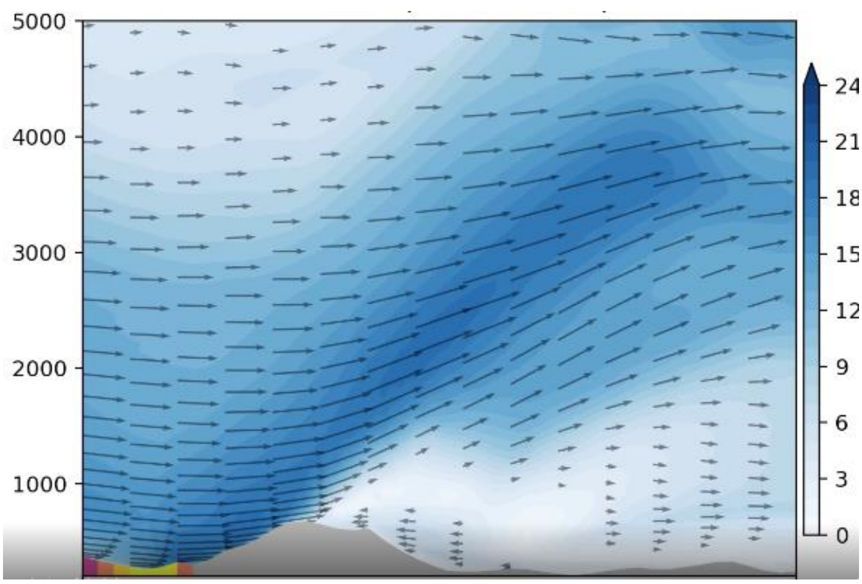


FIGURE 42: VERTICAL WIND PROFILE AT 00:20 LT 31 DECEMBER 2019 SHOWING WIND REVERSAL ON THE LEE SIDE SLOPES OF THE RIDGE. WIND VELOCITY IS IN M/S.

Potential for deep pyro-convection

The Pyroconvective Firepower Threshold (PFT) (Tory and Kepert, 2021) was calculated using a model sounding approximately 20 km upstream north west of the fire (a location assumed to be representative of the atmosphere outside of the fire environment). Values of the PFT compared to the simulated total firepower (Figure 43) show that the firepower exceeded the convective threshold apart from a two-hour period in the late evening of 30 December. Radar observations suggested that deep moist convection was present, although lightning was not observed until around 05:00 LT 31 December near

Cobargo. This reinforces the point made in the Corryong fire report (and elsewhere), that dangerous fire activity and deep moist convection can occur in large fires without a fire-generated thunderstorm being observed.

The firepower calculation in Figure 43 includes heat energy from the *Big Belimbla Creek* and *Bumbo Creek* fires, not just the *Badja Forest* fire. This means that the difference between the PFT and firepower values for the *Badja Forest* fire only, is less than that shown.

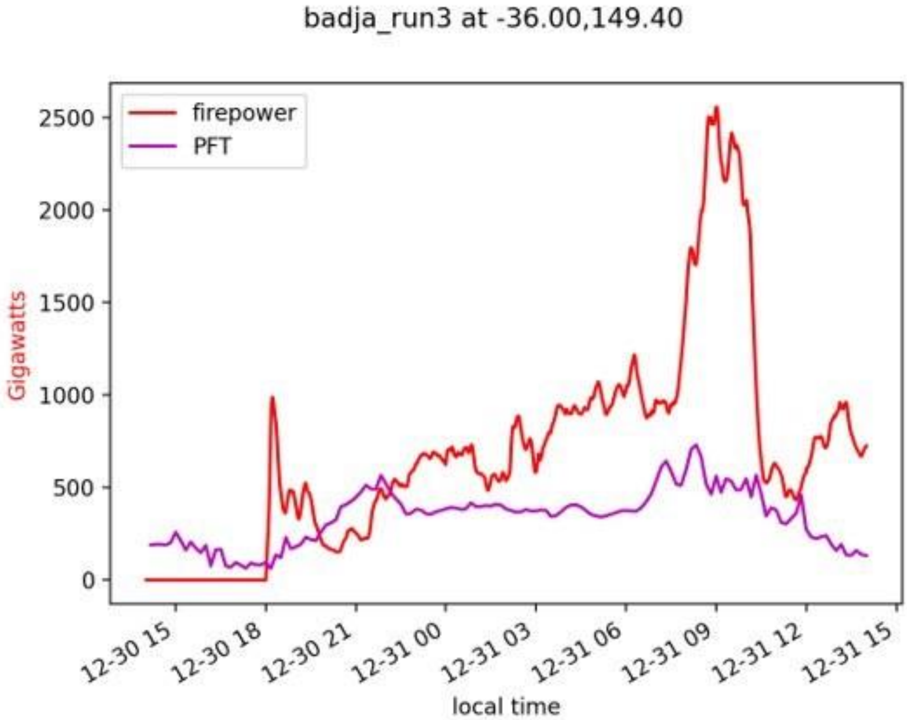


FIGURE 43: SIMULATED TIME SERIES OF UPSTREAM PFT VALUES (PURPLE) AND TOTAL FIRE POWER (RED) FROM THE THREE FIRES; *BADJA FOREST, BUMBO CREEK* AND *BIG BELIMBLA* OVERNIGHT ON 30-31 DECEMBER.

Key points

- The simulations show the development of a strong nocturnal low-level jet just above the elevated terrain, which is drawn downward into the *Badja Forest* fire.
- Hot, dry conditions observed at Belowra overnight and a period of 'Catastrophic' fire conditions between 04:00 and 05.30 LT on 30 December were likely the result of coupling of the stronger winds aloft by the fire.
- Pyroconvective cloud with observed radar tops up to 13 km occurred in the overnight period. The total simulated firepower during the overnight period was generally above the PyroCb Firepower Threshold (PFT), indicating the potential for the fire to cause deep moist convection.
- The simulated rate of spread of the fire increased when fuel load was increased from 20 t/ha to 30 t/ha. A further increase in fire spread speed occurred when the *Bumbo Creek* and *Big Belimbla Creek* fires were included in the simulation. This increase is likely associated with stronger fire-atmosphere coupling.

- It is highly likely that extensive spotting ahead of the fires, which is not represented in the simulations, would have resulted in faster spread of the fires than produced by the model, improving the agreement with the observed spread.
- The model produced extreme fire-generated winds along the fire front, consistent with substantial anecdotal evidence of such winds in large fires.
- The model wind fields show several characteristics consistent with schematic models of wind flow at intense fires, for example:
    - light winds in the wake of the fire, with potential for reversal of the ambient low-level flow
    - confluence of the winds further downstream of the fire, and signs of rotation in the wind field along the fire front.

THE KANGAROO ISLAND 'RAVINE' FIRE (SA), (3 JANUARY 2020)

Introduction

Numerous fires burned on Kangaroo Island between 20 December 2019 and 6 February 2020. During this period nearly half the island was burned, a total of 211,000 hectares. One of the largest and most devastating fires, the Ravine fire, was ignited by a lightning strike in the Flinders Chase National Park on 30 December 2019.

Information on the fire spread and fire behaviour was provided by SA Department of Environment and Water (DEW). On the morning of 3 January 2020, the Ravine fire broke containment lines and spread rapidly towards the island's south coast, driven by hot, dry, northerly winds from the central Australian desert. Fire reached the south coast of the island by 17:00 LT, then a prefrontal trough turned winds westerly, followed by a cold front and stronger south westerly wind change in the evening. The strong south westerly winds turned fire spread north eastwards and the fire moved rapidly through grassland overnight and threatened the township of Parndana, then reached the north coast of the island by around 05:00 LT on 4 January.

Antecedent climate conditions

Kangaroo Island had recorded below average rainfall for several years and very much below average rainfall in the 12 months leading up to the Ravine fire. During December 2019, the island received less than 40% of the usual December rainfall. Mean maximum temperatures for the lead-in 12 months were very much above average across the island and spring maximum temperatures were also above average.

Soil dryness was higher than the long-term average during 2019-20 and approached the driest during the historical record. The Drought Factor was 10, the maximum possible, at all three monitoring locations on the island by mid-December.

Notably, antecedent rainfall was not lowest on record and maximum temperature was not highest on record, which distinguishes Kangaroo Island from other fire areas in this study. The concerning conclusion from the antecedent rainfall and temperature conditions is that they could have been worse, with the potential for worse conditions in future seasons, even in the present climate.

Meteorological situation

The MSLP charts for 3 January (Figure 44) show a trough and cold front to the west of the island at 11:00 LT with a low-pressure system to the south. The trough and cold front moved across the west of the island between 17:00 and 19:30 LT.

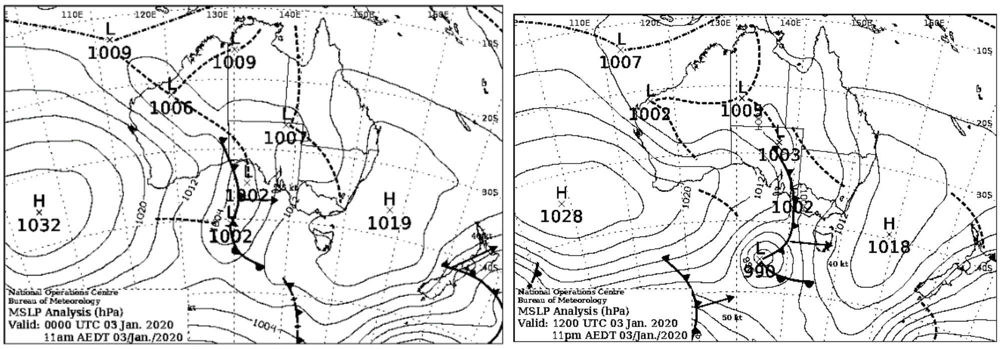


FIGURE 44: MEAN SEA LEVEL PRESSURE CHARTS AT 11:00 (LEFT) AND 23:00 (RIGHT) LT 3 JANUARY 2020.

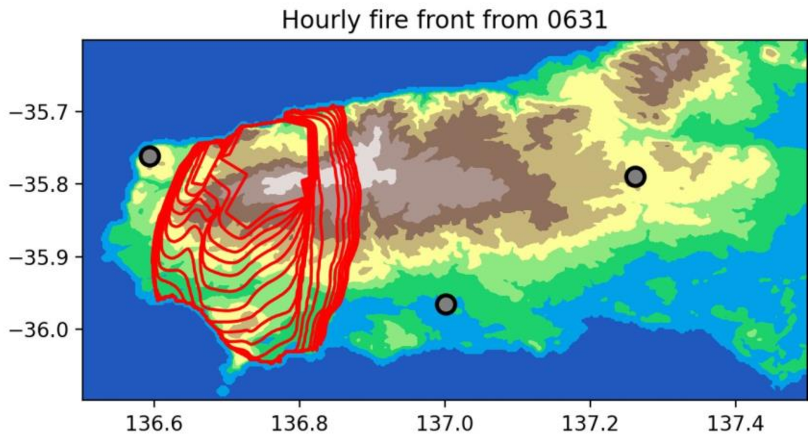
ACCESS-Fire simulations

ACCESS-Fire was run with three initial fire start conditions to explore sensitivity to input conditions. The series of simulations has enabled us to explore the fire spread sensitivity to initial fire breakout time and location. The ignition times, locations and fuel mapping were established and refined in consultation with representatives from SA Department of Environment and Water (DEW). The fuel was predominantly mallee woodland over western parts of the island and grassland in the area where the fire ran overnight.

Run 1 included two main fire perimeter polygons and constant fuel of 20 t/ha. Run 2 used the same ignition boundaries but with variable mapping for fuels to include forest and grass. A third run was made with the same western polygon ignition as Run 1 and included three extra ignition points representative of observed breaks in the containment lines, however fire spread was slower than reality so the run was not analysed in detail. Fire ignition was at 06:30 LT in all runs.

Features of the simulations

The final fire spread was similar for Run 1 and 2 and a subjective assessment indicates that the initial southwards outbreak is captured and the southerly spread to the coast is well resolved. Figure 45 shows isochrones of the Runs 1 and 2. The fire rate of spread was slightly faster in Run 2 than Run 1, with a maximum speed of around 3 km/h.



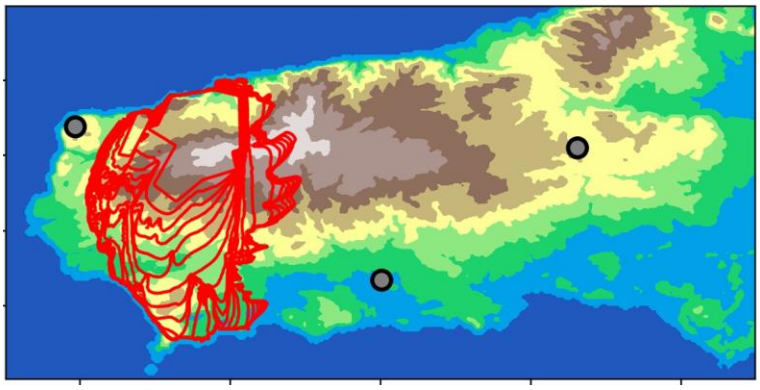


FIGURE 45. HOURLY ISOCHRONES OF FIRE SPREAD (RED) AND TOPOGRAPHY (SHADED) FOR RUN 1 (TOP) AND RUN 2 (BOTTOM).

Fire breakout on the northern edge of the island

The simulations at 300 m horizontal resolution provide evidence of known island processes; in particular, the local variability of wind flow across the island and adjacent waters in response to the land-sea temperature gradients and coastline. Figure 46 shows the 10 m wind at 06:00 LT 3 January, with the purple ellipse highlighting the area where fire broke out early in the morning. The breakout location is coincident with higher wind speeds over land where the stronger maritime flow penetrated inland. The increased inland penetration in this vicinity appears to be due to the details of the local topography and coastline shape.

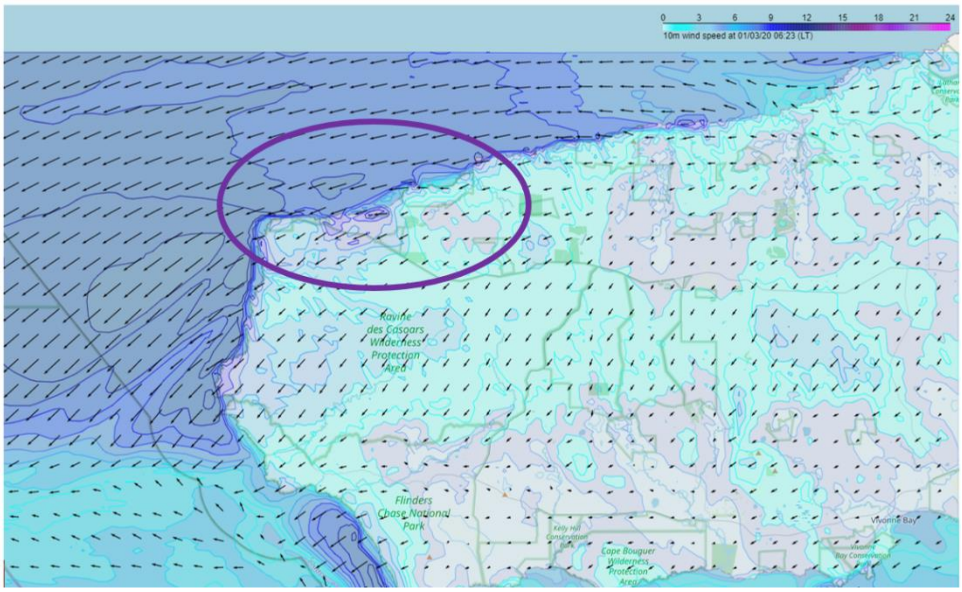


FIGURE 46. 10 M WIND SPEED AT 06:23 LT 3 JANUARY 2019 (M/S).

Comparison of observed and model winds on 3 January 2020

Figure 47 shows observed and simulated temperature and wind at Parndana (near the centre of the island). Observed temperatures ranged from the mid-teens overnight to the high 30°Cs during the afternoon. The winds were light overnight, then 35-45 km/h from the north in the early afternoon, before a lull in wind speed with the passage of the trough in the early evening. This was followed by a surge of south westerly winds after the frontal change in the evening. The strong relationship between wind direction and air temperature and humidity is apparent in these observations.

Figure 47 shows a difference between the observed and simulated evening winds. The observations at Parndana AWS reached 50-60 km/h with gusts to near 80 km/h, which is much stronger than the simulated winds. The actual fire spread to the north east in the late evening and overnight is not captured in the coupled model (or the real-time predictions or reconstruction) due to the under-predicted near surface winds. A detailed examination of the under-forecast winds has not been conducted, however potential explanations include the vertical depth and strength of the change being under-represented in the model initial conditions.

The bottom panel in Figure 47 shows PFT and simulated fire power. The plot shows fire power was lower than the PFT threshold result throughout the event. This result is consistent with the limited observed pyroCu cloud and the absence of pyroCb or lightning above the convection column; as the energy released by the fire was lower than that required for deep moist convection.

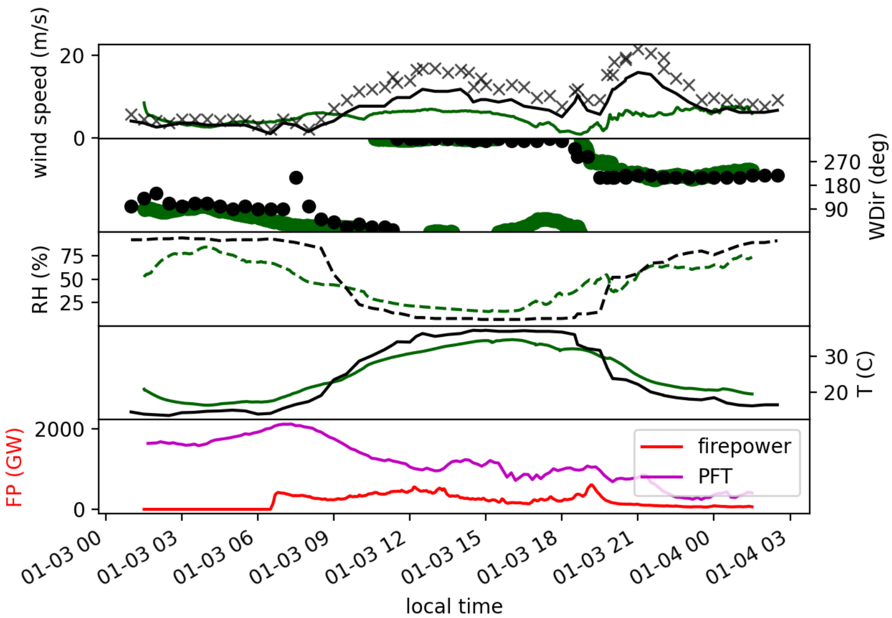


FIGURE 47: COMPARISON OF AWS OBSERVATIONS (BLACK) AND SIMULATION OUTPUT (GREEN) AT PARNDANA. INDIVIDUAL PANELS, FROM TOP TO BOTTOM, ARE: WIND SPEED (LINES) AND GUSTS (CROSSES); WIND DIRECTION; RELATIVE HUMIDITY; AIR TEMPERATURE AND FIRE POWER AND PFT (SIMULATED VALUES ONLY, NO OBSERVATIONS).

Low level wind structure

The modelling revealed a complex and varying near-surface wind structure. The wind speed cross section in Figure 48 shows a wind maximum, or low-level jet in the above-surface wind speed at an elevation between 500-1000 m above the topography. The low-level jet persisted until around midday and was a key driver of the morning fire spread.

Key features that can be seen in the cross sections include:

- At 06:00 LT a shallow layer of lighter near surface winds indicative of a radiation inversion is evident (apart from on the north coast cliffs where an early morning fire break-out occurred)

- By 07:30LT the wind maximum has mixed closer to the surface
- At 07:30, 09:30 and 10:40 LT the strongest near surface winds are just ahead of the fire (shaded yellow/pink), indicating momentum entrainment of the elevated winds in the vicinity of the convection column, thereby producing a mechanism for accelerating the forward fire spread.
- Throughout the morning, the strongest winds lie between 500-1000m, below the 1000 m level which is included in an Incident Weather Forecast. Hence, current practice in incident reports may not fully reveal the possible danger of strong near-surface winds.

In addition, the potential temperature cross sections (not shown) show slightly cooler near-surface temperatures over the northern part of the island, likely to be the residual influence of the cooler maritime boundary layer advecting across the island in the northerly flow. The circulation near the fire front results in the continental airmass and warmer temperatures being mixed to the surface ahead of the fire, which would have enhanced drying of fuels over the south of the island.

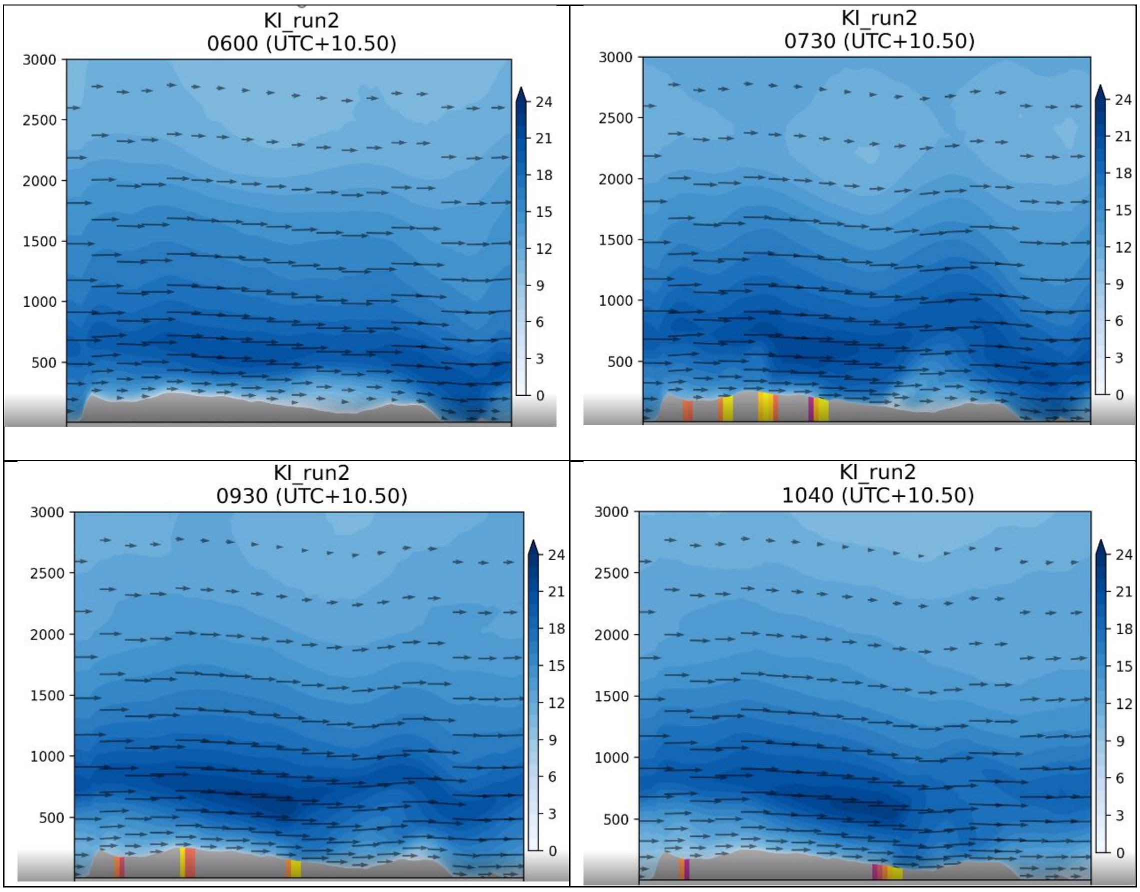


FIGURE 48. CROSS SECTION FROM NORTH (LEFT) TO SOUTH (RIGHT) OF WIND SPEED (M/S) ALONG A NORTH SOUTH CROSS SECTION OF THE ISLAND ALIGNED THROUGH CAPE DU COUEDIC. TIMES SHOWN FROM TOP LEFT TO BOTTOM RIGHT ARE 06:00, 07:30, 09:30 AND 10:40 LT. BOTTOM PLOT SHOWS LOCATION OF CROSS SECTION.

Satellite imagery

Features of the fire as observed by the NOAA Suomi Polar Orbiting Satellite pass at approximately 13:30 LT 3 January in Figure 50 include: high values of fire radiative power; downwind smoke plume advection along several different direction trajectories in response to plume injection height at varying elevations in the vertical wind profile; dark smoke indicative of incomplete combustion; mostly smoke rather than pyro-convective cloud in the dry atmosphere; and the pyroCu cloud pulses to higher levels casting shadows, and partly located over water indicating substantial horizontal displacement from the surface fire. The satellite imagery is consistent with the vertical convection column structure resolved by ACCESS-Fire.

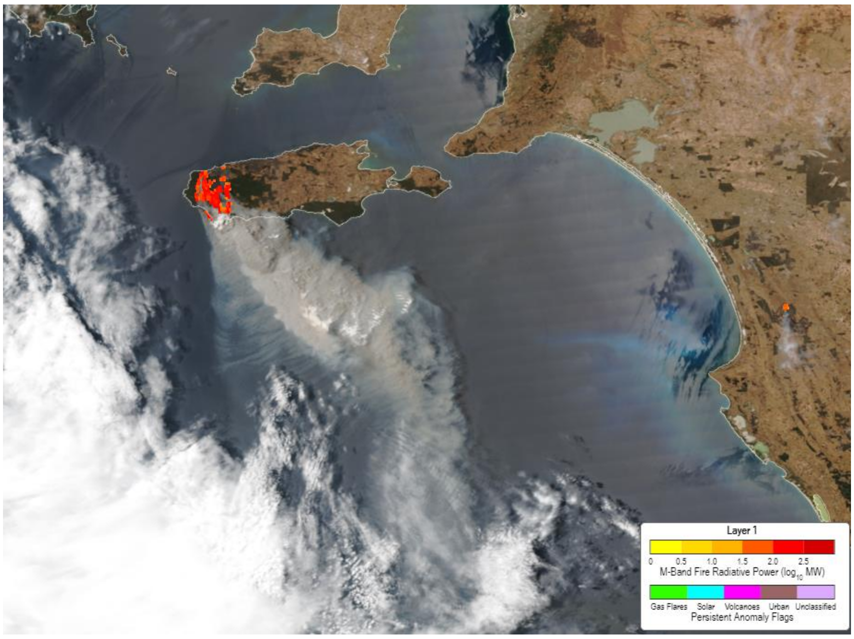


FIGURE 49. NOAA, SUOMI POLAR–ORBITING SATELLITE IMAGE AND M-BAND FIRE RADIATIVE POWER AT APPROXIMATELY 13:30 LT ON 3 JANUARY.

Convection column and plume dynamics

Numerous aerial photographs and videos were taken of the Ravine fire and some examples are shown in Figure 50. The images consistently show a convection column that was tilted well downstream in the strong near surface winds (in both the pre-frontal north westerly and post-frontal south westerly winds) and large numbers of spot fires adjacent the main fire front in the dry fuel beds.

Himawari-8 satellite sequences (not shown) capture short-lived pulses of pyro-cumulus convective cloud around 5 km elevation, penetrating above the extensive smoke. The presence of a dry middle-level atmospheric environment would have been an inhibitor to deep moist convection, along with the strong winds causing a laid-down, strongly entraining plume.

The strong updrafts inferred from the satellite images and photographs are consistent with deep upmotion in the planetary boundary layer, favourable for development of fire whirls or fire generated vortices. Conditions would be particularly favourable in the late afternoon when a lull in the elevated winds occurred, producing more upright convection columns. There were reports of fire whirls near the south coast in the afternoon.

FIGURE 50: IMAGES OF THE RAVINE BUSHFIRE ON KANGAROO ISLAND: TOP IMAGE AT 15:25 LT TOWARDS THE SOUTH, MIDDLE IMAGE AT 15:49 LT LOOKING TOWARDS THE NORTH WEST (BOTH IMAGES PROVIDED BY DEW).

North west winds protected Cape Du Couedic

Figure 51 shows an intriguing local feature of the wind fields that resulted in the lighthouse and cottages at Cape Du Couedic being preserved from destruction by the fire. Figure 51 (right) shows the burn scar at Cape Du Couedic constrained to the north east of the lighthouse, with a sheltered strip of unburned vegetation at the cape. CFS representatives and local residents had thought that the wind change arrived before the fire reached the cape, but the simulated winds in

Figure 51 (left) show that the lighthouse was spared due to local meteorological processes. The local winds adjusted in speed and direction in response to the local elevated topography and the transition from hot land to cold water surfaces, where the surface temperature change exceeded 20°C. It is likely the convergent winds also have a fire-induced contribution (this could be examined by re-running the simulations without a fire present). These local processes resulted in persistent, strong local flow from the north west across the cape which meant that the fire burned as a flank fire across the cape, not a head fire towards the south and the lighthouse and cottages were thereby spared.

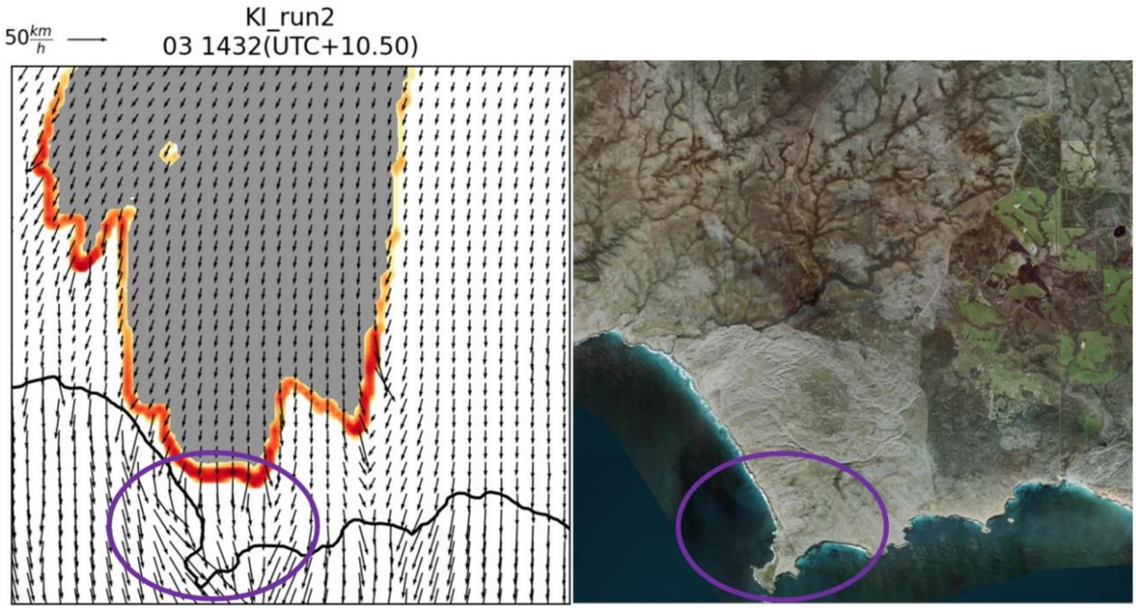


FIGURE 51. LEFT: SIMULATED WINDS AND HEATFLUX AT 14:32 LT. RIGHT: ENHANCED SATELLITE IMAGERY SHOWING FIRE SCAR, TAKEN 8 JANUARY 2020, PROVIDED BY DEW.

Key points

- The antecedent dry and hot conditions intensified over the month or two preceding the fires. Rainfall on several timescales had been below average to very much below average, but not lowest on record.
- The soil and fuel moisture project that has been run in parallel to this study shows that conditions in the lead-in had not been exceptionally dry, either in comparison to local historical records or compared to the extreme values seen in other parts of Australia. This is confirmed by anecdotal evidence from local farmers, who had experienced a good growing season. The availability of grass fuels would have supported fire spread into the evening towards Parndana.
- Fire activity on 3 January was strongly wind driven, as seen in the tilted convection columns in the simulations and confirmed by numerous photographs. Winds were north to north westerly winds during the day ahead of a strong south westerly frontal change in the evening.
    - ACCESS-Fire captured the fire run from north to south, then the shift to easterly fire spread behind the change. The fire run from north to south was reasonably well resolved, but accuracy was highly dependent on the breakout locations or ignition polygons that

were included, as these altered the initial energy release and therefore the rate of forward spread.

    - The strength of the wind speed in the south westerlies behind the evening frontal was under-predicted in the simulations; as a result the fire run to the north east in the evening was too short. It was out of scope for this project to explore the reasons, but future work could include exploring the spread of ensemble members.

- Winds over Kangaroo Island are very strongly influenced by the maritime boundary layer and significant local modifications in the boundary layer, sea breeze processes and maritime flow are evident in the higher-resolution simulations. These processes are highly relevant for fire management on the island.
    - The strong local near-coastal winds on the northern side of the island in the simulations likely assisted the early morning fire breakout from containment lines.
    - Local modification of the winds near Cape du Couedic turned the windflow north westerly over the water for most of the day and therefore the fire burned as a flank, never a head, towards Cape Du Couedic lighthouse.
    - The cross-section plots indicate that the surrounding maritime air acted as a buffer to the hot dry air being advected from the centre of the continent, but close to the fire, the circulation around the plume supported greater entrainment of the continental air.
    - Momentum entrainment of the low-level jet wind maximum enhanced surface fire spread. The core of strongest wind speeds was between 500 and 1000 m, which is below the 1000 m level given in incident weather forecasts, therefore fire managers may not be adequately informed of the potential risk of elevated winds.
- Deep moist convection (pyroCu) was only observed for a short period. This is likely due to the dry atmospheric conditions and strongly tilted convection columns.
- Spotting processes were not included in the ACCESS-Fire simulations, but photographs indicate that spotting was a significant factor in fire spread dynamics and inclusion of spotting in the simulations would accelerate the predicted fire spread.

FINDINGS

The key findings from each of the fires are included in the individual case studies above. Some more generalised findings are presented here.

- In each of the five case studies, there were distinct processes that contributed to the fire behaviour, which differed across the individual cases. This highlights the need for well-trained FBAN and fire meteorologist practitioners who can make skilled interpretation of available information to anticipate potential fire activity in complex environments.
- ACCESS-Fire has been run successfully on five case studies in the short project time frame. The previous code developments have thereby been thoroughly tested and shown to be robust across a range of fire environments. The insights from the analysis show the value that can be gained from the coupled modelling approach.
- At four of the five case studies, unusual fire activity occurred in the overnight period, when fire intensity and rate of spread is typically expected to decrease. Complex three-dimensional interactions between the low-level jet, topography and the fire plume circulation were key drivers of fire spread.
- The potential for dangerous overnight fire activity is not captured in two-dimensional fire spread models which use surface weather variables as input.
- The simulations showed significant variations in local meteorology along active fire lines, for example when a sea breeze front intersects the fire front, or a wind change moves across the fire. These variations illustrate the limitations of a framework where weather forecast information is conveyed using a single point forecast at specific time intervals.
- The simulations show that wind flow across ridgelines can lead to reversal of the ambient flow in the lee of the ridge. If spotting is occurring then strong upslope fire behaviour can result, thereby intensifying the main head fire near the ridgetop.
- Dangerous fire activity and locally destructive winds can occur on large fires without a thunderstorm being observed.
- The model simulations of the surface wind fields show that the fire-modified wind may be much larger in magnitude than the ambient winds.
- Previous studies have emphasised the hazard due to downdraft outflow winds from pyro-convective clouds. This work highlights dangerous winds that can occur in the vicinity of the fire's updraft, such as:
    - Extreme fire-front winds, and
    - Destructive fire generated vortices that form within or just ahead of the main fire updraft.

KEY MILESTONES

A detailed list of project milestones is included in the 'Fire Weather Agreement' contract executed between the CRC and the Bureau of Meteorology.

The key milestones in the agreement are listed below:

1. Compile data on the five fires including meteorological reports (where available) and fire behaviour and fuel information.
2. Consult with state agencies on the five fires and periods or phenomena of particular interest.
3. Participate in informal discussions with fire agencies.
4. Decide format of final reports and presentation in consultation with agencies and the CRC.
5. Simulations of all five fires.
6. Analysis of all five fires.
7. Reports on the five fires. These are expected to be varied in length and detail depending on the findings from the simulations.
8. Workshops and presentations with meteorologists and fire agencies.

Activities against the key milestones:

Milestones 1, 2 & 3: Available information on each of the fires was compiled in consultation with internal and external partners. A series of informal, mostly virtual meetings and discussions were held with representatives from each jurisdiction. Some of these were facilitated by the CRC, some were direct engagement between the project team and end-users. All interactions supported valuable information sharing and were beneficial in informing the directions and findings of the project. Further collaborative investigation would result in a greater quantity of insights and learnings than available project time and resources have permitted.

Milestones 5 & 6: Simulations and analysis of the five fires have been completed, see the chapters above. The scale and complexity of each fire was significant and therefore as with milestones 1-3, the analysis was constrained by the project timeline.

Milestone 4 & 7: This report has been prepared in consultation with the CRC and end users and includes an individual chapter on each fire. On request, the chapters have been made reasonably concise; more detailed descriptions of each fire may be unpacked during workshops and presentations.

Milestone 8: Several presentations have been given to fire agencies during July and August. Most have been virtual due to ongoing COVID-19 restrictions. Audiences include: RFS FBAN workshop (NSW), CFA and DELWP (Victoria), CFS (SA), DFES and DBCA (WA). Presentations are scheduled or dates in negotiation for DEW (SA), Science and Innovation Seminar (Bureau of Meteorology) and QFES (Queensland).

UTILISATION AND IMPACT

SUMMARY

Opportunities for utilisation have been limited by the short project timeframe. Below are four proposed themes to progress the project findings into operational decision support. The themes capture short term training opportunities (6-12 months to delivery) and mid-term applied research projects to develop operational techniques (~2+ years to delivery).

THEMES FOR UTILISATION AND IMPACT

1. **Presentations and training to share learnings**

   Training material on the findings from this project can be developed for specialist FBANs and fire meteorologists as well as for the broader Emergency Management practitioner community. Content material would include descriptions of the drivers of periods of extreme fire activity and approaches for interrogation of numerical weather prediction models to identify similar environments. Training may include appropriate downstream messaging of potential hazard or escalation of fire activity to media and communities.

2. **ACCESS-Fire development and pathway to coupled fire atmosphere (CFA) modelling operational use**

   This work has further demonstrated the value that coupled fire atmosphere models can provide in identifying and understanding the drivers of unusual or extreme fire behaviour. CFA models are used operationally in other countries. Australia's complex fire regime presents an imperative for a project pathway to operational use of CFA capabilities in order to meet future fire prediction needs and community expectations for fire risk information.

3. **Influence of heatwaves on overnight fire behaviour**

   The fire regime during the 2019-20 summer was strongly influenced by heatwaves, particularly through the observed atypical overnight fire activity. A project to quantify the influence and drivers of processes affecting fire behaviour is vital to inform future assessment of the overnight fire hazard in a changing climate.

4. **Meso- to micro-scale extreme fire behaviour processes**

   The simulation results show that extreme fire behaviour processes linked to extreme surface winds (both rotational and straight line), entrainment of energy from low level jets into the near-surface fire circulation, and coalescence of multiple fires may be resolved by ACCESS-Fire. The model capability therefore presents an opportunity for further investigating the predictability of these processes.

5. **Fire prediction tools**

   There is an opportunity to develop new tools based on numerical weather prediction output that highlight the location and intensity of nocturnal low-level jets. Such tools would provide additional information for meteorologists and FBANs on the strength and height of representative winds for input to two-dimensional fire spread models and could be used to alert fire managers to the risk of atypical fire spread in the overnight period. Meteorological information that overcomes the limitation of providing weather forecasts at single points at specific times should also be developed for large fires experiencing variable weather conditions.

UTILISATION AND IMPACT EVIDENCE

The project team have received several invitations from our end-users in fire agencies for targeted training material. Related discussions have indicated a strong appetite for targeted project proposals on the themes captured above.

CONCLUSION

This project has further progressed the development and awareness of the ACCESS-Fire capability. Continued application of the coupled model to dangerous fire behaviour situations is consistent with growing international interest in understanding and prediction of fire-atmosphere feedbacks. Through the work of this project we have:

- Tested the model developments made in the original CRC project on a wider range of fires, and conducted further analysis of the capability of ACCESS-Fire to simulate fire-atmosphere coupling.
- Further realised the investment in, and benefits of further use and development of ACCESS-Fire.
- Provided detailed analysis of five dangerous fire events to fire agencies and help to inform FBAN and meteorologist training and situational awareness.
- Contributed to the development of a library of such case studies, which with further analysis could lead to better understanding of fire-atmosphere interactions and predictive capacity, with operational benefits.

The project has been conducted in close collaboration with partners in fire agencies and has demonstrated that a comprehensive understanding of the mechanisms driving fire behaviour requires a multidisciplinary approach.

NEXT STEPS

From our experience across research and operations, the successful application of fire behaviour and meteorology knowledge in operations requires locally connected specialised expertise, combined with tailored modelling tools to inform objective, evidence-based decisions.

The project team are looking forward to sharing the learnings from this project through workshops and seminars with fire meteorologists and partners in fire agencies, including the national FBAN network. There are substantial benefits to be gained from unpacking the overlaps between results presented here and findings obtained in other projects on aspects of the Black Summer fires.

The insights gathered from these five case studies have further demonstrated the value of this high resolution coupled modelling approach. To progress ACCESS-Fire to an effective operational tool, more robust testing of the model is required, in addition to the more subjective assessments that have been made through the case study work. This would include technical testing, additional sensitivity testing and routine verification. Operationalisation is feasible, as demonstrated overseas (e.g. a coupled fire-atmosphere model is run operationally for parts of the USA).

The national fuel grids for the AFDRS have recently been made available to the project team and planned activities for late 2021 include implementation of these grids so that future simulations can use more accurate fuel information.

To maximise the utility of a coupled fire-atmosphere model in operations, near real-time input will be required of fields such as fuel types, fuel breaks, and real-time line scans of fire perimeters so that rapid updating of simulations can be carried out.

Spotting accelerated the actual fire spread but was not represented in the model simulations and inclusion of spotting parameterisation will be a valuable model development.

Four of the fire cases occurred during heatwave conditions and all firegrounds had experienced heatwaves in the preceding two months. Further research is needed to quantify the relationship between heatwaves, fuel drying and fire behaviour.

The project team looks forward to collaborating with our partners in fire agencies to progress work on the four themes outlined in the *Utilisation and Impact* section above. Continuing the progress on the development of the ACCESS-Fire model and its application to fire behaviour simulations will be important in order to meet our future fire modelling capability requirements and fire intelligence needs.

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End-users: Laurence McCoy (RFS), Mike Wouters (DEW), Lachie McCaw (DBCA), Mark Chladil (TAS Fire), Sarah Harris (CFA)

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