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Welcome from Editor

It is my pleasure to bring to you the compiled papers from the Science Day of the AFAC and Bushfire CRC Annual Conference, held in the Sydney Convention Centre on the 1st of September 2011.

These papers were anonymously referred. I would like to express my gratitude to all the referees who agreed to take on this task diligently. I would also like to extend my gratitude to all those involved in the organising, and conducting of the Science Day.

The range of papers spans many different disciplines, and really reflects the breadth of the work being undertaken, The Science Day ran four steams covering Fire behaviour and weather; Operations; Land Management and Social Science. Not all papers presented are included in these proceedings as some authors opted to not supply full papers.

The full presentations from the Science Day and the posters from the Bushfire CRC are available on the Bushfire CRC website www.bushfirecrc.com.

Richard Thornton

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An extreme fire processes cycle model for the February 2009 Victorian Fires

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Abstract

Following the aftermath of Black Saturday, the most significant bushfire event in Victoria since Ash Wednesday in 1983, the spread and behaviour of eight of the most significant fires on the day were reconstructed from multiple data sources. A chronology of events was created using an enhanced fire isochrone approach which was cross-linked between GIS and Google Earth platforms to interpret and map fire spread and behaviour.

Conditions on Black Saturday produced extraordinarily complex fire behaviour; of note was the rapid development of masses of spot fires, which quickly coalesced into deep large convection columns that created strong pyro-convection and formation of pyrocumulus clouds a great distance into the atmosphere (in some cases approaching 12 kilometres above sea level). The mass fire behaviour and large convection columns were most evident in rugged forested terrain where fuels in both dry and wet forest types were completely available for combustion following a sustained period of drought and a severe summer heat wave, producing a continuous fuel bed for rapid fire spread.

Based on a comparison of the forest-based fire case studies, four distinct phases in fire development were recognised: (1) initial fire run and laying out of spot fires; (2) coalescence of spot fires, leading to mass fire convection and development of pyrocumulus cloud; (3) dissipation or weakening of pyro-convection; and (4) the final decrease in fire convection following a cool change or a lack of fuel.

These fire developmental stages are not as yet fully documented or understood by either the technical fire research or operations, or by rural communities at large.

Keywords: Fire behaviour, fire reconstruction, convection column dynamics, fire processes cycle

Introduction

Following a period of prolonged drought, heat-waves, and severe fire weather conditions, 15 major bushfires, along with some small fires suppressed early on, broke out in the Australian state of Victoria on 7th February, 2009. The desiccating conditions caused both live and dead fuels in dry, damp and wet eucalypt forests to be highly flammable and combustible that saw each fire ignition spread rapidly into large, convection-driven forest fires that burned actively into the late evening. Based on the video and ground evidence gathered as part of the fire reconstruction project, extreme fire behaviour experienced on this day included crowning fire in eucalyptus forest, dense ember production ahead of the fire front, medium and long distance spotting from firebrands (between 2 and 15 km), multiple head fires and fire whirls, either as vertical or horizontal rotors).

The combination of these fire behaviour attributes produced rapid and extreme rates of energy release forming active buoyant pyro-convection above most of the fires. This 'Black Saturday' saw 345,000 ha of land burnt, along with 173 Victorian lives lost and 4,200 homes destroyed (Teague *et al.*, 2010), making it one of the largest fire impacts in Victoria, akin to Ash Wednesday on 16th February 1983 (209,830 ha, 32 fatalities and 2680 homes destroyed) and Black Friday on January 13th, 1939 (2,000,000 ha, 71 fatalities and over 650 homes and other buildings destroyed).

Out of the 15 fires on the day, eight fires in the central and eastern parts of the state were selected for detailed fire reconstruction (Figure 2): Beechworth–Library Road, Bendigo–Bracewell Street, Bunyip–Ridge Track, Churchill, Kilmore East, Murrindindi, Redesdale–Coliban Park Road, and the Dargo–White Timber Spur fires. With the exception of the Bendigo–Bracewell Street fire, these eight fires burnt more than 8,000 ha each. Six out of the eight fires burnt through substantial proportions of native forest, being primarily located in rugged mountainous or hilly terrain.

Amongst these eight fires studied, there was considerable variation in the landscape mosaic of eucalypt forest, plantation, and grassland types, as well as in the shape of topography through which these fires burnt. The largest of all the fires on Black Saturday, the Kilmore East and Murrindindi fires, burnt through a roughly equal proportion of dry, damp, and wet eucalypt forest types located in mountainous relief in ranges to the north and north-east of Melbourne, as well as grassland in the Kilmore, Wandong, Yarra Glen, and Glenburn precincts. The Churchill–Jeeralang fire burnt through predominantly eucalypt and pine plantation forest types on steep, hilly country in the Strezlecki Ranges in southern Victoria. The Bunyip-Ridge Track fire initially burnt through dry and damp eucalypt forest and undulating to flat relief, and then through partially to fully cured grasslands before finally burning up into wet eucalypt forest on to the more hilly Hells Gate North and South ranges in central western Gippsland. The Dargo–White Timber Spur fire burnt on the edge of the Dargo Plains high country through a mosaic of montane and sub-alpine grassy and shrubby forest in steeply dissected escarpment in central northern Gippsland. Further to the west in the Central Goldfields region of Victoria, the Redesdale–Coliban Road and Bendigo–Bracewell Street fires burnt through mainly grassland fuels interspersed with patches of dry grassy and litter dominated eucalypt forests. In the north-east of Victoria, the Beechworth–Library Road fire burnt through dry and damp eucalypt forests on mountainous plateaux and ridges, broken up by broad flat to undulating grassy valley floors.

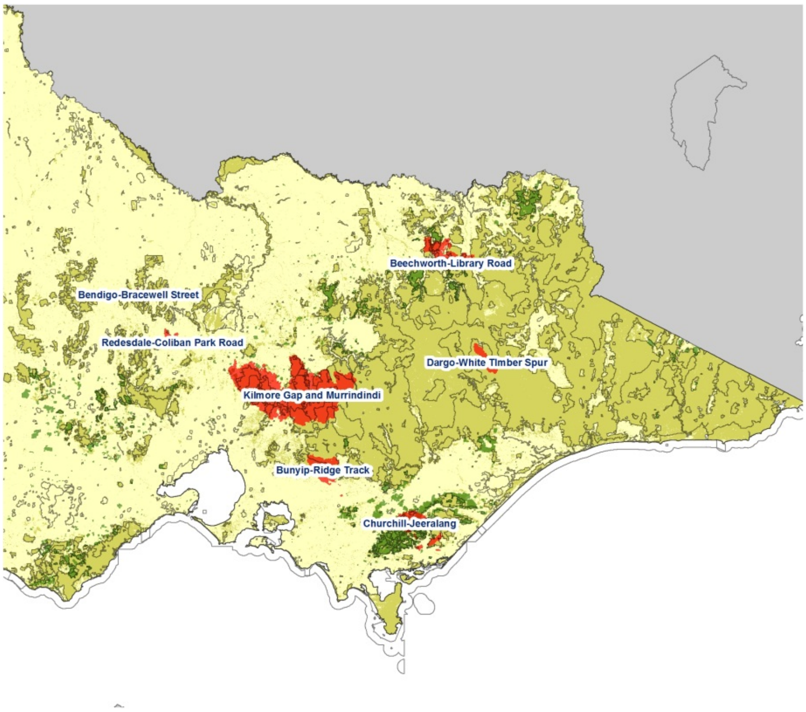


Figure 2. Black Saturday Fires under study

The conventional two-dimensional models of fire behaviour based on estimations of surface fire rate of spread do not account for the convection column and spotting behaviour observed on Black Saturday (McArthur, 1966, McArthur, 1967). An alternative fire developmental phase model is proposed in this paper, which is based on the analysis of detailed fire reconstructions produced by the project, and the vegetation-fuel landscape conditions, and fire weather on the day, a simplified model of the phases of fire development is proposed in this paper.

Fuel and Fire Weather Conditions

To provide some context for the proposed fire process model, the fuel and fire weather conditions on Black Saturday are compared to other significant fire seasons and fire events in Victoria in order to show how severe the landscape and atmospheric conditions were on that day.

Applying critical thresholds of severe drought to a 130-year time series of Soil Water Deficit (SWD) in both wet and dry sclerophyll forests identified historically critical sets of landscape dryness during fire seasons in southern Victoria (Gellie *et al*., 2010b). The results from this exploratory study based on the periods of extreme SWD above those critical dryness thresholds, showed that the 1938/39 and 2006/07 fire seasons were the most severe in the 126 year historical record. The 2008/09 fire season was more associated with fire seasons with less severe landscape dryness, such as 1897/98, 1926/27, 1943/44, 1967/68, and 1982/83. However, this analysis does not take into account the medium-term cumulative effects of a sixteen-year drought spanning the fire seasons from 1996 to 2009 that could have caused a draw-down in soil and vegetation moisture.

Based on anecdotal evidence and the completeness of fuel consumption collected from field interviews and landscape-based photographs, eucalypt litter in dry and damp eucalypt forests had dried throughout their respective fuel bed profiles. Grass, fern, or herbaceous species had fully cured in the dry forests and in many of the grassland areas. The finer coarse woody fuels (between 6 and 75 mm in diameter) such as larger branches and twigs had dried through to the centre. Bark fuels in common rough-barked eucalypt species, such as *Eucalyptus obliqua* (Messmate Stringybark) and *Eucalyptus dives* (Broad-leaved Stringybark) were dry deep into the inner bark. In the Kinglake–Mount Disappointment area, patches of dry eucalypt forest were observed to have orange coloured canopies on exposed northern and western aspect, indicative of drought stress. In wet sclerophyll forest, the litter and herbs were fully available for combustion, while the tall eucalypts and shrubs retained some level of moisture. As a result, fuels available for combustion across all eucalypt forest types were at an all-time high during the 2008-09 fire season, reaching 3–5 kg m^{-2} based on all the live and dead fuel elements (Gellie *et al*., 2010b). At the landscape level, this meant that fire was able to spread unhindered across all eucalypt forest types. The lack of moisture at this time of the fire season blurred the distinction between dry, damp, and moist eucalypt forests.

The fire weather on Black Saturday was largely driven by a deep pre-frontal continental heat trough that drew air from a very stable heat pool over central and western Australia. According to *Parkyn et al.* (2010), the atmosphere on Black Saturday was highly conducive to large-scale three dimensional fire behaviour based the atmospheric instability estimated from atmospheric soundings on the day. As a result, most of Victoria on that day was exposed to an atmosphere with an extremely hot, dry and very windy fire weather conditions in a mixed layer 5500 m deep. Typically, temperatures in excess of 45^0C, relative humidity ranging between 8 and 12% and strong to gale force winds between 45 and 55 km hr^{-1} were found at elevations below 400 m. At higher levels in the mixed layer, winds were blowing at 70 to 100 kilometres per hour (Bureau of Meteorology, 2010). Drawing on historical records, *Parkyn et al.* (2010) claimed that the conditions on Black Friday in 1939 were similar to those on Black Saturday, except that the strength of the winds were more likely to have been 35–45 km hr^{-1} prior to the arrival of the south-west change. The other factor on Black Saturday was the strength of the southerly change on the day, but not as strong or prolonged as that experienced on Ash Wednesday in 1983. The result was that fires burning in dry and wet eucalypt forest had sufficient vertical convective energy to resist mixing despite these strong winds, and the plume was thus able to penetrate above the mixed layer to heights well over 8000 m, and sometimes to over 11,000 to 13,000 m.

Method

A detailed outline of the fire reconstruction methodology has been previously set out in (Gellie *et al*., 2010a). High resolution 15 cm post-fire digital aerial photography was used as a base mapping reference. It also contained fire severity information, which was used to locate fire fronts and their fire behaviour. Spread and behaviour of the fires under study were documented with series of isochrones between 5 and 20 minute intervals for the Beechworth–Library Road and Bunyip–Ridge Track fires. For the other fires, which had less available evidence to reconstruct their spread and behaviour, fire spread and behaviour was documented at a slightly less detailed time scale, with 10 minutes to an hour between isochrone lines.

As well as mapping the surface fire spread in the form of fire isochrones, video and radar-based images were available to study the convective dynamics of six out of the eight fires studied. Fire chronologies and narratives for all the fires were developed in the report, along with a detailed analysis of fire weather, energy release patterns, and spotting dynamics. In addition to the fire reconstruction datasets, BOM radar data was made available to enable analyses of fire convection column dynamics. Although coarse in resolution, the radar data was used to plot the position of the fire and to detect the pulses of energy being out by the fire. There were some limitations to the radar data. For instance, it was not always available and some of the fires were just too far for the radar to pick up sufficient detail of the smoke plumes. For instance, the Laverton high resolution Doppler radar was not operational to monitor the Kilmore and Murrindindi fires between 1430 and 1800 hours, due to a mechanical fault. The Sale radar data was used to track the position, height and density of smoke plumes from the Bunyip–Ridge Track and Churchill–Jeeralang fires.

Based on all the evidence available, patterns and processes evident from these fires were developed into a conceptual model of an extreme fire process cycle on Black Saturday.

The Extreme Fire Processes Cycle Model

The conceptual basis of this model is that the fire environment is an interconnected, three-dimensional realm of interactions between landscape terrain, vegetation-fuel, and fire weather, all determining components of fire spread and behaviour across the landscape. The fuel structure, arrangement and continuity not only vary significantly across a spatial context, but also changes according to seasonal climate. The availability of individual components of the forest played a major role in determining the ease of ignition and onset of either intense sub-canopy or crown fires in eucalypt forest on the 7th of February. This can be directly related to the high water soil deficit levels brought on by drought and heat-wave conditions and intensified by severe surface weather conditions embedded in a pre-frontal continental heat trough. Fuels in wet eucalypt forest types were in a seasonally dry state, and when paired with the existing dry eucalypt forest types formed a continuous available fuel type stretching across multiple broken terrain features.

Fires spread rapidly from ridgeline to ridgeline leaving pockets of unburnt areas to fill in behind while the main front played catch-up to the spot fires ahead. Instability in the atmosphere that day introduced a third-dimension to the Black Saturday story, demonstrating the drastic impact that strong upper level winds and very dry atmospheric moisture conditions of passing air masses can have on energy release and associated convective energy of fire plumes. The fires themselves also affected local atmospheric conditions, by firstly altering stability and lifting condensation levels as forest fuels combusted, releasing significant quantities of heat and moisture was released and secondly altering the wind fields up to 10 km downwind.

In any fire process model, rate and duration of combustion are critical factors in determining a fire's rate of spread and intensity at any point around its perimeter. The duration and intensity of the flaming zone is very much related to the architecture, fuel geometry, and loading of the individual fuel elements. The standard form of fire intensity is the widely used and accepted Byram's formula of fire line intensity (Byram, 1959):

$$BHFI = QMR \qquad \text{Equation 1}$$

where BHFI is equal to fire line intensity (kW m^{-1}), Q is the effective heat content of the fuel (kJ kg^{-1}), M is equal to the fuel load consumed in the flaming front (kg m^{-2}), and R is the rate of spread (m sec^{-1}).

Instead, one can use Byram's alternative form of fire reaction intensity which has units of area instead of lineal fire front:

$$I_R = \varepsilon Q M d \tau_R w \qquad \text{Equation 2}$$

where I_R is equal to the reaction intensity (kW m^{-2}), ε is equal to combustion efficiency, d is equal to the depth of combustion zone, τ_R is equal to the flaming residence time, and w is the width of the head fire.

Reaction intensity (I_R) is a measure of the rate of combustion of fuels in a forest. A large number of fuel bed factors, including size and geometry of fuel elements, their architecture, and their bulk density affect the combustion rate of forest fuels. The most significant factor that affects mass loss in a fuel element is a fuel particle's thickness or diameter (Burrows, 2001), the finest fuels, such as eucalypt, grass, and ferns, burnt up the quickest but within a short time other fuels become involved in combustion, such as twigs and fine branches, as well as tree bark, and live shrub and tree foliage. Combustion rate values (I_R) for eucalypt forest fuel beds are almost non-existent in the literature yet determine fire spread rate and convective heat output around a fire's perimeter.

From evidence gathered during field interviews and from photographs taken during the fire (Figure 3), the mix of fine and coarse dead fuels, near-surface fuels, bark, and sometimes live canopy fuels had a τ_R of 1.5–3 min, extending the previously estimated τ_R of 45–60 sec by ~1.5–2.0 minutes. Combustion rates for a typical set of fuel elements involved in flaming combustion are presented in Table 1.

Table 1 Parameters and combustion rate for fuel elements in a Messmate Stringybark Forest

Fuel Element	Fuel Load	Percentage of fuel element consumed	Combustion Efficiency	Potential HW	Flaming Residence times	Combustion Rate
	(kg m^{-2})			**(KJ)**	**(sec)**	**(KW m^{-2})**
Litter	1.50	75%	90%	18,730	45	415
Ferns	0.40	75%	90%	5,000	30	165
Twigs with a mean diameter (6-25mm)	0.35	62%	90%	3,610	140	25
Bark	0.43	75%	90%	5,370	20	270
Total for a sub-canopy fire	**2.68**			**32,710**		**875**
Canopy	0.80	85%	65%	8,180	12.3	665
Total for a canopy fire	**3.48**			**40,890**		**1540**

Note: The estimates for percentage of fuel consumed, combustion efficiency, and potential QM are best estimates. For instance Q is taken to have value of ~18,500 and 22,500 for dead and live fuels (Pompe and Vines, 1966). The estimates for flame residence times are based on Burrows (2001) and Pompe and Vines (1966).

If one assumes that τ_R of the litter fuels determines the period of flaming combustion and was equal to 45 seconds (Pompe and Vines, 1966), being three times longer than 10 seconds for dry eucalypt leaves the experiments undertaken by Burrows (2001) because of differences in the bulk densities of the two fuel elements. The estimated combustion rates for the litter and the other fuel elements are based on the relative proportion of each fuel element consumed in that 45 second period. Combustion rate for rough-barked fuels is problematic as the mass loss rate depends on the thickness and density of the bark flakes, which increase in density towards the tree core, and being vertical, is highly efficient as the flames run vertically up a tree. Essentially the overall combustion rate for a sub-canopy fire in a Messmate Stringybark forest is estimated to be ~870 kW m^{-2}. A significant contribution of this I_R value came from the litter and fern fuel elements. This combustion rate estimate assumes that all the fuel elements burnt at the same time. If not, then the estimate of combustion rate would be lower and the effective τ_R. would be extended, which is possible based on the observations of flame residence time being extended to nearly 3 minutes on some of the Black Saturday fires. A canopy fire had almost double the I_R value, with a value of ~1500 kW m^{-2} because of the highly efficient combustion of openly packed eucalypt canopy foliage. Thus, crown fires in a dry rough-barked dominated eucalypt forest would have contributed more convective energy and atmospheric moisture within smoke plumes of the forest fires than a sub-canopy fire in a dry, damp, or a wet eucalypt forest on Black Saturday.

As witnessed on Black Saturday, combustion zones at the head of each spot fire or major finger of fire were deep (estimated to have been 60–150 m in depth) depending on forest type and exposure to wind and down-draft currents within and ahead of a convection column. These deep flame zones (usually at the sub-canopy or above the forest canopy) contributed to rapid fire acceleration and large amounts of convective energy available within each fire. The presence of vertical flames (or flame detachment) also contributed to the large amounts of energy release even on steep slopes (Dold and Zinoviev, 2009). A major contributor to this phenomenon was the presence of rough-barked eucalypts enhancing flames in the forest sub-canopy.

Figure 3 Deep combustion zones and detached flames on a forested slope during the Kilmore East fire at ~1630 hours (Photo credit: Richard Alder)

The process of fire spread on Black Saturday can be described in four generalized phases during the south-east runs under north-west winds: (1) formation of incoherent spot fire plumes; (2) plume consolidation; (3) plume weakening; and (4) plume dissipation (Figure 4).

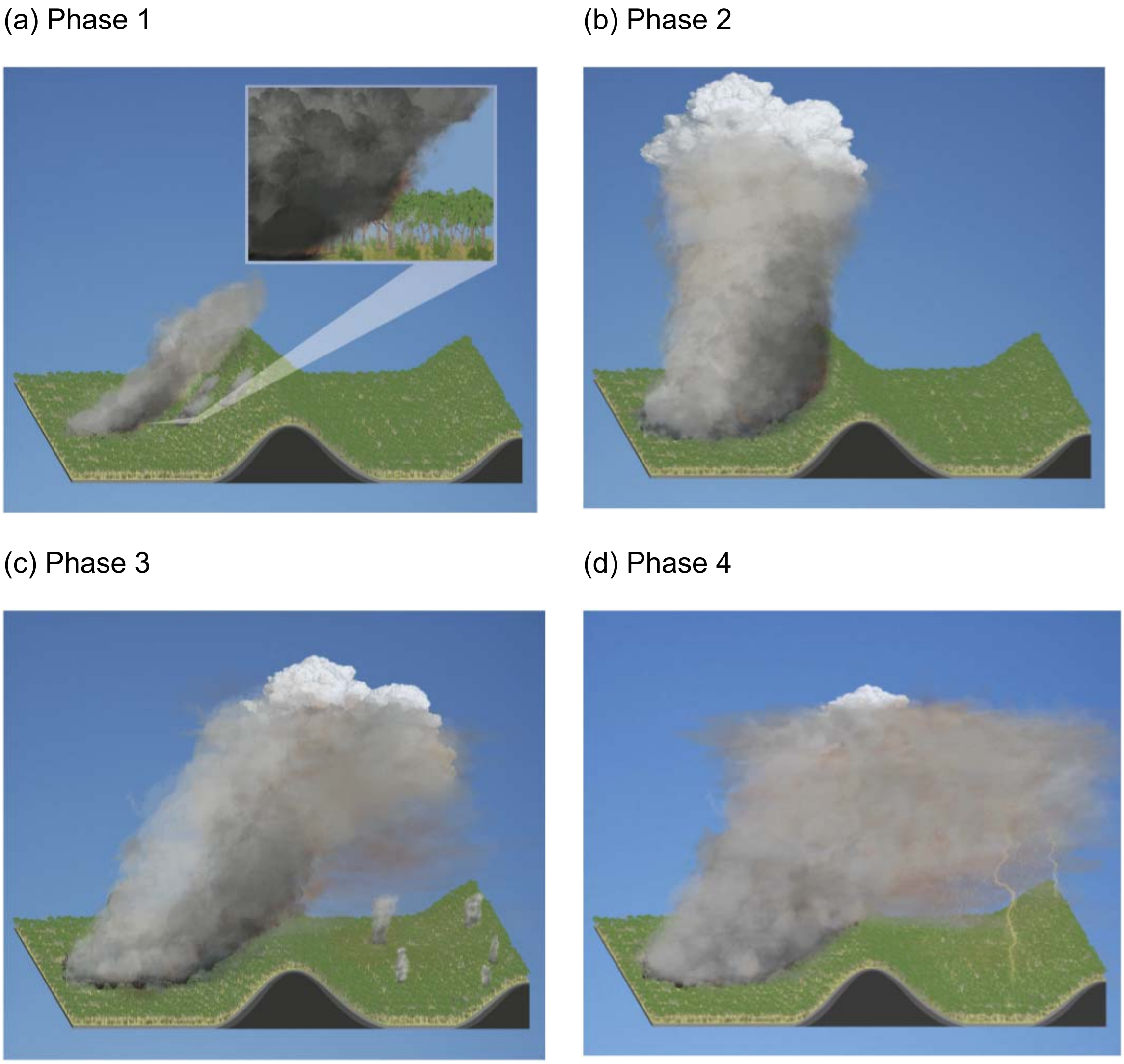


Figure 4 Key Phases in the extreme fire processes cycle model during the six most significant Black Saturday fires.

Note: This cycle pertains to the Beechworth–Library Road, Bunyip-Ridge Track, Churchill–Jeeralang, Dargo–White Timber Spur, Murrindindi, and Kilmore East Fires.

In the first phase, a series of short distance spot fires spaced 500 to 2000 meters apart were laid out and established quickly under the influence of turbulent winds (Figure 4 (a)). If the terrain was configured as a series of ridges at right angles to wind direction, rate of spread would be temporarily stalled as the fire went over the ridge, leading to an interruption in the plume's convective energy supply. This is when firebrands were cast out from the smoke plumes, leading to more spot fires becoming established downwind at distances between 1 and 5 km ahead of the initial fire. This meant that the fire jumped five to seven kilometres ahead, even though some of the area in between remained unburnt. Explanations of fire behaviour, based on atypical fire spread and fire channelling, were found at one location on the Bunyip–Ridge Track fire (Sharples and McRae, 2011). However, for the rest of the time, the propagation mechanism of short–medium distance spotting encountered in this phase was the dominant fire spread process.

In the second phase, individual spot fires developed into larger fires and merged with others nearby. Spot fires that landed at the base of ridges with steep slopes actively crowned uphill and contributed to quickly developing and strongly rising convection columns. The separately developing spot fires in very high available forest fuels, coupled with very low fuel moisture contents, steep forested terrain, and strong turbulent winds on Black Saturday produced deep flaming zones, often involving eucalypt tree crowns that led to more vertical smoke plumes (Figure 4 (b)). Combustion rates slowed as live canopy fuels in the canopy became actively engaged in combustion, creating dark red flames and darker and denser smoke columns (Byram, 1959). At these times, convective energy would increase to the extent that in the larger fires, such as the Murrindindi and Kilmore East fires, a near vertical core between 2000 and 4000 m high above the ground would be established, retaining potential spotting firebrands within the convection column. This effect could last from several minutes to several hours, depending on the extent of forest being burnt out.

During this phase the head of the fire usually did not travel as a coherent front. In most cases the spread of the fire was made of several convective areas centred on the earlier spot fires laid out in Phase 1 ((Figure 4 (a)). This often led to chaotic and fingers and runs developed related to drawing in and eventual coalescence of multitudes of individual spot fires. This is documented in detail for the Bunyip–Ridge Track fire, which shows four or five convective cores on either side of the power line easement and were drawn together by the processes described above.

Once the fires were fully established, a mature convection column formed (Figure 4 (b)). As the column built, forward and lateral spread of the fire slowed as a result of inward flow from entrainment or convective indrafts. If sufficient energy was produced during this stage a pyrocumulus cloud formed above the mixed layer. On the Kilmore East and Murrindindi fires, pyrocumulus clouds formed and lasted for several hours as a result of crown fires at the base of their convection columns. The combustion of live canopy fuels released additional energy into the column, contributing to the development of clouds at its peak. In this phase, longer distance spotting occurred only if the fire's convection was overridden by strong winds.

In the third phase, energy release from convection plumes was either interrupted or slowed, usually related to consumption of all the fuel in the area or the fire reaching the top of a ridge or plateau (Figure 4 (c)). At this point, a few longer distance spot fires (ranged from 6 to 20 kilometres) were initiated downwind, associated with ribbon bark firebrands from the damp or wet forest types becoming detached from the column and carried downwind in the dry air aloft. The transition back to a wind-driven smoke plume often occurred quickly (Figure 4 (a)), sometimes occurring within five to ten minutes. Flank fires now under less control and influence of the central convective core, would spread out at a faster spread rate, with the north-eastern flank becoming more exposed to wind shifts, sometimes leading to the creation of new runs of fire as spot fires landed beside the main flank. By these propagation processes, energy release at this point increased along the flanks without the restraint of the central convection column.

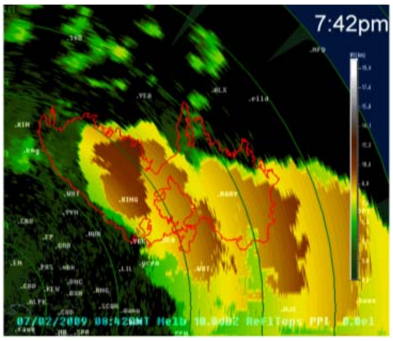
(a) (b)

Figure 5. Energy release influencing convection column dynamics on the Churchill- Jeeralang Fire. (a) intensifying convection column at ~1445 hours and (b) temporary weakening of column at ~1452 hours. Photo credit: J. Wilson.

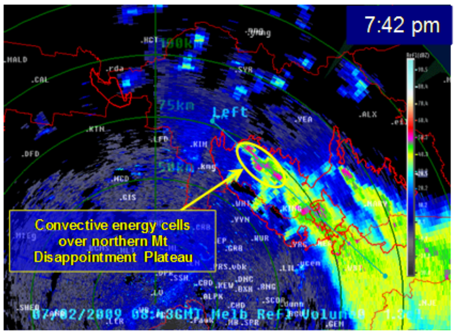
Phases 1 to 3 in the fire developmental cycle were repeated continually until a fire entered the fourth phase as the result of either: (1) major breaks in topographic relief; or (2), the fire spread from forest into grassland (a change in fuel type); or (3), a significant wind shift or a persistent wind change; or(4), a reduction in fire intensity from the combined effects of higher fuel moisture content and lower wind speeds associated with the passage of the cool change; or (5), some combination of all of the above circumstances (Figure 4 (d)). In the first case, the fire plume weakened at the top of an escarpment causing the pyrocumulus cloud atop the convection column to dissipate quickly, usually resulting in short and medium distance spotting between 5 and 12 km. In the second case, scattered spot fires would emerge downwind following the collapse of the fires' main convective centres, causing medium-distance spotting of between 3 and 5 km, resulting in several fingers of fire spreading independently through mixed grassland. On occasions, long distance spotting between 8 and 13 km, and sometimes 18–22 km downwind occurred. In the third case, mass fall-out of fire brands and embers along the north-easterly flank would create an eruptive energy release associated with the newly created set of head fires between 100 and 300 m to the north of it. During the south-east run, this would often create a parallel run of fire alongside the initial run.

After the persistent south-west wind change, pulses of convective energy were seen on the BOM radar trace at intervals between 6 and 15 minutes in the Kilmore East and Murrindindi fires (Figure 6). This time scale was much finer that used in the fire reconstruction of these fires (usually 60 minutes, occasionally 10–30 minutes), suggesting that in future fire reconstruction studies, fire dynamics will need to be based on field fire intelligence closely monitoring the fire processes involved.

(a) Top of smoke plume



(b) Highest within plume radar values



(c)Vertical plume profile

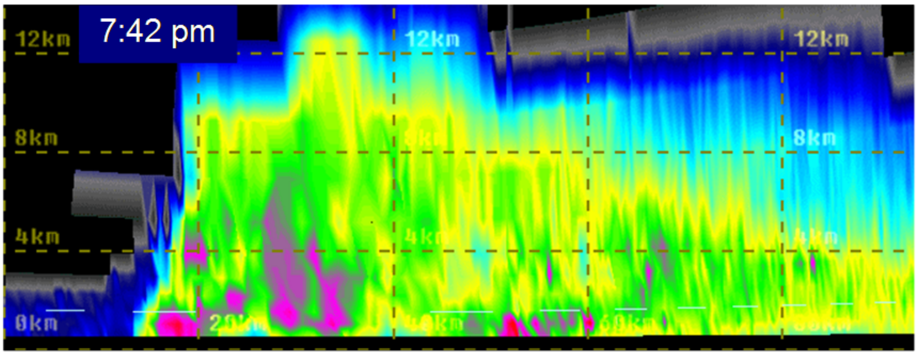


Figure 6. Interpretation of smoke plumes of Kilmore East and Murrindindi fires: (a) top of smoke plume, (b) highest within smoke plume radar values, and (c) vertical plume profile based on 1942 hour high resolution Laverton radar image. Credit: Bureau of Meteorology

Note: The vertical cross-sectional profile in (c) is along the blue line in (b) orientated NW to SE.

The dominant propagation mechanism in this case was mass fallout of spot fires at distances between 500 and 3,000 m, which would then coalesce in areas between ~300 and ~1,200 ha in size, producing energy releases varying between 1,000 and 4,000 GW[1], enabling the convection column to attain elevations over 12,000 m (Figure 5 (c)).

In the fourth case, the convection column would gradually dissipate, lagging 1–2 hours behind the cooler and moister air mass conditions and moderating wind speeds associated with the south-west change. In the fifth case, there happened to have been a combination of a persistent wind shift and a major change in wind direction that caused a fire storm over Marysville between 1900 and 1930 hours, which created an energy pulse that created a smoke plume reaching 8,000–9,000 m, which was ~3,000 m lower than the peak top height of the column over the Kilmore East fire, the surface fire energy being located over the northern parts of Mount Disappointment Plateau.

[1] Estimate based on area growth and fuel consumption in each significant time step involving surface and canopy crown fires in the pink areas highlighted within a yellow oval outline in Figure 6 (b). Combustion rates were estimated to have been between 800 and 1,200 kW m^{-2} (refer back to

Table 1 which suggests a possible maximum estimate of ~1,500 kW m^{-2}).

Conclusion

A conceptual model of an extreme fire process cycle has been developed from six fire reconstructions of six Black Saturday fires, which were three dimensional in nature, involving live and dead forest fuels, set in complex hilly or mountainous terrain, and involving extreme fire weather embedded in turbulent air masses conducive to the development of deep smoke plumes and pyrocumulus. The proposed model is similar to that developed by Wade and Ward (1973) for the Bomb Range fire in Pond Pine-pocossin fuels in coastal northern Carolina. Both these studies reveal a more complex suite of spread and spotting mechanisms than have hitherto been described in most fire reconstruction studies, with the exception of (Chatto *et al.*, 1999). This model of extreme fire processes goes well beyond the conventional explanations of two-dimensional surface fire behaviour in eucalypt forests (McArthur, 1967, Luke and McArthur, 1978).

Improvements to this conceptual model will come from more detailed fire intelligence and analysis of the integrated dynamics of forest fuel combustion, chaotic fire spread, smoke plume development, and fire brand spotting processes. This is more likely to occur when fires burn in highly combustible drought-induced fuels burning under severe to extreme fire weather conditions. Analysing fire behaviour of severe to extreme fires at this level of detail will lead to a better understanding of the underlying fire processes and may lead to better fire simulation models that can better emulate the fire processes involved.

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