Spot fire direction and spread in a severe bushfire attack in Australian vegetation

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CONTENTS

INTRODUCTION

The purpose of this article is to document the spread mechanisms of spot fires and their behaviour that occurred during a severe bushfire attack in a hilly forested landscape. The study will assess the association with wind speed and direction, potential firebrand source areas and the spotting distances. Apart from augmenting the body of knowledge about Australian fire behaviour, it is hoped that this article helps dispel misunderstandings about the nature of severe bushfires and encourages renewed interest in its effective management.
This theory section may also be useful in devising strategies to mitigate or prevent severe fire behaviour.

I observed forest and grass fire behaviour at first hand during one of the most severe weather periods in Victoria, on Black Saturday afternoon, 7 Feb 2009. The fire behaviour I saw was within established bushfire fire behaviour knowledge and expectations. It certainly did not, to paraphrase a former Fire Chief, “rewrite the rule book” of bushfire behaviour.

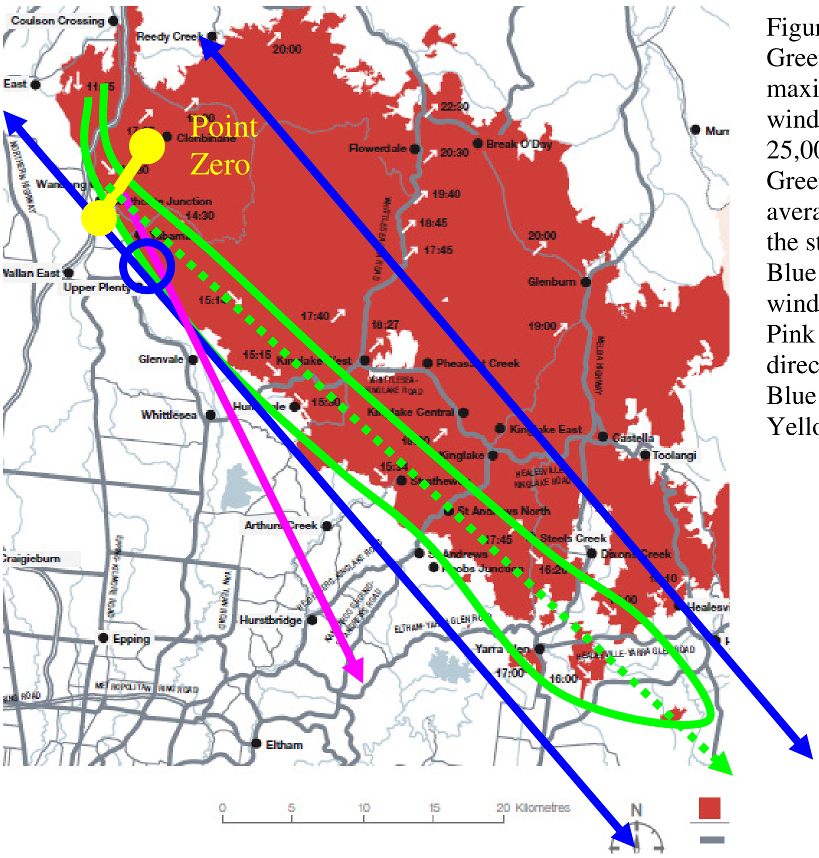


Figure 1
Green solid line is maximum area burnt before wind change = approx 25,000 ha = 50 x 5 km
Green dotted arrow is average fire direction for the study period.
Blue tramlines are NW wind direction
Pink arrow is NNW wind direction
Blue circle is vantage point
Yellow line is Point Zero

This article is one of a series that document aspects of severe fire behaviour in Australian vegetation, much of it observed and recorded during the East Kilmore bushfire on 7 February, 2009.
Some core underpinning theory is incorporated into the first Paper:
1 Manual of Bushfire Behaviour mechanisms in Australian Vegetation
Some more basic theory about spot fire behaviour introduces the second paper:
2 Spot fire direction and spread in severe bushfire attack - Australian vegetation
Together they provide some introductory scientific background for the following papers:
3 Flame spread and flame height in eucalypt forests and grassland in severe bushfire
4 How the East Kilmore Black Saturday fire got away

The foregoing papers become the basis for analysing the findings in major research works on bushfire behaviour in Australian forests:
5 Back to basics approach for bushfire behaviour research
6 Usable findings in major bushfire behaviour research in eucalypt forests – McArthur, Burrows, Vesta
7 Effect of FMC on flammability of forest fuels
8 Predicting spread rate of leap frog spot fires

The analysis in this paper covers the fire's run under the NNW – NW wind, nominally from 2pm until the SW wind change after 5.30 pm. The entire fire area is shown on Figure 1, but the subject area of this study is outlined in green. Spot fires were ignited in this area before the SW wind change. The yellow line on Figure 1 indicates Point Zero, the starting point of this analysis. This study will assess key aspects of spot fire behaviour, particularly spotting distances and direction and their association with firebrand source areas, wind speed and direction.

THEORY

Some aspects of spot fire behaviour theory are now briefly explained to help the reader understand the terms and observations described in the text.

Spot fire distance theory

Recent research has confirmed spotting distance is a function of aerodynamic nature of the fire brand, duration of burning while aloft and wind speed in upper atmosphere. For example, messmate bark firebrands tend to generate shorter distance spotting because they are heavy and burn out in a few minutes, whereas gum bark firebrands tend to generate very longer distance spotting because they are light and tubular and burn for many minutes (Hall et al, 2015).

Figure 2 illustrates the current theory of spotting trajectory (Vesta (2007) and Hall et al (2015). The firebrand rises within the plume to a maximum height H, and then falls at terminal velocity V_{term} towards the ground. Therefore spotting distance is the sum of Horizontal distance travelled during uplift (D_u) and Horizontal distance travelled during free fall (D_f). ***Spotting distance = $D_u + D_f$***

The following equations apply:

$D_u = H \times U / V_{plume}$

$D_f = H \times U / V_{term}$

Where U = wind speed, V_{term} = terminal velocity, V_{plume} = upward plume velocity

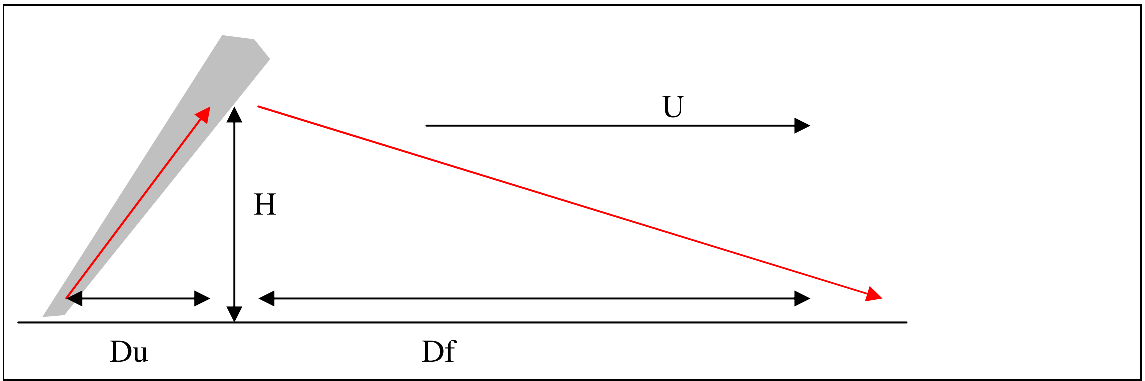


Figure 2 Components for calculating spotting distance from base of plume to ignition point
Du = horizontal distance travelled during uplift to elevation H, Df = horizontal distance travelled during free fall. U = wind speed

On a severe weather day like Black Saturday, say U = 72 kph (= 20 m/sec), and V_{term} = 5m/sec and V_{plume} = 50 or 100 m/sec
Therefore, U / V_{plume} = 0.4 OR 0.2 and U / V_{term} = 20 / 5 = 4
Therefore total horizontal distance = 4.2 to 4.4 x H
When $V_{plume} >> V_{term}$, spotting distance approximates to $D_f = H \times U / V_{term}$
Thus,
If H = 10,000m = 10 km, approx spotting distance = 40 km
If H = 5,000m = 5 km, approx spotting distance = 20 km
If H = 1,000m = 1 km, approx spotting distance = 4 km

The height of the plume at the fire at 7.24pm (two hours after the wind change) was estimated from a photograph of the pyrocumulus cloud to be 8,500 m high, with the smoke rising to around 5,200 m (Tolhurst 2009). This suggests a spotting distance of at least 20km would be expected during the heat of the afternoon.

How long would the firebrand need to remain live?
$\boldsymbol{T_{live} = T_{plume} + T_{fall}}$
Where T_{live} = minimum time plume must remain live, T_{plume} = time rising within plume, T_{fall} = time in free fall.
$\boldsymbol{T_{plume} = H / (V_{plume} - V_{term})}$ = 0.02 x H
$\boldsymbol{T_{fall} = H / V_{term}}$ = 0.2 x H
Therefore, $\boldsymbol{T_{live} = 0.22 \times H}$
Thus
If H = 10,000m, firebrand must remain live for 2,200 sec
If H = 5,000m, firebrand must remain live for 1,100 sec
If H = 1,000m, firebrand must remain live for 220 sec

Example 1 Hall et al (2015) report 40cm long rolled bark (Eucalyptus viminalis) weighing 10 – 15gm have maximum flame out times of 92 to 271 seconds) and burnout times (353 - 1300 seconds respectively. They theorise that a 2.7 m long cylinder of gum bark could burn with flame for almost 2000 sec and if it rose to 9,600m and fell at terminal velocity of 7 m/sec, it could theoretically remain flaming for 37 km downwind.
Example 2 Ellis (2011) reports messmate (Eucalyptus obliqua) bark pieces 1 – 5gm have maximum flame out times of 25 to 50 seconds) and burnout times (100 - 120 seconds respectively.

Spot fire maturity theory
A simple model is now proposed to explain that a freshly ignited spot fire requires a minimum incubation period to generate enough size and uplift for medium to long distance spotting. The following formula describes the basic time components for a new spot fire to mature.
Spot fire maturity time = spot fire incubation period + firebrand airborne time

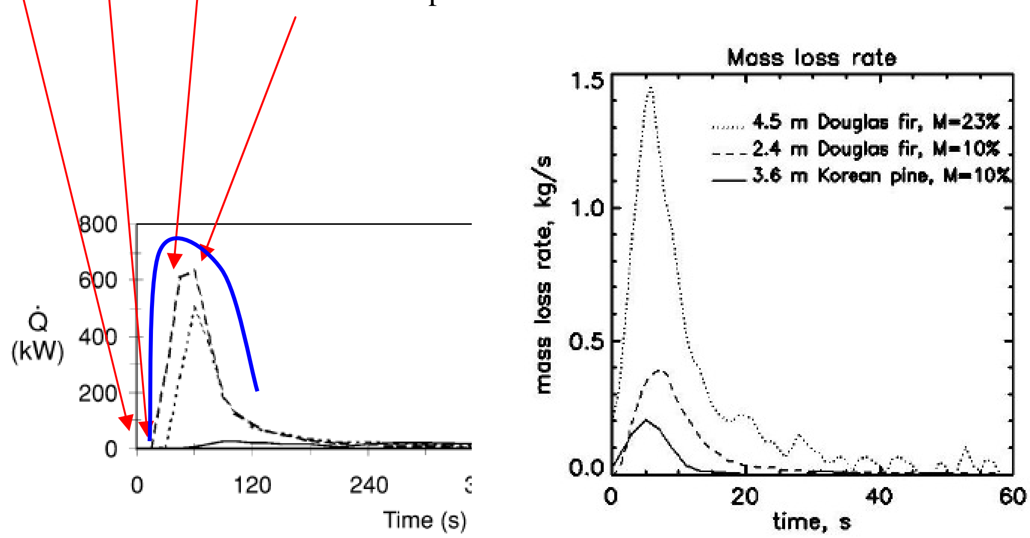
Firebrand airborne time: Firebrand airborne time was addressed in spot fire distance theory (above). It can be estimated as time of free fall at terminal velocity from height H: $\boldsymbol{T_{fall} = H / V_{term}}$ ***= approx 0.2 x H***

Spot fire incubation time: The concept of spot fire incubation time is derived intuitively as follows. A small spot fire with small flame has weak uplift. As time proceeds, the fire grows and flame area increases and plume uplift velocity increases. Thus, it can be deduced that the ability of a spot fire to generate sufficient uplift velocity to lift the firebrand high enough for long distance spotting to occur increases with time since ignition (assuming all other variables are equal). Spot fire incubation time is related to time between ignition and tall flame, height of tall flame, duration of tall flame. It assumes abundant fire brand material occurs within the flame body and within the high velocity part of the plume.

Forest fire behaviour in a multi layer fuel bed or along a flammable trunk has some similarities to well researched flame behaviour in tall vertical racks of cardboard, in particular time to achieve peak flame height and the correlation between variation on the MLR curve and flame height and updraft velocity
The following MLR charts are for Christmas tree flame trials. Q, which is heat release rate for the whole fire and MLR are interchangeable in dry fuel beds by the following formula ***Q (kW) = Heat of combustion (kJ/kg) x MLR (kg/sec)***

Industrial fire researchers classify fires by speed based on time between ignition and start of rapid growth of MLR / Q chart (Karllson and Quintere, 1999). Rapid ignition in dry forest fuels would be the equivalent of ultra fast growth rate. They also found that initial peak flame height coincides with the start of rapid MLR / Q growth. Figure 3A superimposes an indicative flame height curve (blue), showing almost instantaneous peak flame height at start of rapid MLR growth, stable flame height for several seconds and then rapid decline, several seconds after peak MLR occurs.

A vertical fuel bed has two upward speeds to be aware of, (1) the speed of flame height growth after ignition and (2) the uplift air speed due to buoyancy induced by high flame temperature. There are a few key points to note on the MLR curve:
ignition time,
time until start of rapid growth,
time of peak MLR,
duration of peak MLR.



A Source Karllson and Quintere (1999) B Source Manzello et al (2007)
Blue line is indicative flame height curve
Figure 3 These characteristic MLR curves for Christmas tree flame trials are typical for solid fuel fires

(1) Flame height speed after ignition

The new flame tip accelerates upwards via the superficial (= easily accessible) flammable fuel. Rate of upward flame height spread is driven by radiation from the rising flame mass beneath. Eg, Overholt et al (2011) calculated this at 27 kW / sq m for a flame up a cardboard wall, when it rose 10m in 70 seconds (= 0.15m/sec). If radiation increased to 80 kW / sq m, flame spread rate increased to 0.4m/sec. Radiation was low on wall fires because under-flame is restricted to one or two walls. In a forest fire because all sides of a flammable trunk and shrubs are exposed to solid flame below, the higher radiation level may be more appropriate. Eg, an experiment in candling of dead needles in the crotches of pine trees found that when foliage was 20% FMC, vertical rate of spread was 0.33m/sec and at 35% FMC was 0.12m/sec. (Billing and Bywater, 1982).

Overholt et al (2011) report that flame tip reaches the top of the flammable fuel when the pyrolysis zone is at 2/3 height, and that flame height typically peaks when pyrolysis height reaches top of flammable fuel, but suggest that if oxygen supply is limited, free flame (above pyrolysis height) is forced to stretch higher than "typical" to allow more air to be entrained to complete the combustion reaction.

(2) Uplift air speed due to buoyancy induced by high flame temperature

As Figure 3 indicates, the driver of peak flame height is pyrolysis height and the driver of sustained flame height is fuel supply rate, measured as peak MLR. The higher fuel supply rate leads to higher lateral air entrainment, which leads to rapid combustion, which leads to higher flame body temperature, which leads to higher buoyancy, which leads to higher uplift speed and leads to higher lateral air entrainment.

McCaffrey (1979) found that flame height is causally correlated with MLR^0.4, and that vertical uplift velocity is causally correlated with flame height^0.5. Therefore vertical uplift velocity is proportional to MLR^0.2.

This correlation is remarkably similar to Morton et al's (1956) findings that peak plume height is proportional to heat release rate to the power 0.25, and HRR is directly related to MLR. Taylor theorised that peak plume height occurs when plume temperature and density equal that of the surrounding air. They assumed that initial upward plume buoyancy due to high temperature / low density causes uplift velocity and proportionate lateral air entrainment rate that progressively leads to lower the temperature and raise the density of the plume fluid. They distinguished two types of plume – maintained plume (eg, a fire) and instantaneous plume (eg, a flame explosion). Plume height in the maintained fire was driven by HRR (kW), which also means by MLR. For maintained plume, H = 46 x HRR^0.25 (HRR in kW)
Plume height in the instantaneous fire was driven by energy released (joule) and yields a lower plume height. For instantaneous plume H = 1.87 x Q^0.25 (Q in Joules)
Their theory explains why the sustained flame in the forest fire generates a higher plume height and is therefore essential for longer distance spotting.

It has been long known that updraft velocity due to buoyancy within the flame zone is correlated to square root of flame height, and that this applies to a flame in a horizontal fuel bed (eg, McCaffrey (1979) - ***Vertical velocity = 6.5 or 6.9*** $\sqrt{z}$ for flame body temperatures of 800^0C or 900^0C respectively) and flame in a vertically arranged fuel bed (eg, the Russo et al (2006) approximation is ***Vertical velocity ~ 6.5*** $\sqrt{z}$). For example, they measured vertical velocity was 14m/sec at top of a 5m tall cardboard stack fire.

It is proposed that in a given fuel bed, firebrand numbers increase as peak MLR increases. Manzello et al (2007 and 2009) measured firebrand production in D fir. They found that peak MLR increased as foliar FMC decreased, and that firebrand volume also increased as FMC decreased. It might therefore be deduced that firebrand volume increased as peak MLR increased. However, this may apply only to larger firebrands. In their trials, firebrands were cylindrical and size was consistent between species and tree size - average length 34 - 53mm, (range 1 to 400mm), and average diameter 3 - 5mm (range 1 – 15mm). In addition, all species had similar ember size distributions - approx 80% (range 70 – 90%) of embers weighed 0.1gm. But when compared against total mass loss, Korean pine ember mass was 2% of total mass loss, which is up to 10 times D fir. The 2.6m D fir ember mass was 0.45% of total mass loss, and the 5.2m D fir was only 0.2%. [Total ember mass generated by Korean pine was 33gm, compared to 18gm for 2.5m D fir and 50gm for 5.2m D fir]. The postulated reason was this. Because the flame in the high density D fir foliage was much more intense than in the open Korean pine foliage, most of the firebrands produced by D fir were small enough to be consumed within the flame body.

Thus, in summary, if a spot fire develops in a multi layer forest fuel bed, a tall flame can develop instantaneously, generating short distance spotting rapidly, but its ability to generate medium to long distance spotting relies on sustained high fuel supply rate to maintain uplift force. When the fuel bed loading is adequate to sustain flame height for many seconds, vertical air speed is also sustained and this means firebrand uplift force remains strong. Project Vesta (2007) found that the tall flame phase in a multi layer eucalypt forest can last for up to 30 seconds. Uplift force in a moving flame commences with MLR of the flash flame phase of the finest fuels, and continues with MLR of the thicker fine fuels and surfaces of larger fuel particles. Uplift force in forest fuel bed is probably correlated with flame depth. Eg, if a spot fire develops in a fuel bed that generates only a low flame, uplift remains low.

Field observations suggest that a theoretical incubation period of at least 5 minutes in severe weather is reasonable to achieve short distance spotting, at least 10 to 15 minutes in severe weather is reasonable to achieve medium distance spotting (eg, up to 5 km) and 20 - 30 minutes for longer distance spotting (eg, > 10 km).

Hall et al (2015) apply 22m/sec as typical forest fire updraft velocity. Such high air speed generates over 100 kg force per sq m. which is high enough to tear loose bark and branchlets from the sides of trees and lift them aloft.

Theory of leap frog spotting

McArthur (1967) described the mechanics of simple leap frog spotting in a bushfire through a tall forest at Daylesford during severe weather. The mechanism can be explained as a theoretical model as follows:

The mother flame throws the firebrand down wind. The firebrand ignites the fuel bed as a second generation (2G) spot fire, and grows in size and uplift force. After an

incubation period, it throws a 2G firebrands downwind, initially short distance and as spot fire grows, then medium to long distance. Each 2G firebrand ignites as a 3G spot fire, and grows in size and uplift force. After an incubation period, it throws 3G firebrands downwind, initially short distance and then longer distances, which each ignite as a 4G spot fire … and so on.
The model assumes that each ignition point has a similar fuel bed and similar potential for spotting distance.

Spot fire direction theory
Weather data shows that upper winds on Black Saturday were consistently more westerly than the surface winds. Tolhurst (2009) advised the VBRC that most spot fires started to the west of ground level wind direction.

Two intuitive theories can be articulated:
Theory A If a firebrand rises and falls in an atmosphere where wind direction is constant with elevation, its direction of travel is the same as the direction of the wind.
Theory B If the wind direction varies with elevation, the firebrand's direction of travel is the net vector of distance travelled at each wind direction level during its trajectory, both uplift and free fall phases.
Distance travelled at each wind direction level
= wind speed at each level X time spent within each level

It can be deduced that on Black Saturday, when spot fire ignitions occurred downwind of the firebrand source area, firebrands remained within the lower atmosphere and were consistent with Theory A. On the other hand, when spot fires ignited in a different direction from wind at fire ground, firebrands rose into the upper wind stream and were consistent with Theory B.

Spot fire spread mechanisms
It has been long known that there are three categories of spotting distance in eucalypt forest, short, medium and long (McArthur, 1967; Luke and McArthur , 1978). They can be characterised respectively as a few hundred metres ahead of the fire front (eg, up to 500m), a few km ahead (eg, 1 – 3 km) and several km ahead (5 to 25+).

Two spot fire spread mechanisms can be indentified - *wind driven spot fire mechanism* and *plume driven spot fire mechanism*, and they can be categorised into four distinct sub mechanisms. They are explained in more detail in the Manual of bushfire behaviour mechanisms, but are summarised here:

Wind driven spot fire mechanism
- Short distance spotting

Identifying features: spot fire ignites up to a few hundred metres down wind of mother fire front (eg, 100 - 500m); low speed mother fire can retard development of these spot fires or high speed mother fire can overrun

Plume driven spot fire mechanisms
- Medium or long distance spotting

Identifying features: spot fire ignites several kilometres down wind of mother fire front. Spot fire ignites and runs independently of convection influence of mother fire

Distance is determined by spot fire distance theory, direction is determined by spot fire direction theory

- Leap frog spotting

Identifying feature: fire front spreads rapidly by multiple spot fire jumps. Distance is determined by spot fire distance theory, direction is determined by spot fire direction theory, rate of spread of leading spot fire is determined by spot fire maturity theory.

- Wandilo effect – simultaneous mass spotting

Identifying feature: massive simultaneous ember dumping into an area; mother fire may or may not overrun these spot fires.

Different rates of spread

There are three rates of spread of relevance in a spot fire driven bushfire that can be easily confused - rate of spread of original mother fire front, rate of spread of an individual spot fire, rate of spread of leading spot fires. If the fuel bed and all other variables are equal, mother fire ROS and spot fire ROS are equal.

For leading spot fires, there are two spread rates – spread of most distant ignitions and spread of most distant running fire. The distinction accounts for the spot fire ignitions that occur in isolated or discontinuous fuel beds that prevent a running flame.
ROS of leading spot fire occurrence = distance from fire origin to furthest spot fire ignition point / time from origin to ignition
ROS of leading spot fire front = distance from origin to furthest spot fire front / time from origin to establish as a viable flame (eg, 5 - 10m width)

METHODS

This analysis covers the fire's run from 2pm until the SW wind change after 5.30 pm. Point Zero (Figure 1) is the starting point of this analysis. It marks the origin of sustained firebrand production in a continuous forest. Evidence to the VBRC described the first spot fires running through the grass towards the forest at Point Zero around 2pm. The spot fires entered the forest and immediately adopted 3D flame behaviour in multi layer fuel beds.

The final VBRC report was the major source of information and data, together with the huge body of ancillary evidence it collected. This analysis makes particular use of its weather data and reported spot fire times and locations. This was supplemented by witness statements and personal observations of spot fire behaviour from our vantage point.

Details about location and timing of spot fire reports were extracted from evidence and reports of the Victorian Bushfire Royal Commission (VBRC, 2010) and located onto Google Earth. Figure 4 shows these locations, colour coded by time of report. This allows distances and slopes to be calculated and when time intervals are ascribed, rates of spread can be calculated.

Weather data and reports were provided by Bureau of Meteorology (BOM) to the Victorian Bushfire Royal Commission (VBRC, 2010). The BOM Kilmore Gap weather station was approx 25 km to the WNW of the vantage point. Upper atmosphere wind speed and direction data from Tullamarine airport, some 50 km SW, was also compiled from VBRC records.

To identify influential firebrand source areas, the spot fires reported to the VBRC were reclassified into two groups - the "longest distance" and the "infillers" by time blocks. Possible firebrand source areas for the longest distance spotting were identified by deduction based on presence of forest, type of firebrand material, slope of terrain and elevation.

Some forested and semi forested areas had high proportions of messmate or stringybark species, which are known to have shorter spotting distance potential than gum barked species. Other areas, eg, the Mt Disappointment source area, had more gum barked species, well known for long distance spotting potential. On the day of the bushfire, spot fires in the vicinity of Mt Disappointment at 800m ASL were already within the upper air stream. This means they were a readily available source of medium to long distance firebrands.

Within a forest area, typical influential firebrand source areas were the steep uphill runs that acted as firebrand launching ramps and generated very tall flash flames at the ridge tops.

Some landscape areas can be excluded as firebrand source areas. Treeless flat paddocks were not firebrand source areas. Eg, many firebrands ignited in paddocks north of Whittlesea and elsewhere, but did not contribute to further firebrand activity. The downhill sections of forest were not firebrand source areas, primarily because spot fire ignitions occurred on sheltered, down slope sites, which meant spot fires stayed narrow and run back uphill towards the top of the hill, sometimes at 180^0 to the prevailing wind direction.

Observed spot fire distances and rates of spot fire spread were compared to prediction models for eucalypt forest.

RESULTS

Weather data during observation period

The vantage point (Figure 1) was approx 25 km to the WSW of the Kilmore Gap weather station (Lat -37.38, Long 144.97, Elevation 527.8m). When NW wind speeds are between 40 and 60 kph, a change in wind at Kilmore Gap is likely to reach the vantage point approx half an hour later. Table 1 shows the regular half hourly weather readings and significant changes when they occur in between. Forest Fire Danger Index (FDI) is calculated using Drought Factor of 10.

Table 1 Weather data at Kilmore Gap Weather Station 7 Feb, 2009 (BOM, 2009)

Estimated time at vantage	**Kilmore Gap Time**	**Temp C**	**RH %**	**Mean Wind speed**	**Wind direction**	**Forest Fire Danger Index (FDI)**

point				**Kph**		*
2.30 pm	2 pm	42	10	46	NNW	110
2.43 pm	2.13 pm	41	10	72	N	> 120
3 pm	2.30	41.1	10	61	NNW	> 120
3.11 pm	2.41 pm	42.5	10	41	NNW	100
3.12 pm	2.42	42.5	9	43	NNW	100
3.15 pm	2.45	41.7	9	65	NNW	> 120
3.30 pm	3 pm	41.4	10	63	NNW	> 120
4 pm	3.30	41.8	10	57	NNW	> 120
4.30 pm	4	41.6	9	54	NW	> 120
5 pm	4.30	40.5	9	54	NW	> 120

* The author argues that FFDI calculations above 100 are invalid because they extrapolate the McArthur FFDI Meter beyond its design criteria. McArthur's maximum of 100 was chosen as an approximation of the worst possible weather (McArthur, 1967). In fact, to reinforce his meaning of approximation, when his original weather examples are used to calculate FFDI, they range between 100 and 120. Noble et al (1980) derived equations from the Meter, which has a peak FFDI of 100. Therefore to use these equations to calculate FFDI above 100 is an invalid extrapolation. To be true to the intentions of the McArthur Meter, the 100 level should be recalculated to incorporate more severe weather examples.

Upper level winds

The Weather Bureau measured upper level winds twice daily at Tullamarine airport which is 53m ASL and approx 50 km SSW - SW of the Kilmore fire. Typically, weather systems in Victoria move eastwards, and weather at Tullamarine was approx a half hour ahead of Kilmore Gap (BOM, 2009).

Table 2 Upper atmospheric winds – speed and direction
At 10 am at Tullamarine = 10.30am at fire ground

Height above sea level (ASL)	Wind speed	Wind direction
10m above ground level	54 kph	N (= blowing from North)
113 m ASL	52kph	N
600m ASL	87 kph	N
900 – 2100 m ASL	78 – 94 kph	NNW
3100 – 4000 m ASL	70-75 kph	NW
4200 m ASL	64 kph	NW – WNW
5800 m ASL	70 kph	W

At 4 pm at Tullamarine = 4.30pm at fire ground

Height above sea level (ASL)	Wind speed	Wind direction
10m above ground level	46 kph	NNW - NW
113 m ASL	50 kph	NNW - NW
300 m ASL	59 kph	NNW - NW
600 – 2100 m ASL	76 - 85 kph	NW
3100 – 6500 m ASL	72 – 91 kph	NW – WNW

The Tullamarine wind profile shows that at 10am, the base of the NW wind layer occurred at 3000m ASL. By 4pm, the NW wind layer base had fallen to 600m ASL. Assuming the rate of descent was steady at 400m per hour, the base of the NW wind layer at Tullamarine was approx 1500m ASL at 2.30 pm. This means its base was 1500m at the Kilmore weather station at 3pm. This approximate timing was confirmed at the vantage point, where the smoke plume was overhead until 3.15 pm, blocking the sun. But suddenly it moved northward. This means the lower part of the smoke plume, eg, 1500 – 2500m was NNW until 3.15. After 3.15, the air movement above 1500m was from NW. At this stage, the Kilmore fire was running in fuel beds between 300 and 600m elevation (ASL). Thus, if firebrands were lifted 900 – 1200m above the fire ground, they entered the base of the NW wind layer.

Influence of upper atmosphere winds

Table 1 shows that the prevailing wind after the spot fires entered the forest at Point Zero was from NNW. It shows that the NW wind did not blow across the fire ground until after 4.30pm. Why then do Figures 1 and 4 show that the average fire direction was to the north of NW wind direction? The only feasible explanation is that the upper atmosphere winds were more influential on the fire's direction than the wind at ground level.

The NW and the NW to WNW winds varied in height and thickness through the day above the fire ground as follows:
At 10.30am, the NW air layer at 3100m ASL was 900m thick and blowing at 70 – 75 kph and the NW – WNW layer at 4,200m ASL was 1,600m thick and running at 64 kph. These layers gradually lowered through the day at an average of 400m per hour. At 2pm, the base of the NW layer was approx 1,400m.
By 4.30pm, the NW air layer was 1500m thick with a base at 600m ASL and blowing at 76 – 85 kph. The NW – WNW layer was 3,400m thick with a base at 3,100m, blowing at 72 – 91kph.

If the fire was wind driven (ie, controlled by the wind spread mechanism), it would have been controlled by the NNW wind at ground level. Some spot fires were reported in the paddocks NW and N of Whittlesea (evidence to VBRC), and if they had escaped suppression, they would have been pushed by the NNW wind as grass fires through Whittlesea, via the Yan Yean Reservoir forest and towards Hurstbridge. [This demonstrates that suppression can be effective in severe weather where accessibility is good, where fire trucks can get close to a spot fire while small and where grass in the paddocks is low and sparse.]

Observations about spread and direction of spot fires

Evidence to VBRC confirmed the bushfire crossed the Hume Highway just before 2 pm as a rain of firebrands which ignited as spot fires. By 2 pm, the spot fires were rapidly incubating in the forest east of Wandong, growing in size and uplift force, and soon began throwing firebrands down wind. This is consistent with the leap frog spread mechanism.

Figure 4 shows the most distant spot fire reports for each time period and shows enough of the infillers to demonstrate they ignited within unburnt areas but not too many, to avoid clutter in the diagram. It illustrates that this bushfire spread by an unrestrained attack by firebrands. They ignited as spot fires and caused the fire to spread some 70 km from it origin in 4 hours and 45 minutes, which is an average of 14.7 kph. If measured from Point Zero, the spot fires had an average spread rate of 60 km in 2.5 hours, or 24 kph.

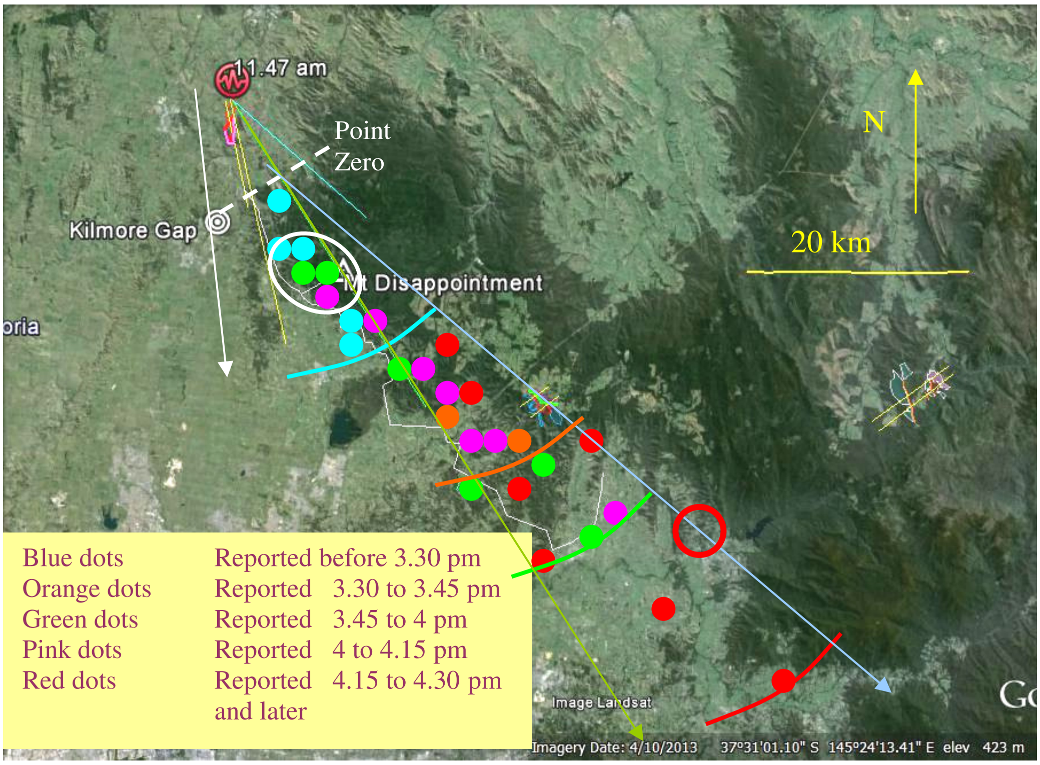


Figure 4 Colour coded map of representative spot fires reported in evidence to VBRC
White arrow is wind at Kilmore Gap before 2 pm (= N to NNW)
Green arrow is wind at Kilmore Gap til 4.30 pm (= NNW)
Blue arrow is estimated wind direction above 1000m ASL since 2pm and at Kilmore Gap after 4.30 pm (= NW)
White dashed line is the fire's location at 2pm as it entered the eucalypt forest east of Wandong under the NNW wind. Called Point Zero in the text.
Blue arc is leading spot fire at 3.30 pm; orange arc is leading spot fire at 3.45 pm; green arc is leading spot fire at 4 pm; pink arc is leading spot fire at 4.15 pm, red arc is leading spot fire at 4.30 pm.
Red circle is the Chum Creek area. Spot fires ignited here after 4.30pm. They were the source of deaths and destruction after the SW wind change at approx 5.45pm.

Observation 1 The rate of spread of leading spot fires

The "most distant" spot fire reported in a given time block is used to calculate the spread rate of leading spot fires. The infiller spot fires are reported in a given time block in the unburnt areas between the origin and the most distant. Together, they confirm that bushfire attacks by spot fire are an amalgam of short, medium and long distance spotting, and that at any one time, the spreading bushfire in mixed forest / grassland landscape is a patchwork of burnt and unburnt areas.

Table 3 derives from Figure 4. It shows how the rate of spread (ROS) of the leading spot fires can be calculated and how it increased as the afternoon progressed. Distance is measured from Point Zero. Time is measured from Point Zero, defined as 2pm. The equation is:

ROS of leading spot fires = Distance from Point Zero / Time since 2 pm

Table 3 Indicative Rate of spread of leading spot fires between 2 and 4.30 pm

Location of furthest spot fire from Point Zero (PZ)	Distance	Duration	Maximum leap frog ROS and number of "leaps" **
Point Zero line to blue arc reported before 3.30 pm	18 km	1.5 hrs	12 kph / 2 leaps from PZ

Point Zero line to orange arc reported 3.30 - 3.45 pm	31.5 km	1.75 hrs	18 kph / 3 leaps from PZ
Point Zero line to green arc reported 3.45 – 4 pm	42 km	2 hrs	21 kph / 3 leaps from PZ
Point Zero line to red arc reported 4.15 to 4.30 and after	60 km	2.5 hrs	24 kph / 4 leaps from PZ

** The estimated number of leaps was based on capability and probability of each source area to generate long distance spotting and the respective ignition sites to develop a large flame quickly and to also generate long distance spotting. The key criteria were density of forest, presence of steep upslope runs and estimated percentage of tall gum barked eucalypts.

The increase in rate of spread of the leading spot fires during the afternoon is consistent with the increasing area burnt and the burgeoning size of the cumulative spot fire plumes as they merged through the afternoon. The maximum spread rate was achieved at 4.30pm, but then came to a sudden halt despite the gale force winds continuing. The forest area ended near Yarra Glen, meaning the firebrands were mostly falling into grassy paddocks which were not firebrand source areas. The forest firebrand source area at that time was predominantly stringybark, meaning spotting distances were probably shorter than from the gum forests earlier in the afternoon. However, it is clear there were some unreported spot fires in the Chum Creek forest area after 4.30pm (see Figure 4), because after the SW wind change, they caused deaths and destruction in that area. The Chum Creek area was some 15km from the Yarra Glen forest edge. This jump may have been a single one or it may have been a two or three step leap frog between the intervening strips of forest. Nevertheless, the fact remains that the run of spotting towards the SE stopped approx 1.3 hours before the wind changed in the Yarra Glen area to the SW at approx 5.50 pm.

The estimated number of leaps was based on capability and probability of each firebrand source area to generate long distance spotting and the respective ignition sites to develop a large flame quickly and to also generate long distance spotting. The key criteria were density of forest, presence of steep upslope runs and estimated percentage of tall gum barked eucalypts.

Regarding these calculations as indicative estimates, the average distance per leap was initially 9 (= 18 / 2) and 10.5 km (= 31.5 / 3), and later 14 (= 42 / 3) and 15 km (= 60 / 4). The times per leap from Point Zero were between 0.75 (= 1.5 / 2) and 0.6 hours (= 2.5 / 4), ie, 36 to 45 minutes, or average 40 minutes.

The two elements in the spot fire maturity theory are incubation time and airborne time. Assuming 80 kph air speed aloft, airborne times were 7 to 8 and 10 minutes respectively, average 10 minutes in round figures. This suggests average incubation time was 30 minutes (= 40 – 10). These must be regarded as ball park figures at this stage, but it seems reasonable for consideration in planning or forecasting purposes in severe bushfire conditions, ie, half hour incubation time for a spot fire and 10 minutes airborne time for the firebrand to travel 10 km downwind when winds aloft are 80 kph.

Observation 2 Firebrand source areas

The influential firebrand source areas are shown on Figures 5 to 7.
Between 2 and 3 pm, the only firebrand source area was the white oval on Figure 5.
By 3.30 pm, its extent was approx 7 km x 2 km, but most of that area was yet unburnt.

The eastern third was the most likely source of firebrands that fell into the green and blue oval areas. The green oval area was a downhill forest and therefore did not become a firebrand source area. The blue oval area was predominantly messmate forest running uphill towards the Kinglake Whittlesea Rd. It burnt intensely and probably threw medium distance firebrands into the pink area on Figure 6, which includes Humevale and Strathewen.

The average distance from the white area to the blue oval was approx 10 km, and the likely maximum throw distance at this time into the 3.30 pm reported area was 15 km.

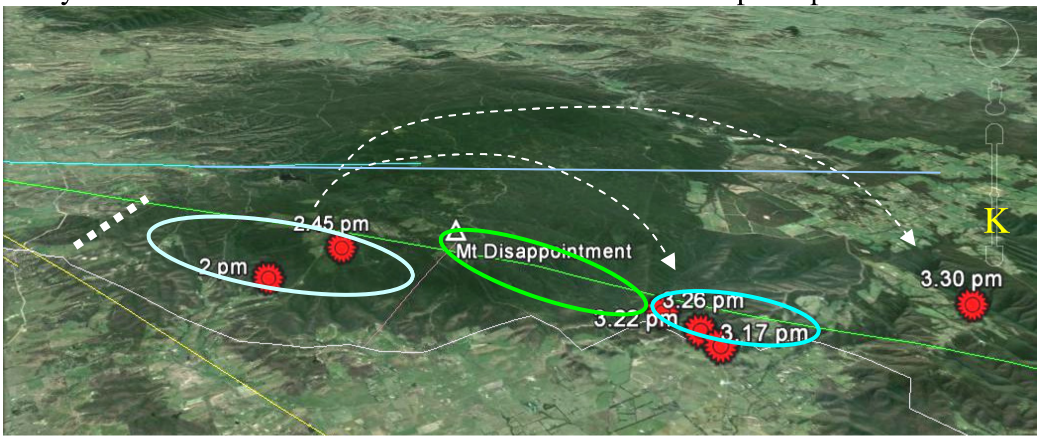


Figure 5 Oblique view, looking NE across Mt Disappointment and Kinglake (K), showing reported spot fire locations pre 3.30 pm. White dotted line is Point Zero.
Pale green line is NNW wind direction; pale blue line is NW wind direction.
Note that most spot fires are in line with NNW wind line, but the 3.30 pm spot fire is to its north.
White oval is a substantial firebrand source area. Length is 7 km , width is 2 km max.
Green oval is a forested down slope, length 5 km. Unreported spot fires will have landed within this area at this time, but it was not a firebrand source area
Blue oval area is a 3 - 4 km uphill run through forest to Kinglake Whittlesea Rd. It will become a significant firebrand source area in the next 30 minutes or so.
Distance from the 2.45 mark to blue oval is approx 10 km and to the 3.30 spot fire is approx 15 km.

From 3.30 to 4 pm, the white firebrand source area continued to generate large volumes of short, medium and long distance firebrands, and the blue oval area generated large volumes of short and medium distance firebrands. Figure 6 indicates that most would have landed within the pink area, which would become a major firebrand source area in the next period. It is theoretically possible that the most distant 4pm spot fire originated from the Mt Disappointment summit area, a distance of 36 km. It is unlikely to have originated from the blue source area unless the firebrand arose within a patch of tall gums. However, it most likely generated from a steep uphill run sites within the pink area from a spot fire that ignited soon after 3.30 pm, a throw distance of some 15 – 20 km.

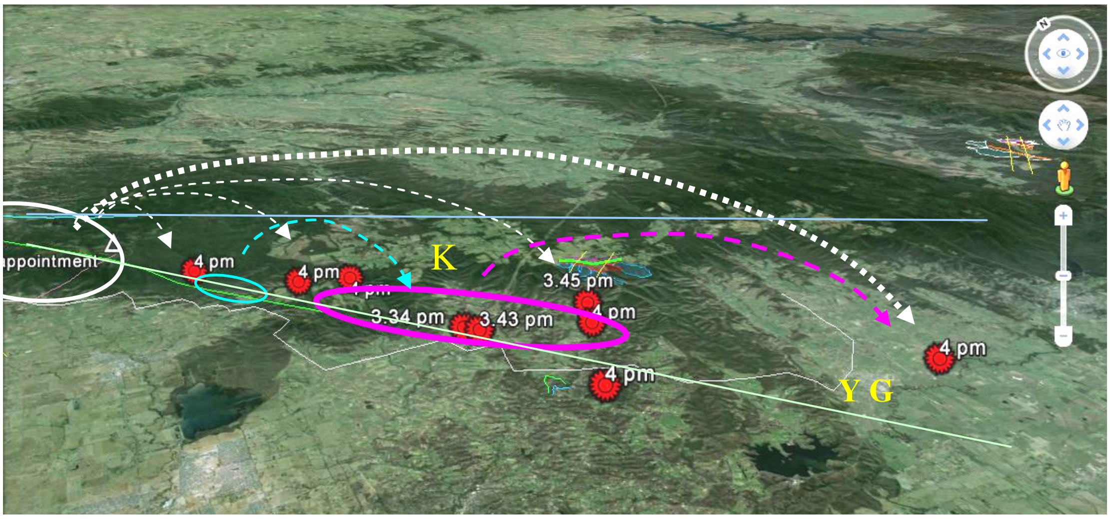


Figure 6 Oblique view, looking NE across Kinglake (K) and Yarra Glen (Y G) areas showing reported spot fire locations 3.30 to 4 pm.
Pale green line is NNW wind direction; pale blue line is NW wind direction
Note that almost all spot fires were between the NNW and NW wind lines.
White firebrand source area had now expanded to approx 10 x 3 km, throwing fire brands a few km to 25 km. Blue oval area was now 4 x 1 or 2 km, throwing short and medium distance fire brands, up to several km.
Pink area was rapidly igniting with multiple spot fires, one of which probably ignited the distant 4 pm spot fire report, a throw distance of 15+ km.
White dotted arrow indicates distance from white source area near Mt Disappointment to most distant 4 pm spot fire was approx 36 km, and therefore an unlikely source area.

After 4 pm, Figure 7 shows the pink firebrand source area expanded a further 10 km or so downwind to approx 15 x 5+ km. Spot fires burnt vigorously in National Park forest just west of Yarra Glen. White and blue firebrand source areas had by then exhausted most of their medium to long distance firebrand supply. Eastern half of the pink area was now the major source of firebrands, one of which probably ignited the distant 4.30 pm spot fire, a likely throw distance of some 30 km. Another ignited at 4.45 pm, a likely throw distance of some 15 km.

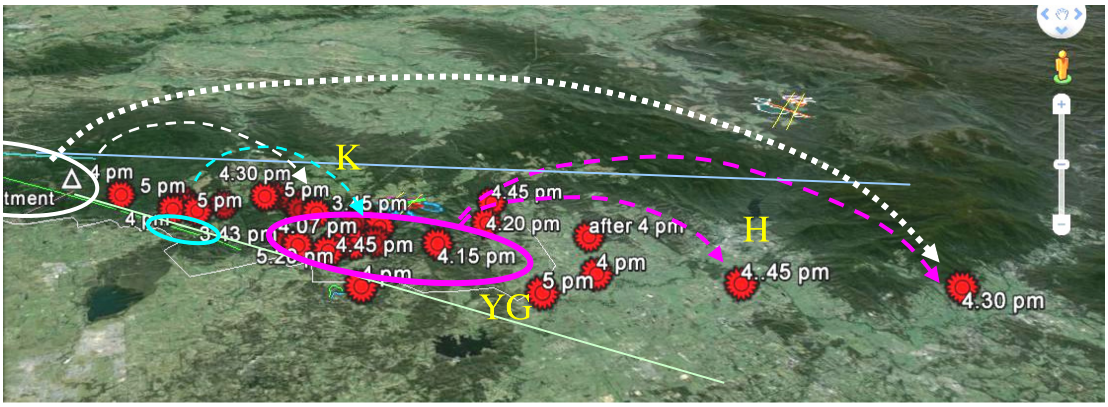


Figure 7 Oblique view, looking NE across Kinglake (K), Yarra Glen (YG) and Healesville (H) areas, showing reported spot fire locations between 4 and 4.30 pm and later.
Pale green line is NNW wind direction; pale blue line is NW wind direction
Note that all spot fires were between the NNW and NW wind lines.
White dotted arrow indicates distance from white firebrand source area near Mt Disappointment to most distant 4.30 pm spot fire was approx 55 km. It was not its source area.

Observation 3 The direction of firebrand trajectory

Figure 4 shows that the pre 3.30 pm spot fires were generally aligned with the NNW wind direction, but the post 3.30 pm spot fire reports were between the NNW and NW direction lines. On Figures 5 to 7, the pale green arrow is wind direction (= NNW) at the fire ground level until 4.30 pm, when it changed to NW. The pale blue arrow is estimated wind direction above 1000m ASL since 2pm. Thus, if firebrands remained below the 900m ASL level before 4 pm, they remained in the fire ground wind stream and spawned spot fires immediately downwind of their source areas. If they were lifted above 900 – 1200m ASL before 4 pm, they entered the NW air movement layers and spot fires ignited more northerly direction.

Figure 5 shows that most spot fires reported before 3.30 pm were in line with NNW wind line. This is consistent with a spotting direction theory A, ie, source area being in the low level foothills to the west of Mt Disappointment. The 3.30 pm spot fire is substantially to its north, which suggests the firebrand spent considerable time within the NW air stream above 1000m ASL. This is consistent with spotting direction theory B

Figure 6 shows that almost reported spot fires between 3.30 and 4 pm were clearly north of the NNW wind direction. This suggests the firebrands spent substantial time above 1000m in the NW air stream. This is consistent with a firebrand source area near the summit of Mt Disappointment, which is 800m ASL.

Figure 7 shows that all reported spot fires between after 4 pm were substantially north of the NNW wind line. Because the firebrand source areas were at low elevation, it suggests the fire ground uplift was sufficient to lift the firebrands very high into the upper air stream for most of their airborne journey.

Observation 4 Maximum spotting distances

Table 3 summarises data from Figures 5, 6 and 7. Ignition time indicates the end of a time block and spotting distance is the furthest downwind reported spot fire within that period, eg, 4 pm = 3.31 to 4pm, 4.30 pm = 4.01 to 4.30 pm.

Sensitivity: The distances are not precise because the exact source area is estimated. For example, the likely source of the 4 pm spot fire is deduced to be the eastern third of the white firebrand source area because it is the closest part of the fire to the spot fire and is likely to be the most vigorous. By that time, the white area was approx 10 km long. The spotting distance was assigned as 25 km, but it is reasonable to apply a 10% margin of error to account for two unknown variables, (1) if the source was the eastern third, the source site has a 3 km range, and (2) if the source was in the central third.

Table 3 Estimated maximum spotting distances and likely firebrand source areas

Spot fire ignition time / **Likely firebrand source area**	**3.30 pm**	**4 pm**	**4.30 pm**	**4.45.pm**
White	10 and 15 km	25 km	< 10 km	
Blue		10 km	< 10 km	
Pink		15 km	25 km	15 km

The possibility exists that the source area for the distant 4 pm spot fire was near the Mt Disappointment summit area. To achieve a 35 km distance would require 30 min (1800 sec) of airborne time in aloft winds of 80 kph (22 m/sec). Accounting for the terminal velocity of 6 or 7 m /sec, this means the firebrand must have been well above 10,000 m by 3.30 pm. Whilst it was possible, it is unlikely there was sufficient uplift at that time.

DISCUSSION

The rate of spread of leading spot fires after Point Zero was 24 kph. This rate of spread can be distinguished from ROS of the original mother fire front and the speed of individual spot fire fronts. Luke and McArthur (1978) said that once the spotting process starts, the fire appears to accelerate in a series of jumps or surges. "The apparent rate of spread can be very high but does not represent the movement of the true flame front" (P 106). VBRC evidence suggests that the fire control teams were unaware of the speed or impact of rapid long distance leap frog spotting.

Three major firebrand source areas were identified. Based on Project Vesta (2007) observations and local knowledge, the criteria to qualify as a source area for firebrands include density of forest, species of eucalypt (especially proportion of gum bark or rough barked species), steep upslope runs, capability of rapid 3D flame development and high volume spot fire production, as indicated by age since previous fire.

The average spotting direction from Point Zero at approx 2pm was WNW to NW when the prevailing wind direction at fire ground level was NNW. The wind direction above 3000m was NW and WNW. Therefore, the upper wind direction had predominant influence on spotting direction. VBRC evidence suggests that the fire control teams were unaware of the true spot fire direction. They believed the fire was being driven by on the ground wind direction.

Based on the longest part of the spotting distance equation, free falling time at terminal velocity of 5-7 m/sec when wind aloft is 72kph, a feasible maximum spotting distance was 20 km. The potential for 35+km spotting was remote because, according to current theory, it required elevation of 10,000m.

Comparison with current prediction tools

McArthur's (1967) Meter does not predict ROS of spotting but notes that the prediction table incorporates the booster effect of short distance spotting, especially ignitions within 400 – 800m ahead, which have "an immediate effect on rate of spread". The maximum ROS on the Tables is 3kph, so presumably this is the mother flame front under influence of massive short distance spotting. Luke and McArthur (1978) distinguish between original fire front ROS and "apparent ROS" due to spotting surges.

McArthur's Meter (1967) predicts average spotting distance, approximating 3 x ROS. The deduced algorithm from the McArthur's Meter is as follows:

Average spotting distance (km) = 3.4 x predicted ROS (kph) – 0.3

Examples in severe weather, when FDI = 100:
When Meter predicts ROS at 1 kph, average spotting distance is 3.1 km
When Meter predicts ROS at 3 kph, average spotting distance is 9.6 km
This study estimates that ***maximum spotting distances*** were 14 to 20 km, which suggests that the McArthur Meter underestimated substantially.

By deduction, the ***speed of the leading spot fires*** are 4.1 kph (1 + 3.1) and 12.6 kph (= 3 + 9.6) respectively. As the observed ROS of leading spot fires was 24 kph, the McArthur Meter again underestimated substantially.

Project Vesta displays a sample provisional table for predicting maximum spotting distances (Project Vesta, 2007 - Appendix V111, Table 1). The input variables are Vesta's predicted ROS of flame front and open station wind speed. The algorithm is not provided, but for a given ROS, maximum spotting distance (MSD) decreases with increasing wind speed to the power -0.33 (0.3 – 0.36)
(***MSD in metres = 2000 x wind ^-0.36***)
Also, for a given wind speed, maximum spotting distance increases linearly with predicted ROS. (***MSD in metres = 0.95 to 1.2 x predicted ROS (in m/hr) – 260)***

Examples for severe weather, when wind in open is 50 kph:
When Vesta predicts flame ROS at 1 kph, maximum spotting distance is 0.7 km
When Vesta predicts flame ROS at 3 kph, maximum spotting distance is 2.6 km
When Vesta predicts flame ROS at 7 kph, maximum spotting distance is 6.4 km
This study estimates that ***maximum spotting distances*** were 14 to 20 km, which suggests that the Vesta underestimated substantially.

By deduction, the speed of the ***leading spot fires*** are 1.7 kph (1 + 0.7), 5.6 kph (= 3 + 2.6) and 13.6 kph (= 7 + 6.4) respectively. As the observed ROS of leading spot fires was 24 kph, Vesta again underestimated substantially.

To conclude so far, spot fire behaviour prediction by both Vesta and McArthur use predicted ROS as a key independent variable to predict spotting distances, yet there is no evidence for a causal correlation. In fact, the opposite is true. The core causal variables for maximum spotting distance are uplift plume velocity and wind speeds in upper atmosphere, and the core variable for ROS is wind speed at fire ground level. This helps explain their awry predictions. As such, neither is helpful in understanding spot fire behaviour.

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Appendix

How to use knowledge of Black Saturday spot fire behaviour to manage defence against spot fire attacks - preparedness and response

Until risk of live firebrand escapes from known source areas is eliminated, firebrands must be regarded as an inevitable component of a bushfire attack. To ensure lives and assets are protected, they must therefore be professionally managed within an environment made safe beforehand for fire fighters and residents.

Preparedness
Fire agency role
Protect towns with perimeter infrastructure that stops the running fire at a safe distance away.
Eliminate risk of lighted firebrands escaping from known source areas upwind or down hill from a town or settlement or other flammable asset.
Prepare internal neighbourhood areas to deal with ember attack

    Prepare residents to expect ember attack
    Train residents to manage spot fire ignitions
    Coordinate residents to manage spot fire ignitions

Residents' role
Residents should expect firebrands and protect their assets against firebrand attack. Property owner will expect that firebrands will arrive and that spot fires will ignite in flammable fuel. Therefore, define a no flame zone that will be used for active asset defence against spot fires that ignite within it. A no flame zone is achieved when known flammable sites within it are made non flammable.
Understand that legally, each property owner has duty of care to prevent spread of lighted firebrands from their property.

Suppression
Fire authority role
Expect that in forested landscapes, firebrands spread by medium and long distance spotting.
Be aware if wind speed and direction in upper atmosphere is different to fire ground level.
Fire fighters must suppress medium and long distance spot fires when small.
If towns are adequately prepared to stop the moving flame beforehand, safe defence against firebrand attack is achievable using existing fire agency resources.
If safe defence is not achievable, the fire authorities must be held accountable for consequences.

Residents' role
Remain in pre prepared asset protection zone to patrol and to extinguish unexpected spot fire ignitions when small.