

Article The Destructive Sir Ivan Fire in New South Wales, Australia; Simulations Using a Coupled Fire—Atmosphere Model

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Abstract: The destructive Sir Ivan Dougherty fire burned 55,000 hectares around 250 km northwest of Sydney in New South Wales on 12 February 2017. Record hot temperatures were recorded in the area during the lead-in days and the fire conditions at the time were described as the 'worst ever seen in NSW'. The observed weather conditions were hot, dry and very windy ahead of a synoptic frontal wind change during the afternoon. 'Extreme' to 'catastrophic' fire weather was predicted, and the potential for extreme fire behaviour was identified several days in advance. The Australian coupled fire-atmosphere model ACCESS-Fire has been run to explore the characteristics of the Sir Ivan fire. Several features resulting from fire-atmosphere interaction are produced in the simulations. Simulated heat flux along the fire perimeter shows increased intensity on the northern fire flank in response to gradual backing winds ahead of the main frontal wind change. Temporal and spatial variability in fire activity, seen as pulses in fire intensity and fireline wind speed, develop in response to boundary layer rolls in the wind fields. Deep moist convection consistent with the observed pyrocumulonimbus (pyroCb) cloud is simulated over the fire at around the time of the frontal wind change, and matches guidance from the 'PyroCb Firepower Threshold' tool, which showed transient favourable conditions. After the wind change, short-lived near-surface and elevated vortices suggest organised rotating features on the northern flank of the fire. The coupled model captures processes that cannot be produced in uncoupled fire predictions and that are not captured in current operational meteorological forecast products provided to Australian fire agencies. This paper links the features from coupled simulations to available observations and suggests pathways to embed the learnings in operational practice.

Keywords: Sir Ivan fire; ACCESS-Fire; coupled fire–atmosphere modelling; pyrocumulonimbus; fire-generated vortices

1. Introduction

The Sir Ivan Dougherty fire (hereafter the 'Sir Ivan' fire) burned 55,000 ha of grass and bushland approximately 250 km northwest of Sydney, NSW, on 12 February 2017. A church, a community hall, 35 homes, and 131 outbuildings were destroyed and some 6000 head of livestock were lost. Fortunately, there was no loss of human life.

In the days leading up to the event, record maximum temperatures were observed over southeastern Australia, and the fire conditions on 12 February 2017 were described by the Commissioner of the NSW Rural Fire Service as the 'worst ever seen in NSW'. Several days ahead of the fire, meteorologists at the Australian Bureau of Meteorology identified the dangerous conditions, and 'catastrophic' fire danger was forecast (the highest rating level); fires were expected to be uncontrollable, unpredictable and fast-moving, with significant spot fire activity.

The fire ignited from a lightning strike and smouldered for a few days before it flared up on 11 February, when it burned through grass and inaccessible bush in difficult terrain near its namesake road 'Sir Ivan Dougherty Drive'. The fire was contained overnight



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). on 11 February, then on the morning of 12 February it breached containment lines and was suppressed twice before it escaped at around 1120 AEDT and started its main run towards the east-southeast. The fire ran southeast for approximately five hours before being turned towards the northeast under the influence of a gradual southwesterly wind change. Figure 1 shows isochrones of fire spread and the final fire perimeter. Features of the fire mapping include the initial containment (yellow), the run to the southeast (pink to dark orange) and the run to the northeast after the wind change (light orange to grey). The fire burned through a mix of agricultural land and thick wooded scrub on the western slopes of the Great Dividing Range. Firefighting efforts were challenged by the mix of numerous individual farming properties and undulating rocky hills that were inaccessible to firefighting vehicles.



Figure 1. Isochrones of the Sir Ivan fire. Reconstruction prepared by the NSW Rural Fire Service.

A distinguishing feature of the Sir Ivan fire was the development of a large pyrocumulonimbus (pyroCb) cloud, or fire-generated thunderstorm [1] over the fire in the late afternoon. The potential for pyroCb development was included in the prediction report issued by the Bureau of Meteorology on 11 February with the statement 'pyro-convection is likely if free burning as (sic) is impacted by front'. This was accurate guidance, as pyroCb developed over the fire near the time of the wind change.

PyroCb clouds are associated with extreme fire behaviour and hazardous conditions at fire grounds (e.g., [2,3]); therefore, Australian fire agencies have expressed a strong desire for methods of predicting pyroCb. In response to this, the Pyrocumulonimbus Firepower Threshold (PFT) has been developed [4]. PFT can be calculated from any NWP (numerical weather prediction) or from observations.

The Sir Ivan fire was described by [5], with an emphasis on the thermodynamic features of the environment that were favourable for the development of the pyroCb. Of particular relevance to the current study is that they document a meso-cyclonic circulation that was observed on radar inside the pyroCb structure, which they describe as having similarities to rotating phenomena seen in supercell thunderstorms. Their analysis of the radar data shows that the pyroCb was vertically oriented between 0510 and 0530 UTC, then was sheared after 0600 UTC along the interface demarking the vertical extent of the frontal wind change. They also show that turbulent structures developed below approximately

4000 m at around 0620 UTC, and that these turbulent features were spatially distributed parallel to the orientation of the surface front.

Several studies have described vortices at wildland fires and [6,7] provide detailed reviews of these. The scale of vortices ranges from (1) small metre-scale fire whirls near a fire line to (2) 'firenadoes', or fire-generated vortices (FGVs) with tornado strength winds with a spatial scale of tens of metres to (3) situations wherein the entire convection column above a fire is rotating at a scale that can be hundreds of meters across and resemble a supercellular thunderstorm. The rotating convection columns can shed FGVs or firenadoes, and these events have been associated with firefighter fatalities in Australia and the USA (see [8–10]).

Fire vortices were described by [8] as a transient dynamic fire phenomena that are an example of extreme fire behaviour; the authors state that direct-attack suppression should be stopped if they occur due to the hazard presented when they develop rapidly near a fireline. Due to the threat presented by FGVs, there is interest in their predictability, and the results in Section 5 show that ACCESS-Fire may be used to further explore favourable environments for fire vortex formation.

The coupled fire–atmosphere model ACCESS-Fire was developed to explore fire–atmosphere interactions at the Kilmore East fire on Black Saturday [11], and used to examine five fires during the 2019–2020 Black Summer [12]. In this study (which uses similar techniques to the study of the Waroona fire described in [13]), our analysis focuses on how well the simulations reconcile with observations on the northern flank of fire and aspects of the pyroCb, including similarities with the descriptions in [5].

The remainder of this paper is set out as follows: Section 2 provides a meteorological overview, and Section 3 contains a brief description of ACCESS-Fire and the model configuration. Section 4 discusses features of the simulated fireline and fuel load sensitivity to producing deep moist convection as well as the fireline intensity response to temporal fluctuations in the boundary layer winds. The simulated pyroCb and sensitivity to fuel loads are described in Section 5, which also compares the PFT to the simulated heatflux and the timing and short-lived nature of pyroCb. In Section 6, we show rotating mesoscale features resolved in the simulated wind fields. Following these results, in Section 7, we make suggestions for the future use and development of ACCESS-Fire and improved practices for the provision and interpretation of meteorological information for operational fire prediction, particularly in the context of extreme fires.

2. Meteorology

Observations of the Sir Ivan fire included satellite imagery, lightning detection data, linescan imagery and Automatic Weather Station (AWS) records. Figure 2 shows the Mean Sea Level Pressure chart for 1100 AEDT 12 February, with a heat low over central Australia linked to an intensifying trough near the NSW coast. The trough preceded the passage of a cold front and a strong pressure ridge to the south.

A feature of the meteorology on the day was the afternoon frontal wind change, which progressed as a gradual backing trend over several hours rather than as an abrupt change. The strongest expression of the change in airmass was an increase in relative humidity rather than a marked decrease in temperature or sudden shift in wind direction. Consequently, the timing of the wind change was difficult to establish. Such gradual changes are common during the daytime, particularly over inland Australia during the warmer months, and are likely due to the "mixing out" of a sharper discontinuity via the strong turbulent mixing and differential heating across the boundary [14,15]. In contrast, more abrupt changes are often observed over southern coastal areas. Whether a wind change is abrupt or gradual has implications for fire management, as the active flank of the fire may change rapidly or gradually in response to the prevailing wind direction. Figure 3 shows observations from the closest site, a portable AWS deployed around 22 km west of the fire, which recorded the change in airmass between 1530–1600 AEDT. Comparison between the Automatic Weather Stations (AWSs) and ACCESS-Fire parameters show the simulations were verified



reasonably well, with the exceptions that temperature and winds were both under-forecast early in the day, and that variations in wind speed during the day were not captured.

Figure 2. Australian region Mean Sea Level Pressure chart, 1100 AEDT 12 February 2017. The red dot shows the approximate location of the fire.



Figure 3. Time series of meteorological parameters from ACCESS-Fire simulation (blue) and Portable Automatic Weather Station deployed by RFS approximately 22 km west of the fire (black).

The maximum temperature at the AWSs near the fireground reached the low 40 °C, with the lowest dewpoint temperatures just below 5 °C. Mean wind speeds reached 45–55 km h⁻¹, with gusts to 60–85 km h⁻¹ at exposed sites. Forest Fire Danger Index (FFDI) values were observed to exceed 100 (the threshold for a 'catastrophic' rating) at the nearby AWSs at Dubbo (FFDI 110 at 1330 AEDT, approx 78 km to the WSW) and Mudgee (FFDI 128 at 1430 AEDT, approx 68 km to the SSE).

Figure 4 shows the observed aerological diagram at 1232 AEDT from a portable radiosonde launcher deployed by NSW RFS near the fire site. The airmass was generally too dry for deep moist convection. However, the AWS data and satellite imagery (as well as the simulations) show that the near-surface moisture increased later in the afternoon with the passage of the wind change, and this resulted in short-lived favourable conditions for a pyroCb to develop. It is likely that lifting along the frontal line, the heat released by the fire as the length of the active flank expanded, and the erosion of the temperature inversion at around 500 hPa during the afternoon were other factors contributing to the pyroCb's development.



Figure 4. Observed Skew-T, log-p diagram from remote launch site at 1232 AEDT.

3. Modelling Approach Using ACCESS-Fire

The Australian Community Climate and Earth Systems Simulator (ACCESS) [16] is the Australian implementation of the UK Met Office Unified Model (UM). ACCESS-Fire couples the numerical weather prediction model to a fire code, and was developed to simulate the Kilmore East fires on Black Saturday 2009. The Kilmore East fire was the most destructive of the Black Saturday fires; in the first 12 h of the fire, 1242 homes and other buildings were burned, and 119 people died. The complex meteorology and fire–atmosphere interactions observed during the event motivated the development of the coupled fire atmosphere model ACCESS-Fire to explore the processes that drove the extreme fire behaviour. [11] describes the Kilmore East simulations; Section 2 of their paper describes the UM model, and Section 3 has a detailed description of the fire code. The code was subsequently updated and used for five simulations of the 'Black Summer' fires [12] and for a comprehensive study of the Waroona fire [13]. The Waroona simulations were performed in parallel to those shown here for Sir Ivan; therefore, interested readers are referred to the other papers for further information on the model's code and development.

The Sir Ivan simulations use the standard nesting suite with UM version 10.6 (code trunk u-aa753), using a Rose-Cylc scheduler. The UM nesting suite allows a finer resolution domain (child) to be nested within a coarse resolution one (parent). The global domain is the N768 Global Atmosphere 6.0 (GA6.0). The 'start dump' initial condition was on N320 for 2017, with the nested simulations initialised using the 2100 UTC archived grids on 11 February. The 'UKV OS38' science configuration was used. Because of the high resolution in the inner domains, a large number of vertical levels were needed; a vertical level set with 140 levels is used through a height of 40 km on the terrain, following a hybrid height coordination system that ensures smooth contours over topography. The vertical configuration was the same for all the nested limited area models.

The simulations were run with the global model at a resolution of about 17 km and three nested limited area models with resolutions of approximately 4 km, 1 km and 300 m. Figure 5 shows the nested domains. The time steps used were roughly proportional to grid spacing, with a time step of one second used on the innermost nest. The nests run to completion sequentially, so the outer nests provide lateral boundary conditions for their inner nests, and fire coupling only occurs on the innermost nest. The most computing-intensive part is the innermost domain, which needs 240 processors and takes about 36 h to run a 24 h simulation. The two-dimensional fire spread model is implemented through a level set method on the same grid resolution as the ACCESS output. The orography used in the fire model is the 3 arcsecond data from the Shuttle Radar Topography Mission (https://earthexplorer.usgs.gov/ (accessed on 4 September 2023) [17]), while fuel data are discussed below.



Figure 5. Map of eastern Australia showing the three nested domains used in the ACCESS-Fire simulations.

4. Fireline Progression and Features of the Wind Fields

In this section, key features of the meteorology and fuel conditions that affect the simulated fire progression are described, including (1) sensitivity to fuel loads, (2) boundary layer rolls, and (3) the structure of the wind change.

Fire ignition in the model was presented as a polygon representing the mapped fire boundary prior to the late morning breakout (approximately the yellow area in Figure 1). Fuels were set at zero (no-fuel) inside the polygon. The fire was started at 1120 AEDT (when it was observed to escape containment lines) and run until 0800 AEDT the following morning.

Fuel type in the simulations was a mosaic of DEFFM (Dry Eucalypt Forest Fuel Model) [18] and CSIRO grass [19]. An overview of Australian fire fuel models and their inputs may be found in [20]. Both the DEFFM and CSIRO grass models are extensively used in fire danger ratings and ongoing fire predictions in Australia, and are used to characterise fire conditions over substantial parts of the landscape in the national operational system. The implementation of the DEFFM fuel model in ACCESS-Fire is described in [13]. The grass and forest fuel mapping was taken from fuel maps provided by the NSW Rural Fire Service (RFS). Forest fuel inputs for DEFFM (see Table 1) were set in consultation with Dr Lachlan McCaw [21].

Experiments were conducted with three fuel settings to capture uncertainties in the available fuel loads, and this fortuitously presented the opportunity to test the sensitivity of deep moist convection (an elevated convective cloud with significant vertical extent) to the energy released by the fire. The fuel settings for surface fuel hazard score (FHSs), near-surface fuel hazard score (FHSns) and near-surface fuel height (Hns) for the three simulations are shown in Table 1. The interpretation of these values is given by [20].

Table 1. Fuel settings for DEFFM (CSIRO forest).

Run	FHSs	FHSns	Hns
high	3.5	2.5	20
medium	3.3	2.2	18
low	3	2	15

The predictive mapping prepared by NSW RFS on the evening of 11 February (not shown) indicated that the eastwards extent of fire spread would be highly dependent on the time of fire escape, with the potential for impact on the town of Cassilis in the evening. The results from the coupled simulations for the low, medium and high fuel settings (shown in Figure 6) are largely consistent with RFS predictions, particularly given the uncertainty regarding the time that the fire would escape containment. The difference in the three simulations in response to relatively small changes in the fuel settings shows the sensitivity of fire spread to fuel estimates. The increase in heat output results from an increase in fire spread rate and hence an increase in fuel consumption rate, and this determined whether or not deep moist convection developed in the simulations, a result that will be discussed further in Section 4.

Figure 7 shows wind speed (top) and heatflux (bottom) at 1501 AEDT, when the fire was being driven by northwesterly winds ahead of the frontal wind change. Boundary layer rolls (counter-rotating vortex rolls in the atmospheric boundary layer that develop parallel to the direction of the flow) are evident in the wind speed as faster and slower bands (the banding is also present in wind direction but not shown), with the simulated roll distribution comparable to the orientation of the convective cloud seen in Figure 8. The boundary layer roll phenomenon is a feature of hot windy days (see, for example, [22–24]). Figure 7 shows wind speed variability of up to 10 m s⁻¹ due to boundary layer rolls within 10 km of the fire, with the range increasing to 4–20 m s⁻¹ (>50 km h⁻¹) adjacent the fireline in response to fire-modified winds.



Figure 6. Simulation output from the 'low' (orange) 'medium' (black) and 'high' (pink) fuel settings (see Table 1 for fuel settings). The inner contour for each simulation shows the simulated fire perimeter just after the wind change at 1800 AEDT, and the outer contour shows the fire perimeter at the simulation's end at 0800 AEDT the following morning, 13 February. The small inner red boundary shows the initial fire polygon.

Animations of the simulations show the boundary layer rolls produce a response in the fire-modified winds of faster pulses that propagate along the fire flanks. Similar pulsing was shown in simulations of the Rocky River fire using the WRF-SFire framework [25], and is consistent with anecdotal observations from fire grounds of transient pulses in fire behaviour. Figure 7 shows considerable variation in wind speed between the environmental winds and the fire-modified winds along the fire perimeter, with speed fluctuating from 5 to over 20 m s⁻¹ across small distances, which as expected, produces a response in the simulated heatflux.

The simulated heatflux also shows a strong response to the gradual shift in observed and simulated wind direction from northwest to westerly that begins two hours in advance of the frontal wind change. The backing wind trend produces an expansion of the fire on the northeastern flank, which can be seen in the pink to dark orange perimeters in Figure 1. Figure 9 is a linescan (thermal imagery taken from aircraft) taken at 1447 AEDT, which is well ahead of the forecast southwest wind change. It shows more intense fire activity on the northern flank of the fire in response to the gradual backing shift in wind direction ahead of the main frontal wind change. This is consistent with the simulated heatflux in Figure 7.



Figure 7. Wind speed (m s⁻¹, **top**) and heat flux (log scale, **bottom**) and streamlines at 1501 AEDT. Boundary layer rolls can be seen as the lighter and darker blue streaks aligned parallel to the wind direction from west–northwest to east–southeast.



Figure 8. True colour satellite image at 1505 AEDT. Moderate-resolution Imaging Spectroradiometer (MODIS) Aqua, NASA Goddard Space Flight Centre, USA. Accessed 27 July 2020. (Gridlines show a 1-degree latitude and longitude scale).



Figure 9. Linescan image of the Sir Ivan fire at 1447 AEDT (provided by NSW RFS). Yellow areas show actively burning fire, and blue represents cloud.

5. Pyrocumulonimbus Development

The mid-afternoon satellite image in Figure 8 shows a high-based cumulus cloud field oriented from northwest to southeast in alignment with the boundary layer rolls, and the largest smoke plume over NSW originating from the Sir Ivan fire. As previously discussed, the strongest indicator of the frontal line on AWS observations was an increase in dewpoint temperature. Somewhat incongruously, the frontal line coincided with a decrease in cloud cover, as the convection cleared in the more stable (albeit moister) boundary layer air behind the frontal wind change, seen in the southwest corner of Figure 8.

The pyroCb was a short-lived event triggered on the airmass boundary as the front traversed the fireground between 1620–1640 AEDT; the deep moist convection was slightly delayed from the frontal passage at the closest (portable) AWS of 1530–1600 AEDT. A se-

quence of satellite images in the late afternoon showed the rapid vertical development of deep moist convection near the wind change, and five individual 'turrets' or vertical cloud puffs were identified as being elevated higher than the main convection column. These turrets were transported rapidly towards the southeast in strong northwesterly elevated winds, as seen in Figure 10.



Advanced Himawari Imager, VIS/IR: 2017-02-12 05:20 UTC

Advanced Himawari Imager, VIS/IR: 2017-02-12 05:50 UTC



(b) Advanced Himawari Imager, VIS/IR: 2017-02-12 06:20 UTC



Figure 10. Sequence of Himawari satellite images using combined visible and infrared bands at (a) 1620 AEDT, (b) 1650 AEDT, and (c) 1720 AEDT. Colour enhancement shows elevated cold cloud top temperatures, and orange and red crosses show the locations of lightning strikes.

Lightning activity started between 1640–1650 AEDT. The strikes were located near the coldest cloud top temperatures, which were displaced from the surface fire (see Figure 10). Lightning strikes from the pyroCb were recorded at a minimum distance of 5–10 km and a maximum distance of around 80 km to the southeast. The pyroCb decayed rapidly after around 1800 AEDT, as the highly sheared post-frontal winds resulted in separation between the surface fire and the elevated convective cloud. Lightning continued downwind of the fire for another hour after convective cloud had stopped developing over the fire (until 1840–1850 AEDT). The electrification in the cloud well after the surface-driven convection had ceased and the horizontal displacement between the surface heat flux and the coldest cloud top temperatures indicate separation between the surface fire and the pyroCb. This negates any likelihood of feedback from the pyroCb cloud onto the fire for most of the pyroCb's lifecycle.

Evidence for the high wind shear environment can be seen in the aerial photograph (Figure 11) through the strong tilting of the convective column. The highly sheared vertical structure of the convection over the Sir Ivan fire after the wind change differs from the pyroCb structure above other fires, wherein environmental winds support a vertically coherent convection column (for example the Waroona fire [26]).



Figure 11. Photograph of the Sir Ivan fire taken from an aircraft at 1719 AEDT, looking from northeast to southwest. Provided by RFS.

The simulations using ACCESS-Fire produced deep moist convection consistent with the observed pyroCb. The timing, location, and vertical extent of the simulated convection was similar to that observed. Figure 12 shows a three-dimensional visualisation of the pyroCb, from the 'medium' fuel simulation.

For the three simulations using varying fuel settings, the 'low' fuel simulation did not produce deep moist convection, but the 'medium' (shown here) and 'high' fuel simulations did. The results of these fuel sensitivity experiments suggest that the Unified Model boundary layer settings implemented in ACCESS-Fire and the heatflux from the fuel settings are appropriate for producing deep moist convection (or that errors in the heatflux and simulated plume offset each other). This result is particularly encouraging, as the environment above the Sir Ivan fire was deemed marginal for deep moist convection.



Figure 12. Three–dimensional representation of cloud structure and fire heat release at 1800 AEDT. The dimensions in x, y, and z, respectively, are longitude, latitude, and altitude above ground level. Purple and yellow shading show the cloud contents of liquid water and ice above 0.1 g kg⁻¹. Red (up) and blue (down) shading show vertical motion in the range 3–6 ms⁻¹ up to 2 km above ground level. Near the surface, black–red–yellow shading shows potential temperatures greater than 311 K as the fire releases heat. At the base is a teal to brown contour of the area's topography.

The pyrocumulonimbus fire power threshold (PFT), which calculates the potential for a pyrocumulonimbus cloud to develop above a fire of sufficient intensity [4], has been calculated for the simulations. The PFT uses the Briggs plume model (equations that describe the trajectory of hot buoyant plumes) to determine a theoretical minimum firepower required for the formation of a pyroCb in a given atmosphere. It incorporates estimates of the minimum height that a plume must rise to with a minimum amount of buoyancy to achieve free convection in constant winds. Figure 13 shows a time series of the simulated fire energy output and the PFT for a location just upwind of the fire. The red ellipse highlights the favourable period for a pyroCb near the wind change, when the PFT decreases in response to the instability near the change and the firepower (energy released) is temporarily greater than the PFT (the energy input to the plume required for a deep convective cloud to form).

Ref. [27] state that non-fire convection is primarily fed by air that is mixed and entrained into the updraft well above the base of the cloud. The lifting mechanism for the pyroCb may have had an elevated component above the cloud base, as well as being driven by the convection from the surface fire. It is also possible that the backing wind profile helped support extra lift through the mid-levels from near the top of the boundary layer.



Figure 13. Pyrocumulus Firepower threshold (orange), calculated from the ACCESS diagnostics following the method of [4]; and firepower (blue), taken from integrated firepower on the simulated firefront.

6. Model Simulation of Meso-Scale Rotation in the Convection Column

Mesoscale rotation of the convection column above the fire has been observed within a number of fires. Documented events include the Green Valley fire during the 2019–2020 Australian fire season [9] and in [10]; video footage of many other fires has been posted on the internet. Rotating convection columns are associated with plume-driven fires and very hazardous fire behaviour, including erratic fire spread direction, 'spawning' of fire-generated vortices with tornado strength winds, and extreme spotting (e.g., [9]); investigation into these processes is a focus of current research efforts.

Ref. [5] describe rotating features embedded in the Sir Ivan pyroCb. They identify an increase in in-plume turbulence and discrete vortices at kilometre scale on radar imagery within the plume at an altitude of around 2500 m on radar from 1720 AEDT, after the time of frontal passage and pyroCb growth. Figure 14 shows the wind direction at several vertical levels at 1830 AEDT, with perturbations in the wind field that are consistent in size and location with those described by [5].

Figure 15 shows velocity couplets in the near-surface wind fields. The scale is of the order of kilometres (noting the limits of the model resolution). Some of the velocity couplets are stationary, and some move in the direction of the prevailing wind with a temporal duration of 5–10 min. The location of the simulated vortices would place them over unburned assets and fuels, where suppression activities and fire crews would likely be located, and they consequently present a hazard to firefighters, as described by [8]. The ability to forecast the likelihood of these phenomena in advance may enable fireground warnings to be issued.

Figures 14 and 15 show rotating features ahead of the fireline at two different spatial scales and elevations. The features in both figures are ahead of the fireline, which is consistent with the favourable formation location of firewhirls [6]. Analysis of the intermediate model levels concluded that there was no clear link between the surface and elevated circulations.



Figure 14. Elevated wind direction at 1830 AEDT (top (3900 m), middle (3040 m), lower (2520 m)) showing meso-scale circulations near the northern edge of the fire. The dashed outline shows the fireline.



Figure 15. Wind direction at 10 m at 1830 AEDT. The dashed line shows the fireline. Ellipses highlight small-scale vortices in the wind flow ahead of the main fire front.

7. Discussion and Conclusions

This study has examined observations and coupled fire–atmosphere simulations of the Sir Ivan fire. The simulations produced several features of the meteorology and fire behaviour that were observed during the event, including local wind variability, pyroCb development, and vortices.

7.1. Fuel Model Applicability

The simulations used the DEFFM or Vesta fire spread model, and this configuration produced fire perimeters that were a good match for the observed fire spread for both the Sir Ivan and Waroona fires [13], with no adjustments or calibration factors required. This may be partly explained through the conditions under which field experiments for fire spread models are typically conducted. Field experiments with low-intensity fires are likely to be mainly influenced by the surface meteorology conditions, and they are unlikely to capture fire–atmosphere feedback processes. In contrast, field experiments with high-intensity fires with deep fire plumes are more likely to implicitly capture fire–atmosphere feedback processes. They will therefore have greater applicability to landscape-scale events burning in high-end weather conditions. Both the Sir Ivan and Waroona fires were high-intensity fires that burned in environments representative of the meteorological conditions that the DEFFM experiments were conducted in. So, it may be that the DEFFM forest model is well suited for implementation within a coupled framework because it was established in high-end burning conditions.

7.2. Fuel Model Development

The consistency between the observed and simulated fire spread for the Sir Ivan fire is considered good rather than excellent, which may be attributed in part to the heterogeneous fuel mosaic that the Sir Ivan fire burned through, the details of which were not included in the simulations. The implementation and testing of more complex fuel information in ACCESS-Fire is needed in order to improve simulation accuracy and enhance future use of the model. Initial steps have been taken to implement fuel maps that were developed for the Australian Fire Danger Rating System [28]. Providing detailed fuel inputs and accurate representation of the sensitivity of fire spread to fuel estimates is a challenge for all fire prediction efforts; it is not unique to coupled modelling. However, it is expected that improving current fuel representations will result in substantial benefits.

7.3. Fire Response to Boundary Layer Rolls

The simulated fire intensity around the fires' perimeter varied temporally and spatially in direct response to cellular boundary layer rolls in the wind fields. The pulses in wind speed likely occurred at a scale too fine to capture in the present operational weather prediction models. The boundary layer rolls are a mechanism for producing transient surges and lulls in fire intensity that are independent of fuel or topography. These surges and lulls are inconsistent with the assumption that wind-driven fire spread occurs as a steady-state process. This local wind variability exposes the operational challenge of selecting the appropriate wind speed to use as a single input for fire danger ratings and ongoing fire predictions.

7.4. Fire Response to the Gradual Wind Change

The northwest to southwesterly wind change that impacted the fire during the afternoon was a gradual shift in direction rather than an abrupt change. This gradual shift resulted in an early increase in simulated fire intensity on the northern flank of the fire, which matches the linescan imagery. The gradual wind shift has implications for firefighting operations as there is an early risk to firefighters engaged in suppression activities on the exposed edge, ahead of the expected time of wind change. Wind change charts are a fire weather forecast product issued in Australia that depict a wind change as a series of distinct lines on a map, representing a sharp boundary at a sequence of times, whereas the reality here was a gradual shift in direction. They do not communicate the transitional risk of a fire flank that results from a more gradual wind direction change. The simulated and observed increased fire intensity and elevated risk on the northern flank ahead of the main synoptic change provide the rationale for including a more nuanced operational description of the temporal and spatial details of wind fields.

7.5. Simulated pyroCb and Comparison with PFT

The simulations produced deep moist convection consistent with a pyroCb that was well verified by the observed pyroCb's timing and location. Both the observed and simulated pyroCb were short-lived in the highly sheared and marginally unstable environment. Experiments were run with three fuel settings (low, medium, and high). The low fuel setting did not produce deep moist convection, and the medium and high fuel settings simulated a pyroCb. The sensitivity of deep moist convection to fuel load (and thereby heatflux) indicates that the settings in the Unified Model can appropriately resolve the energy fluxes into and above the boundary layer.

The simulated heatfluxes that produced deep moist convection were compared to the PFT, and the results showed very good consistency; both approaches captured the short-lived favourable conditions for deep moist convection near wind change. More testing is required against a range of conditions to establish efficacy; however, the pyroCb results suggest that ACCESS-Fire may be used to explore the processes surrounding deep moist convection above a fire, an environment in which it is very difficult to take direct measurements.

The Sir Ivan pyroCb occurred in a highly sheared environment. The implications for cloud thermodynamics and fire-modified winds directly impacting surface fire behaviour are different for a vertically sheared pyroCb compared with a pyroCb with a vertically coherent convection column. Any lightning strikes that produce secondary ignitions from a sheared pyroCb are likely to be well downwind of the surface fire; this is seen in the horizontal displacement between the fire and lightning strike locations within the Sir Ivan fire. Similarly, any convective downdrafts from a pyroCb in a sheared environment are unlikely to produce surface gusts that impact the main fire front due to the decay phase of the storm cloud being well downstream and therefore decoupled from the surface fire.

Ref. [27] make the important point that pyroCb (and pyroCu) are generated by high energy release from a fire and are often triggered by a change in fire size or intensity, and that no studies have established pyroconvective cloud as a precursor to a substantial change in fire behaviour (i.e. despite anecdotal reports linking the two, no conclusive study of cause and effect has shown that pyroCb's can cause enhanced fire behaviour).

Interest in pyroCb's in Australia is high across the research and operational fire communities. Detailed examination of processes surrounding pyroCb, including wind flow around and into the plume, smoke and other particulate transport, downburst potential and structure, and upper atmosphere injection heights and particle trajectories, would improve current understanding of the phenomenon.

To date, we are unaware of a coupled fire–atmosphere model other than ACCESS-Fire that has resolved pyroCb within a coupled fire–atmosphere framework for a landscape scale fire, although [8] presented CAWFE (Coupled Atmosphere-Wildland Fire Environment) as a tool for understanding fire–atmosphere interactions in cases in the USA. Ref. [27] state that although fire convection-related phenomena have been extensively studied, there is considerable uncertainty regarding how deep moist convection interacts with wildland fires, and further research is warranted. The findings here present ACCESS-Fire as a modelling tool to contribute to that understanding, with the advantage that it is a research tool that harmonises Australian operational meteorology and fire prediction, because the atmospheric model is the same as that used operationally by the Australian Bureau of Meteorology; also, the fire component is being upgraded to use similar spread and fuel models to those used operationally by Australian fire agencies.

7.6. Fire-Generated Vortices

Elevated and near-surface circulations in the wind fields developed in the simulations ahead of the northern flank of the fireline post wind-change. The near-surface features resemble firewhirls or fire-generated vortices, and they developed in a favourable location for horizontal environmental vorticity (rotation in the horizontal plane)= to be tilted into the vertical plane and stretched by updrafts. The timing and location of the elevated rotation is consistent with the structures on radar described by [5].

Fire-generated vortices as well as non-rotating extreme winds at local scales present a hazard to firefighters. One benefit of coupled fire–atmosphere modelling is that it can depict strongly rotating features in fire-modified winds that are difficult to observe in situ. Coupled models may be used to explore the parameter space of vortices and further understanding of the generation processes and favourable environments for rotating (and non-rotating) extreme winds. This presents a pathway for understanding vortex formation within landscape fires, and may assist in the development of predictive techniques.

7.7. Future Development and Use of ACCESS-Fire

ACCESS-Fire simulations have been examined here in combination with other analysis techniques including radar and PFT. The overlaps and reinforcing results that have been demonstrated are pleasing, and show that a multi-faceted research investigation can strengthen weather and fire behaviour narratives.

Planned improvements to ACCESS-Fire through developments and testing to both the ACCESS and fire code components will facilitate future ease of use and collaboration. Activities underway include making the code available to other researchers (by placing it on the UM 'trunk') and upgrading the fire fuel models to be the same as those in the operational national fire danger rating system. As both components of the coupled model framework (ACCESS and the updated fire spread models) are used in operations and research, there is a relatively direct pathway from research applications to making predictions of extreme fire behaviour at high resolutions in real time. This capability may also be applied to explore questions that address the future requirements of fire simulation models and fire prediction approaches.

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