Reconstruction of the path and behaviour of the Lower Hotham fire

31 January – 6 February 2015

[1]Neil Burrows, [2]Paul Rampant and [2]Theo Menne

[1]Science and Conservation Division; [2]GIS Branch Corporate Services Division

Department of Parks and Wildlife

May 2015

(Photo courtesy Leigh Sage DPaW)

Summary

The Lower Hotham fire was one of two large bushfires in south-west WA that were started by lightning strikes in January 2015. Over seven days, this fire burnt ~52,000 ha of forest and farmland. Fortunately, there was no loss of life, no severe injuries and relatively minor damage to property and infrastructure. However, the physical and environmental damage to the forest and its wildlife was considerable and it will take many decades to fully recover.

During the course of its run, this fire displayed extreme and unpredictable fire behaviour with violent pyro-convection and formation of pyro-cumulonimbus cloud. Head fire rate of spread and fire intensity peaked at ~3.7 km/h and ~45,000 Kw/m respectively, and spotting was up to 5 km. Flame heights in excess of 30 m resulted in about 60% of the forest being defoliated as a consequence of high intensity crown fire. At times, observed rates of spread were up to double that expected and predicted by the Vesta fire behaviour model, suggesting that this fire may have created its own fire winds when it transitioned from a surface-driven fire, to a 'plume-driven' fire. Plume-driven, or atmosphere- coupled fires are poorly understood, but occur when strong convection columns resulting from high energy release fires create strong in-drafts at the flaming zone. In addition to heavy, dry forest fuels and steep slopes, spot fires ahead of the main fire may have been an important factor contributing to the development of extreme fire behaviour, especially in complex terrain.

Although the Forest Fire Danger Rating was <40 (Very High), this fire became large, intense and was difficult, dangerous and expensive to control. Apart from 3 year old fuels in Hakea forest, which stopped the westerly spread of the fire in its initial stages, it burnt in long unburnt, dry forest fuels, and at times, complex terrain. Of the factors contributing to the severity of this fire, management can only influence fuel hazard by prescribed burning. The large area and perimeter of recently burnt forest now provides an opportunity to safely carry out prescribed burning in the region to reduce the future potential for large fires that could threaten communities and damage infrastructure and the environment.

1. Introduction

The Lower Hotham fire between the towns of Harvey, Collie, Boddington and Quindanning (Fig. 1) was one of two large bushfires that occurred in the south-west forest region of Western Australia in late January-early February 2015. Over 7 days, it burnt about 52,000 ha of which 45,000 ha was native forest managed by the Department of Parks and Wildlife (DPaW) and 7,000 ha was private property comprising forest, woodland and cleared farm land. Of the forest and woodland burnt, about 60% was totally defoliated and 30% was fully scorched. This level of canopy damage reflects the overall severity of the fire, with defoliation being the result of high intensity crowning fire. Despite the size and severity of the fire, there was no loss of life or serious injury and relatively little property and infrastructure damage. The area and perimeter growth of the fire is shown in Figure 2.

This report focuses on the path and behaviour of the Lower Hotham fire from its origin on 31 January 2015 until its shape stabilised and the fire was essentially contained around midday on the 6 February.

It is important that significant landscape fires are formerly analysed and documented, not only for the record, but to better understand fire behaviour in relation to the prevailing fuel, meteorological and topographical conditions. An analysis of such fires can also inform fire management strategies aimed at reducing the risk of large fires that can threaten communities and other values. The Lower Hotham fire at times displayed significant and surprising fire behaviour and had the potential to threaten settlements, farms, mining and other infrastructure and utilities. While the McArthur

Forest Fire Danger Index (FFDI) was mostly in the range Moderate to High, with brief periods of Very High, the fire was difficult, dangerous and very costly to suppress because:

- fuels were dry,
- forest fuels were long unburnt,
- terrain was steep and difficult to access, particularly in the northern and western portion of the fire ground.

The damage potential and suppression difficulty of a bushfire is directly related to its behaviour (rate of spread, flame dimensions, size, spotting potential and intensity) so this report also discusses factors that contributed significantly to the fire's behaviour. It is not the purpose of this report to analyse fire suppression strategies, tactics and resources deployed on the fire.

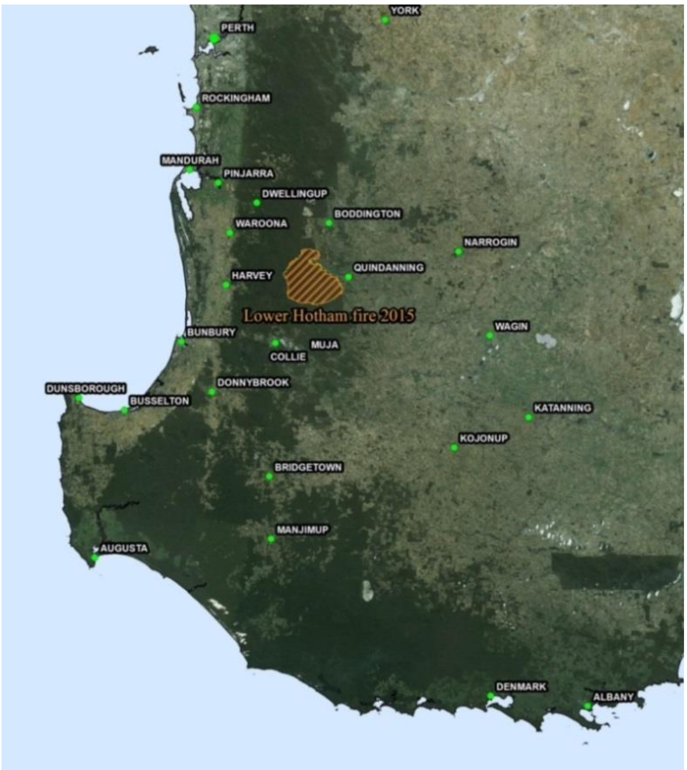


Figure 1: Location of the Lower Hotham fire in south-west Western Australia

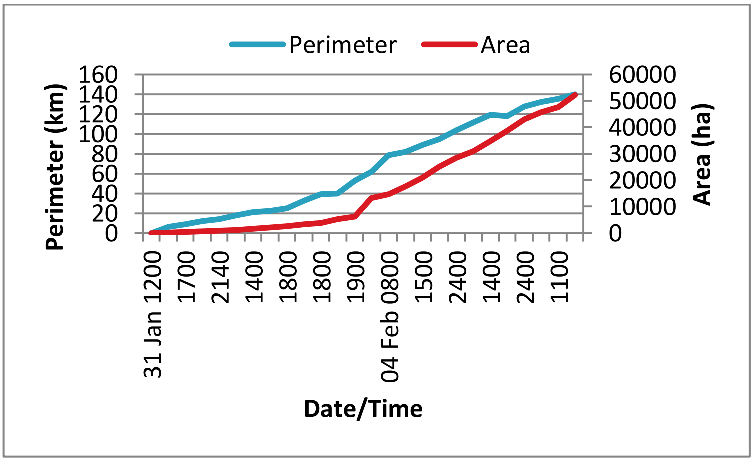


Figure 2: Increase in area and perimeter of the Lower Hotham fire from its origin on 31 January 2015 to when its shape stabilised ~1100 hrs on 6 February 2015.

2. Methods

Structure of this report

First, an overview of the fire environment, being the regional condition of fuels, drought, topography, meteorology and weather that prevailed for the duration of the fire is presented. The path and behaviour of the fire is reconstructed in phases, each phase being associated with significant fire runs, usually in response to wind shifts. For the purpose of this reconstruction, five phases are recognised:

Phase 1: 31 January to 2 February (run west from the origin)

Phase 2: 3 February (run south-west)

Phase 3: 3-4 February (run south)

Phase 4: 4-5 February (run east)

Phase 5: 5-6 February (run north)

For each phase, details about weather, fuels, topography and fire behaviour are presented and discussed. Information about the location and behaviour of the fire at various times was reconstructed using evidence from a variety of sources including:

- Documents such as fire perimeter maps from the Incident Management Teams, office logs, Incident Action Plans, aircraft operations logs, fire fighter's dairies.
- Interviews with fire fighters including aerial observers.
- Photographs (including stills and video from aerial observes, Western Shield trail cameras, post-fire high resolution vertical aerial photos), satellite imagery (Landsat and MODIS), IR line scanner imagery (limited), and the Bureau of Meteorology's (BoM) Serpentine radar.
- Fire ground evidence (defoliation, scorch, stem char, vegetation freeze, fuel consumption). Vegetation 'freeze' refers to the orientation of scorched leaves, twigs and finer shrub stems following the passage of the flames. The heat of the flames makes finer plant material supple and those components that are scorched but not consumed are bent by the wind. On cooling, the vegetation remains 'frozen' in this direction (pointing downwind). Freeze is very useful for determining wind direction at a location, and for finding changes in wind direction. From this, the direction of head fire run can be inferred. It can also be used as a crude indicator of wind strength – the more pronounced the freeze (greater freeze angle), generally, the stronger the wind. Freeze is sometimes difficult to find under conditions of extreme fire behaviour when fine material has been consumed, and under conditions of very mild fire behaviour usually associated with calm or light wind conditions.
- Vesta fire spread and fuel moisture content predictions.
- Fuel age plans from DPaW's Fire Management Services.

Post-fire high resolution aerial photography and subsequent classification and patterning of overstorey canopy damage was valuable in reconstructing the fire's path and aspects of its behaviour. Four band (RGB and NIR) imagery was captured approximately 2 weeks after the fire. Data were captured with 30 cm pixels but for this analysis the imagery was resampled to 3 m pixels. The analysis provided a classified image delineating forest areas with green canopy, scorched canopy, defoliated canopy and cleared areas (gravel pits, roads, etc.). Ashbed from burning logs was also clearly visible and was categorised with the cleared areas. Analysis was performed in ENVI® image analysis software and processing was performed using decision tree analysis. The result was a high resolution map of canopy damage categories (Fig. 3).

There are no weather stations in close proximity to the fire ground, the nearest stations being the Department of Agriculture and Food's (DAFWA) automatic weather stations (AWS) at Marradong (32.86S; 116.45E), ~12 km north-east of the northern boundary of the fire ground, and at Harvey, ~35 km south-west of the western boundary, and the BoM weather station at Collie East (33.36S; 116.17E), ~20 km south of the southern boundary of the fire. Generally, the Harvey AWS wind speeds were about 25% higher, up to 45^{o} different in direction, temperatures were generally lower by several degrees and RH higher by 5-10% than Marradong and Collie East so data from Harvey AWS were not used.

The BoM Collie East AWS observations were similar to those recorded at Marradong. Average wind speeds measured at Collie East were generally 5-10% higher than Marradong, but the maximum wind speeds at Marradong were generally 10-15% higher than Collie East. Based on proximity, the Marradong AWS data were used for phases 1, 2 and 3 of the fire, while Collie East data were used for phases 4 and 5. The Marradong anemometer is mounted 3 m above ground so a correction factor of 1.3 was applied to standardise wind speed to the equivalent of a 10 m above ground open wind speed (L. McCaw pers. com.). The anemometer at the Collie East station is at 10 m in the open so no corrections were necessary.

Vesta fire behaviour predictions were made using Newland's Excel spread sheets (DPaW) and averaging the observed (AWS) weather and calculated (Vesta) surface fuel moisture (SMC) conditions for the prediction period. For comparison, fire behaviour predictions were also made using spot weather forecasts provided by the BoM throughout the fire. In making Vesta predictions, we assumed;

- weather conditions observed at the nearest AWS was representative of weather experienced at the fire ground,
- average conditions of weather, fuel moisture content, fuel hazard (Vesta) and slope over the prediction period was representative of average conditions over the fire ground for that period.
- slope was the net slope of the fire run from the start to the finish of the prediction period.
- observed locations of the fire were of the main fire and not spot fires ahead of the main fire. Spotting was a feature of this fire, but its specific influence on the behaviour of the main fire is unknown.

Recent fire history was obtained from DPaW fuel age plans which show years before present that various forest blocks were burnt either by prescribed fire or wildfire. The Vesta fuel hazard classifications were applied based on time since last fire and whether the forest was in the higher rainfall area west of the Muja-Boddington power line (jarrah north west) or the lower rainfall area east of the power line (jarrah east). Topography (slope and aspect) were obtained from DPaW COG maps and from Google Earth.

It should be noted that due to the large scale of the fire and the limited field intelligence on the fire's behaviour and location at various times, the reconstructed fire isochrones (location of the fire perimeter at various times) shown here are approximations by reconstruction based on the available (above) evidence. As discussed above, the reconstruction assumes that ground and aerial observations of the fire's position were of the main fire and not spot fires in advance of the fire.

3. Overview of the Lower Hotham fire environment

Land use, vegetation, fuels and topography

The fire was started by a lightning strike to a marri tree in a grass paddock on private property farmland before burning into native bushland. The structure and fuel load of the grass in the initial phase of the fire was variable, ranging from partially eaten out pastures (<0.3m high; fuel load <2.5 t/ha) to ungrazed wild oats and other grasses to 1 m high (fuel load ~3-4 t/ha). Most (~87%) of the area burnt was forest managed by the Department of Parks and Wildlife for a range of purposes including wildlife conservation, recreation and amenity, mining and timber production. A breakdown of the area burnt by severity classes for each forest block involved in the fire is provided in Table 1. Important utilities and infrastructure such as a mining conveyor belt, high voltage power transmission lines, road transport corridors, timber bridges and culverts, and recreation sites were affected by the fire.

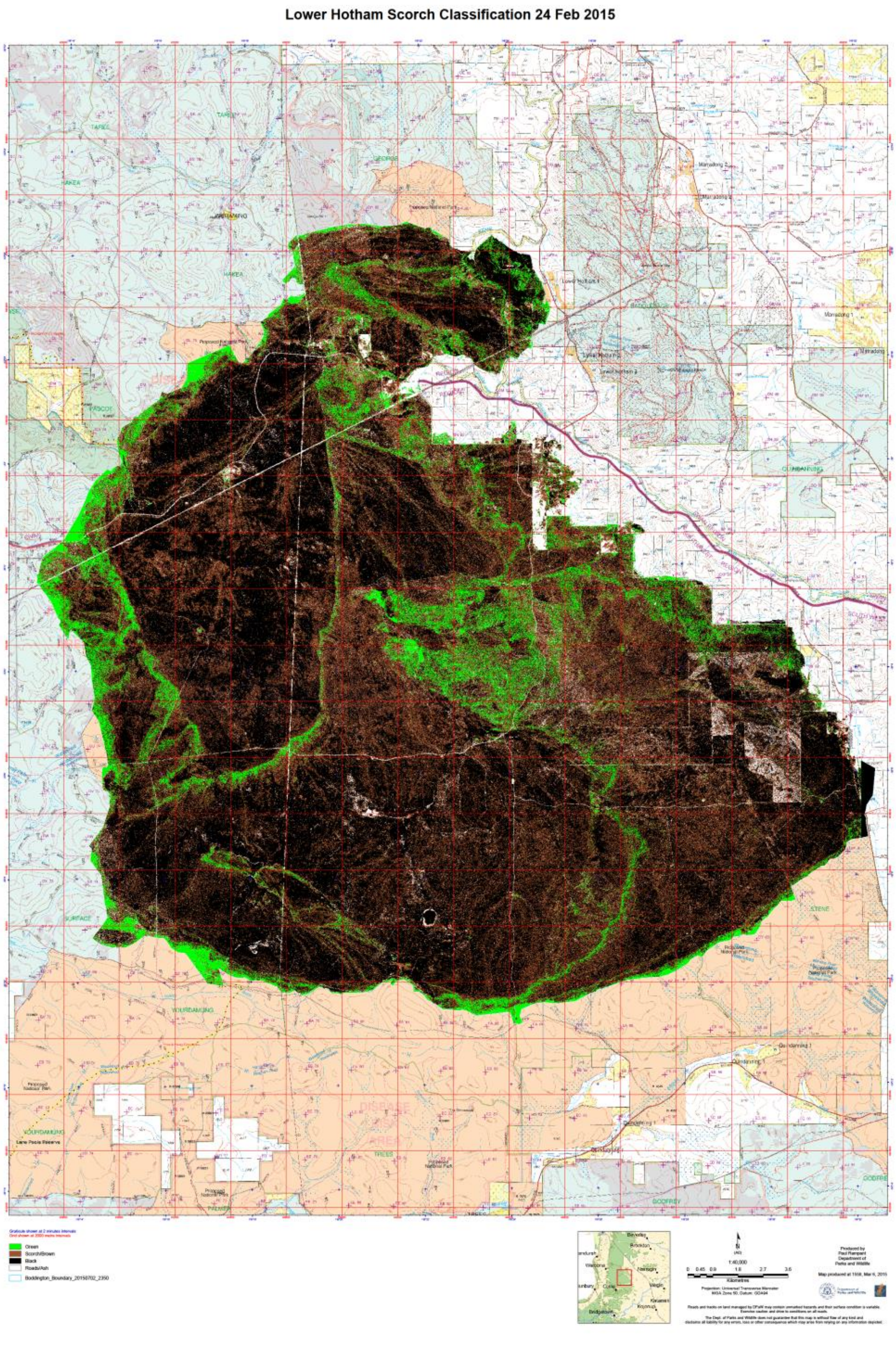


Figure 3: Aerial photo mosaic of the ~52,000 ha Lower Hotham fire showing defoliated (black), fully scorched (brown), unscorched or partial scorched canopy (green) and cleared areas/ashbed (white). About 60% of the forest area was defoliated. Note green bands and patches associated with a) low fire intensity at night, b) 5 year old fuels in Bednall forest (centre) and c) edging.

Plate 1: Farmland-forest interface – north-east boundary of the Lower Hotham fire

Forest block	Fuel Age (yrs)	Area of forest block (ha)	Area burnt (ha)	Area low scorch (%)	Area full scorch (%)	Area defoliated (%)	Area roads, ashbed (%)
Bednall	5	5094	5094	13.9	39.6	42.7	3.8
Bell	9	5313	5313	6.0	33.8	55.9	4.3
Chalk	6,7,10	10256	7113	8.7	26.6	63.5	2.5
George	15,26	6122	2201	7.0	37.9	50.1	4.2
Hakea	3	4849	263	11.0	34.2	47.9	6.8
Morgan	9	4118	4083	9.9	42.7	42.5	4.8
Nalyerin	11	9670	7414	1.8	23.7	71.5	3.0
Pascoe	9,18,23	3752	2112	5.6	22.4	68.7	3.3
Stene	12	5975	2901	2.7	25.9	69.3	2.1
Stockyard	8	5787	3991	4.3	35.6	58.1	2.1
Surface	5,7	5955	4479	4.8	23.8	68.3	3.1
Tumlo	16,19	6523	303	29.3	36.9	29.0	4.6
Private property bush & pasture	Bush 35+		6801	7.3	30.4	51.2	1.2
Total/overall			**52068 ha**	**6.4%**	**30.8%**	**58.4%**	**4.4%**

Table 1: Fuel age, area burnt and canopy damage levels for various forest blocks and private property.

Plate 2: 8 yo 'jarrah east' fuels in Stockyard forest block.

Vegetation in the higher rainfall western portion of the fire, approximately west of the Muja-Boddington 81 power line, is predominantly tall open forest of jarrah (*Eucalyptus marginata)* and marri (*Corymbia calophylla)* to 30 m on lateritic uplands with a mid-canopy of scattered bull banksia (*Banksia grandis)* and sheoak (*Alocasuarina fraseriana)* and an open understory of woody shrubs to 1-1.5 m. Vegetation on low lying areas and valley floors is a mosaic of closed shrubby swamps comprising *Myrtaceae* spp. to 1.5 m and sedgelands of *Baumea* and *Leptocarpus* spp. The drier eastern portion (approximately east of the power line) is predominantly open forest of *E. marginata* and *C. calophylla* to 20 m on lateritic uplands and plateaus with a low open understory <0.5 m. Wandoo (*E. wandoo*) forests/woodlands with a low open understorey occur on valley floors and adjoining slopes. Also making up the mosaic are depressions and swamps comprising *Myrtaceae* spp. shrublands.

The recent fire history (prior to this bushfire) is shown in Figure 4. Key fire management objectives on lands managed by DPaW are to minimise the risk of damaging wildfires to communities, infrastructure and a range of forest values (including amenity, water and timber), and to protect and maintain forest ecosystem health. Since the 1960s, prescribed burning has been the cornerstone of fire management and integral to achieving community protection, conservation and other land management outcomes. However, for a variety of reasons including climate variability, land use changes, population growth and resource constraints, the prescribed burning program has been falling behind targets since the 1990s. This has resulted in an increasing area of the forest landscape carrying long unburnt, heavy, flammable fuel. Large areas of relatively long unburnt vegetation contributed significantly to the size, behaviour and suppression difficulty of this fire. In order to increase the likelihood of suppressing summer wildfires while they are relatively small, about 40-50% of the landscape must be carrying fuels <5 years old, with most of the remaining landscape being < 6-7 years old. Small patches of older habitats are not only acceptable but often desirable for conservation reasons. As can be seen from Table 1, Figures 4 and 5, the vegetation/fuels burnt during this fire were mostly older than 5 years.

Young (3 yo) fuel in the eastern portion of Hakea forest block stopped the westerly progress of the head fire in the early stages (phase 1), and 5 yo fuel in Bednall forest block reduced rate of spread and fire intensity in the latter stages.

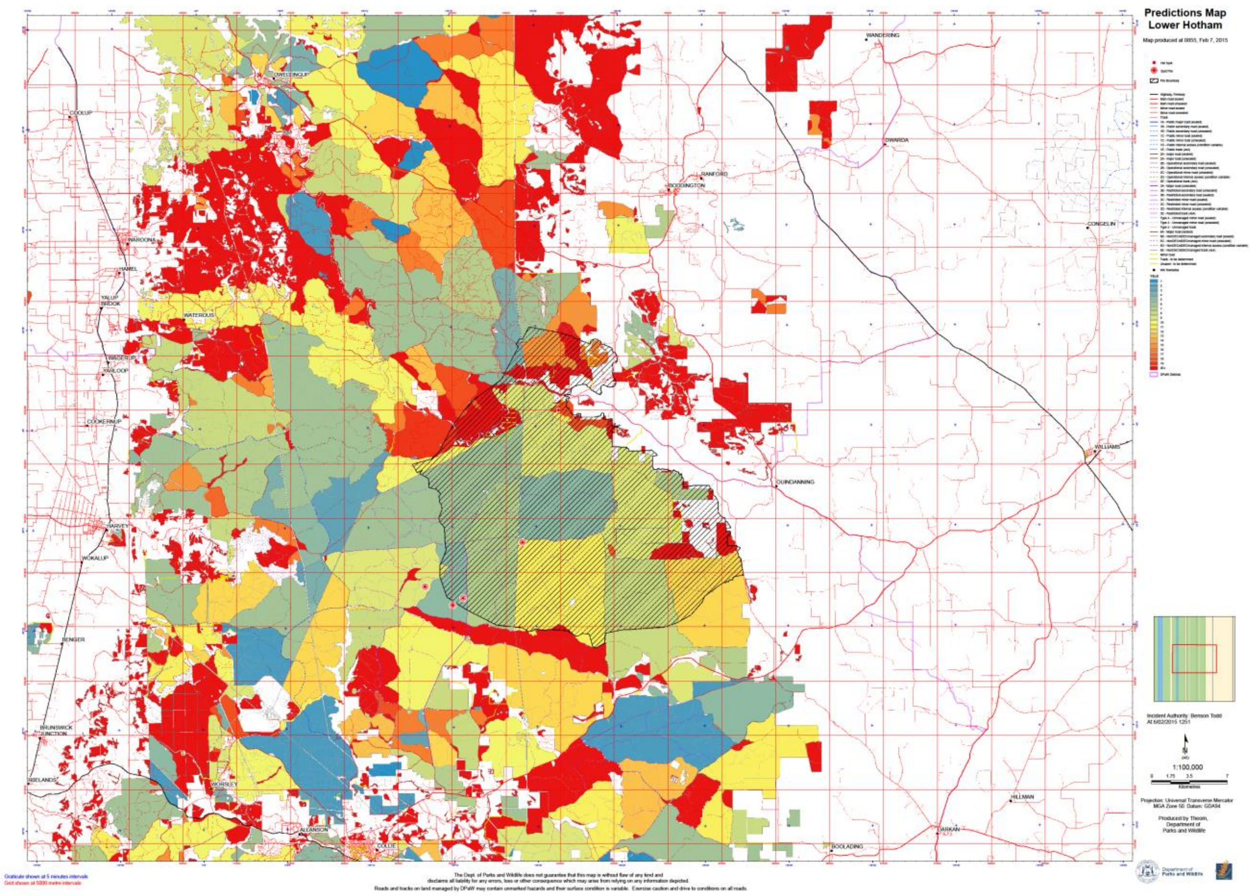


Figure 4: Recent fire history (DPaW-managed land) of the Lower Hotham fire ground (shaded) and surrounding landscapes prior to the fire.Blue= 1-4; Green = 5-7; Yellow = 8-12; Orange = 13-18; Red = 18+

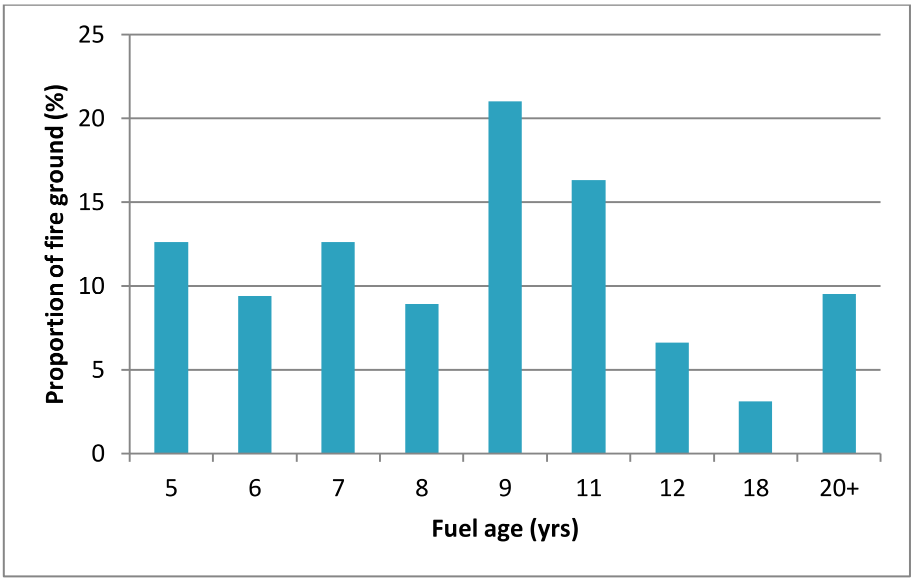


Figure 5: The proportion of the Lower Hotham fire ground by fuel age prior to the fire. Of the native forest/woodlands burnt, about 88% carried fuels older than 5 years.

Regional climate, drought factor and topography

The climate of the region is typical Mediterranean-type with cool wet winters and warm to hot dry summers. There is a strong rainfall gradient, with rainfall declining from west to east. Annual average rainfall varies across the fire ground from ~900 mm in the west to ~700 mm in the east. The following antecedent weather conditions were derived from the DAFWA AWS at Marradong and the BoM AWS at Collie East.

Prior to the re-ignition and escape of the fire (31 January 2015) the last significant rainfall events (>5 mm) were on 27 November 2014 (11.2 mm at Marradong; 13.6 mm at Collie East) and 29th/30th January 2015 (6.2 mm at Marradong), the latter being associated with patchy thunderstorm activity. The Soil Dryness Index (SDI) is a measure of regional dryness or 'drought' and ranges from 0 when the surface soil (top 30-40 cm) is saturated (field capacity) to 2000 (200 – Fig. 6) when the surface soil is dry. During the fire run, the SDI at Collie East peaked at ~1700 (170), some 240 (24) points higher than the average value at the same time for the past five years. This indicates that surface soil, heavy forest fuels including logs and deeper forest fuel profiles, were exceptionally dry for this time of year, as was the forest understorey and bark on standing trees. Grass in paddocks was 100% cured.

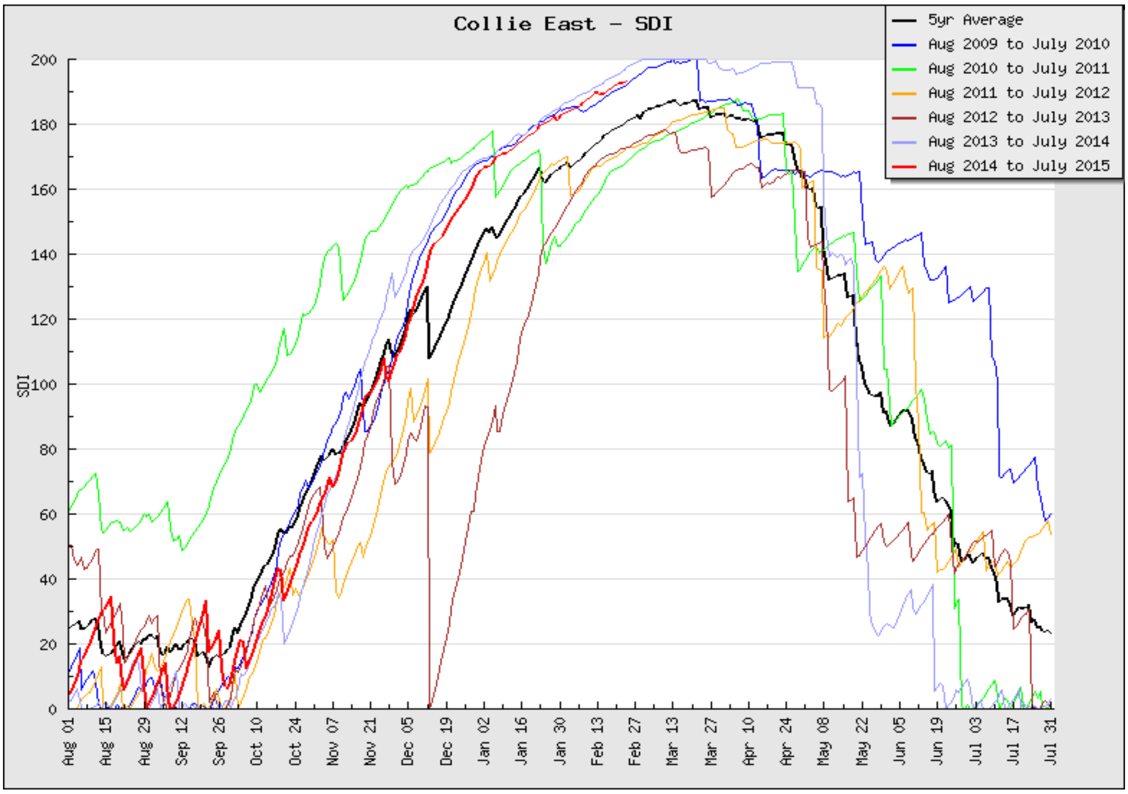


Figure 6: The last 6 years of Soil Dryness Index (SDI) for Collie East, ~20 km south of the fire ground (source: BoM).

Synoptic situation and atmospheric stability

During the summer months, a high in the Southern Ocean or Great Australian Bight, and the west coast trough are regular features of the synoptic chart for WA and are dominant features of weather experienced in the south-west. Typically, areas east of the trough experience hot, dry winds from the north-east whereas areas to the west experience mild, cooler weather associated with southerly breezes. Atmospheric instability and thunderstorms are common features east of the trough line. The pattern of trough formation and movement is variable and sometimes difficult to predict accurately, but usually the systems move east with the general weather pattern within a couple days of formation. However troughs can persist for extended periods, particularly in association with extended periods of very hot weather in the northern interior/Pilbara region of the state. Movement of the weather systems from west to east is accompanied by changing temperature, moisture, wind speed and wind direction. As the high pressure system moves east, winds back from the east in an anticlockwise direction. Generally, if bushfires burning in heavy, dry forest fuels are not controlled in the initial stages and before the anti-clockwise movement in wind direction, they usually become large as long flank fires become wide head fires.

The synoptic charts in Figure 7 show the position of the trough and the high pressure system at 1400 hrs on 29 and 30 January. An interesting feature of these charts is the persistence of the west coast trough. Over this time, and through to 4 February, lightning associated with the trough started 16 bushfires in the Wellington (Collie) DPaW District alone. Twelve of these fires were contained to less than 2 ha, two were contained to less than 10 ha and one fire (Addison Road) was contained to 456 ha. It was also during this period that a lightning strike started a fire on private property, which eventually became the Lower Hotham fire. The synoptic charts also illustrate the eastward movement of the high pressure system and associated anti-clockwise backing in wind direction over the period when the fire was most active.

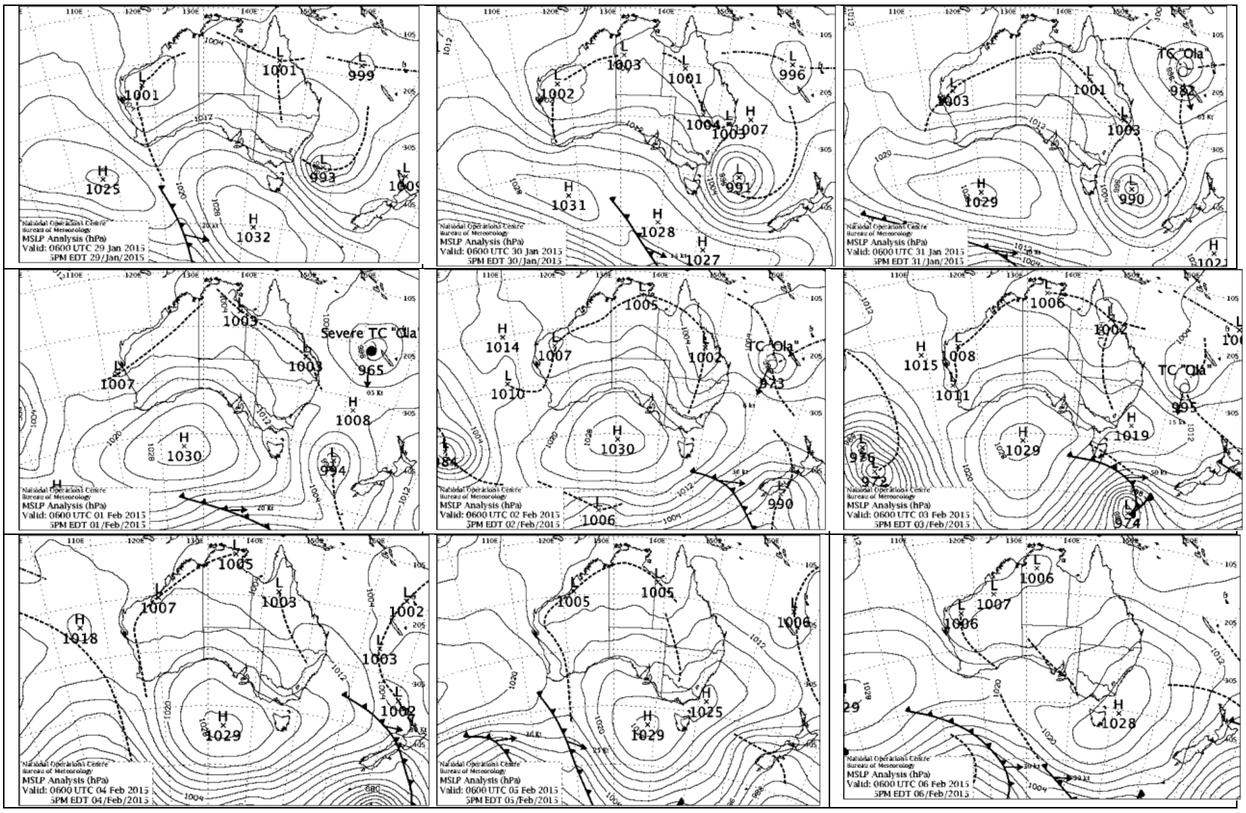


Figure 7: 0600UTC daily synoptic (weather) charts for the period of the Lower Hotham fire from 29 January (top left) to 6 February 2015 (bottom right). A high in the Bight and a lingering west coast trough are features that influenced this fire.

Atmospheric stability

Atmospheric stability, or the rate of change of air temperature with altitude, can influence fire behaviour through its influence on the buoyancy or rate of rise (kinetic energy) of the convection column. Atmospheric air temperature usually decreases with increasing altitude (environmental lapse rate - ELR), although the actual rate of cooling varies in space and time. At some altitudes air temperature may increase with increasing altitude (temperature inversion). A smoke plume, or convection column, rises because it is warmer and therefore less dense than the surrounding air. As it rises, it expands and cools at about 10^{o} C per 1000 m (dry adiabatic lapse rate - DALR) and providing it is warmer than the surrounding air, it will continue to rise. A stable atmosphere exists when the ELR < DALR and an unstable one exists when the ELR>DALR. Extreme or erratic fire behaviour is usually associated with an unstable atmosphere because of the increased kinetic energy or buoyancy of the convection column. Beyond recognising broad associations, our knowledge of the complex processes and interactions between bushfires and the upper atmosphere is limited and documenting large fire events such as this provides an opportunity to improve our knowledge.

Aerological diagrams constructed from BoM balloon flights provide information about the vertical structure of temperature, moisture (dew point) and winds in the upper atmosphere so can be used to determine atmospheric stability and to provide information about the strength and dryness of winds aloft. The diagrams can also detect layers of warm, very dry air (dry slots) and there is some evidence that, under some circumstances, bushfires can induce mixing of dry slots to the surface, significantly influencing fire behaviour. Aerological diagrams (balloon flights ex Perth) for 0800 hrs daily over the period of the Lower Hotham fire are shown in Figure 8. Below is a summary of the interesting features (to 500 hPa; ~ 6,000 m) of these diagrams from a bushfire context. Apart from 31 January, there does not appear to be any indication in the diagrams by way of dry slots or unstable conditions that is likely to significantly influence surface burning conditions.

31 Jan: Neutral. Radiation inversion. Dry slot? strong ENE winds 800-1000 m
1 Jan to 4 Feb: Neutral to stable. Radiation inversions.
5 Feb: Stable. Radiation inversion. Warm dry air mass 1000 m – 3000 m

There are a number of measures of atmospheric stability at various altitudes including the continuous Haines Index (c-Haines). Interpreting the c-Haines index in relation to potential fire behaviour should be done in a local context rather than an absolute one, so recognising unusually high index values for the south-west region may indicate potential for unusual fire behaviour. The 95th percentile c-Haines value for the Perth region (September to April) is ~8.8, so values above this could be significant. Over the period of the Lower Hotham fire, the index was relatively high (8-10 – 10+ (source – BoM ACCESS Regional)) on 31 January and 3 and 4 February but was otherwise not unusual. In addition to the BoM charts, we manually calculated the c-Haines for 31 January and 3 and 4 February (periods of most active fire behaviour) as follows:
Temperature Depression term: CA = (T850-T700)/2 -2
Dew Point Depression term: CB = (T850-TD850)/3 -1
If (CB > 9) then CB = 9; If(CB > 5) then CB = 5+(CB-5)/2
Data used were for Perth 00Z time (0800 hrs). Raw data were accessed from the University of Wyoming Dpt. of Atmospheric Science website.
31 Jan:
T850 = 20.0°C, DP850 = -2.0°C, T700 = 5.4°C
CA = (20.0-5.4)/2 – 2 = 5.3
CB = (20.0+2)/3 – 1 = 6.3
c-Haines = CA+CB = 11.6
3 Feb:
T850 = 20.0°C, DP850= 3.0C, T700 = 5.6°C.
CA = (20.0-5.6)/2 -2 = 5.2
CB = (20.0 - 3)/3 -1 = 4.6
C-Haines = CA+CB = 9.8
4 Feb:
T850 = 19.0°C, DP850 = 3.0°C, T700 = 8.6°C
CA = (19.0-8.6)/2 – 2 = 4.2
CB = (19.0-3.0)/3 – 1 = 4.3
c-Haines = CA+CB = 8.5

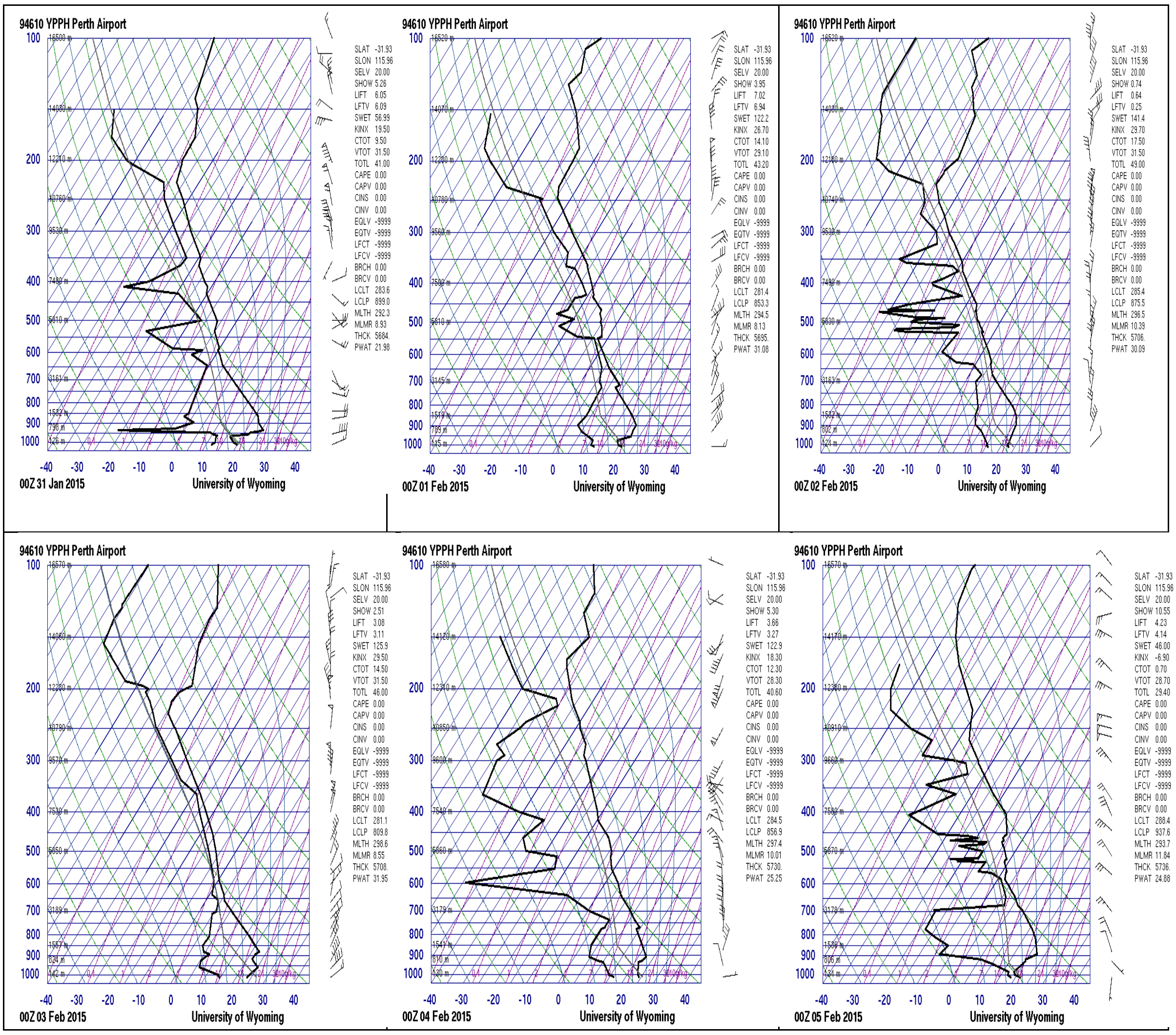


Figure 8: Daily (00UTC – 0800hrs WST) aerological diagrams from near Perth for the period of the Lower Hotham fire. Top left = 31 January, bottom right is 5 February.

4. Reconstructing the Lower Hotham fire

As discussed above, for the purpose of this reconstruction, five phases of the fire are recognised and discussed. During phase 1, the fire travelled from its origin in a WNW direction. Ground and aerial observations of the head fire location at various times have enabled a reliable reconstruction of its path during this phase. After breaching containment lines on 3/2/2015, the fire travelled rapidly in a south-west direction. A single aerial observation of the position of the head fire several hours after making this run enabled a reliable reconstruction of this short but active phase. During phase 3, under the influence of a NNW wind, the fire travelled south. The ~10 km eastern flank became a head fire, so the fire's area and perimeter grew rapidly during this phase (Fig. 2). During phase 4, the fire travelled east on a ~20 km front. Finally, during phase 5, under cooler southerly winds the fire spread north and more-or-less burnt back on itself. It was contained at the interface between bush and cleared farmland. Due to the size of the fire and mostly poor visibility (due to smoke), there are few reliable known locations of the fire after phase 2, so reconstructing the fire during latter phases relied on interpreting scorch and defoliation patterns on the aerial photography and relating this to weather conditions, using MODIS imagery (App. 1) and using field indicators such as vegetation freeze. Figures 9 & 10 are the results of this process.

Spotting

Given the conditions of fuel and weather, spotting was a significant feature of this fire. The extent to which it influenced head fire rates of spread and fire shape cannot be determined, so for the purpose of this reconstruction, we have assumed that the observed locations of the fire at various times was the main fire rather than advanced spot fires. There is anecdotal evidence from the fire line that most short-to-medium distance spot fires were generally over-run by the main fire. However, it remains an area of uncertainty.

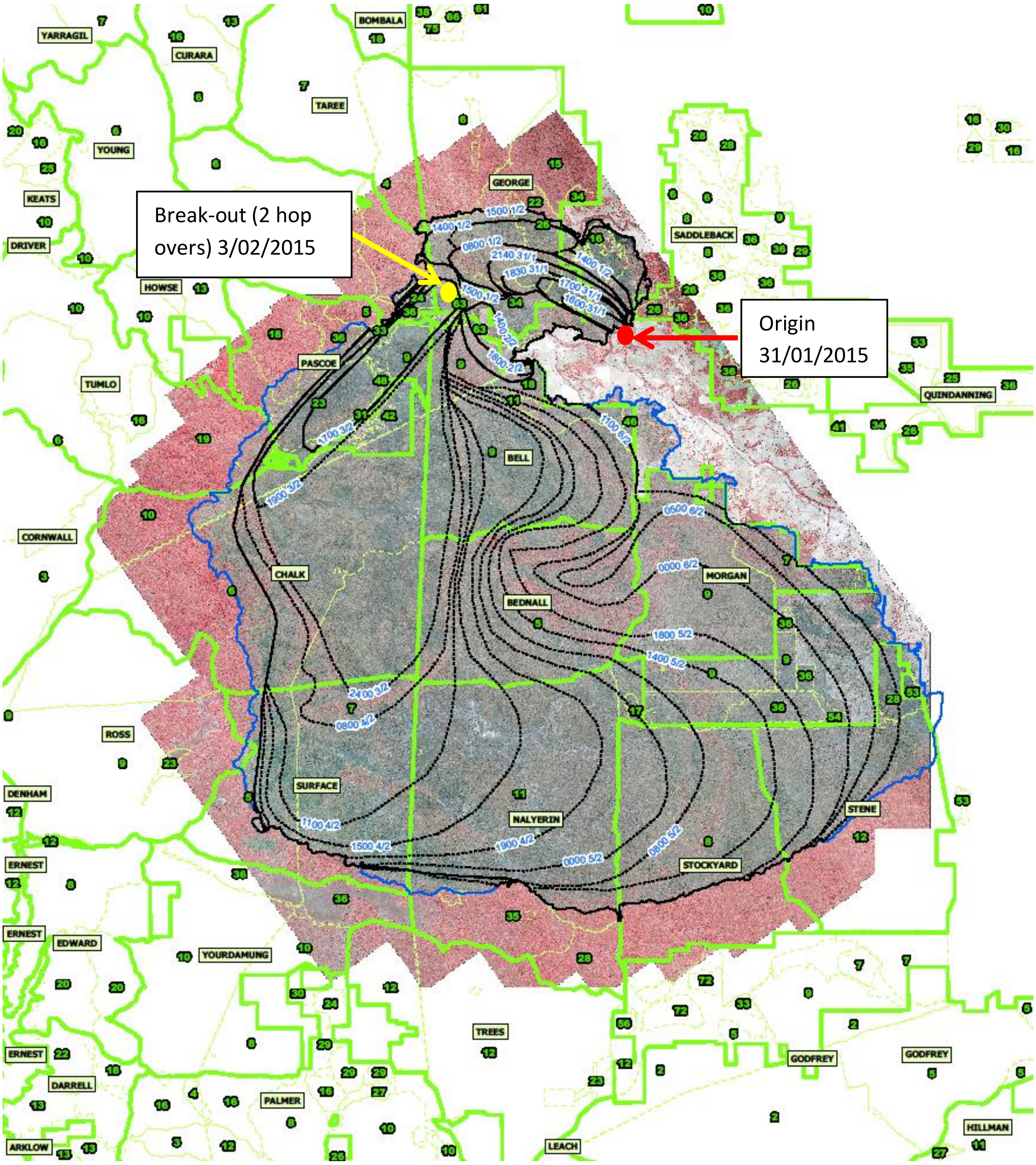


Figure 9: The reconstructed path of the 52,000 ha Lower Hotham fire, 31/01/2015 to 6/02/2015 overlaying post-fire aerial photo. Solid isochrones indicate reliable observations of the position of the head fire; broken isochrones indicate reconstruction from other evidence. Red dot = origin 31/1/2015; Yellow dot = break out 3/2/2015; Green = forest blocks and fuels ages; Blue line = final perimeter;.

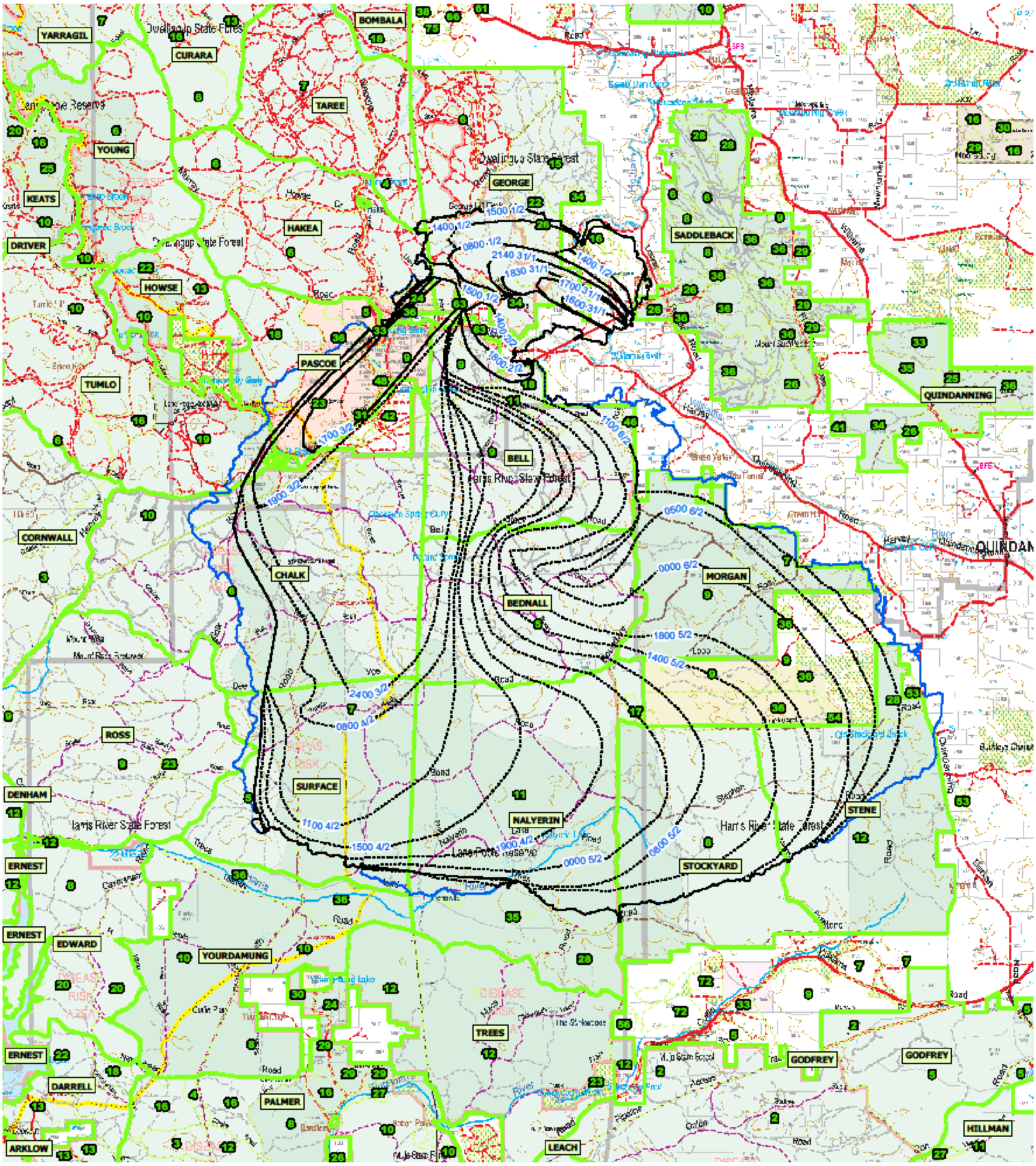


Figure 10: As for Figure 9, but isochrones overlain on a COG map for spatial context.

5. Phase 1: 1525hrs/31/1 – 1800hrs/2/2

The Lower Hotham fire was started by a lightning strike to a marri (*Corymbia calophylla*) tree in a paddock on private property (~32.9656S; 116.4083E; ~DM8348) sometime on 29 January 2015 (see Plate 3). It was initially contained while small, but flared again on 31 January 2015 at about 1525 hrs. Under the influence of a moderate strength, hot, dry ESE wind (Figs. 10 & 11) it developed quickly and spread rapidly WNW through cured grassland before crossing the Worsley Conveyor Belt into bushland. On crossing the Hotham River, it burnt rapidly upslope through long unburnt forest fuels on private property and the Lane Poole National Park. On reaching the plateau in George forest block, fire behaviour moderated. It continued burning in a WNW direction and by about 1830 hrs the head fire had travelled ~5.2 km from its origin, was ~2.7 km east of the Muja-Boddington 81 power line (the power line) and ~2.7 km north of the Murray River (see Fig. 8). By 2140 hrs, the head fire had travelled a further ~800 m (Figs. 8 & 9). Weather and fuel moisture conditions moderated overnight (Figs. 10 & 11) and the head fire burnt slowly in a westerly direction. Flank fire behaviour was very mild (estimated at 30-50 m/h) due to the combined influence of mild overnight conditions and that the flanks were mostly burning downslope. By about 0800 hrs on 1 February it was ~ 1 km east of the power line and ~7.5 km from its origin. It continued west, crossing the power line at about 1445 hrs (see Plate 2). Having crossed the power line, it burnt into Hakea forest block, which had been prescribed burnt 3 years previously. Although penetrating about 150-200 m, the low fuels in Hakea forest stopped the progress of the head fire. The north-east perimeter of the fire was observed by fire fighters to have 'blown out' against the prevailing wind.

Aerial photography from air observers during the fire, and scorch and defoliation patterns on the post-fire photography suggests a spot fire(s) may have originated to the north of the origin and developed in parallel to the main fire before coalescing, expanding the width of the northern flank and the head fire. This is shown as a broken line in Figures 8 & 9.

Plate 3: Location of the origin of the Lower Hotham fire (~32.9656 S 116.4083 E). Worsley conveyor top left.

Plate 4: Infrared imagery of the fire crossing the power line and burning into Hakea forest where the head fire stopped in 3 yo fuels (phase 1). (Image courtesy DFES Air Intel).

During 1/2/2015, the south boundary was tracked 1-2 km north of the Murray River. However, a series of hop-overs along the south boundary around 1130 hrs on 2/2 developed rapidly, several of which coalesced to form a single fire front that burnt strongly in a southerly direction through long unburnt bush, crossing the Harvey-Quindanning Road (H-Q Road) at about 1330 hrs. Fire behaviour on the northern flank was very mild (50-80 m/h) and this was tracked by 1000 hrs on 2/2. By the early hours of 3/2, the fire was contained 1-2 km south of the H-Q Road and its shape stabilised at this point (see Figs. 8 & 9).

Weather, fuels and topography

Phase 2 weather conditions are shown in Figures 11 and 12. During this phase, daily maximum temperature and minimum RH were 30-35^{o}C and 20-28% respectively. Average daytime (corrected) wind speeds recorded at the Marradong AWS were 15-17 km/h gusting 35-40 km/h (Fig. 12). Cool, moist conditions prevailed overnight (31 January-1 February) and wind speed dropped to below 10 km/h. Light easterly winds continued through to the following morning and in the afternoon increased slightly to 10-15 km/hr. Calculated (Vesta) diurnal trends in fine surface fuel moisture content (dead leaves and twigs on the forest floor - SMC) are also graphed in Figure 11, from which it can be seen that minima over the three days ranged from ~4-6% during the mid-afternoon and overnight maxima ranged from ~14-17%.

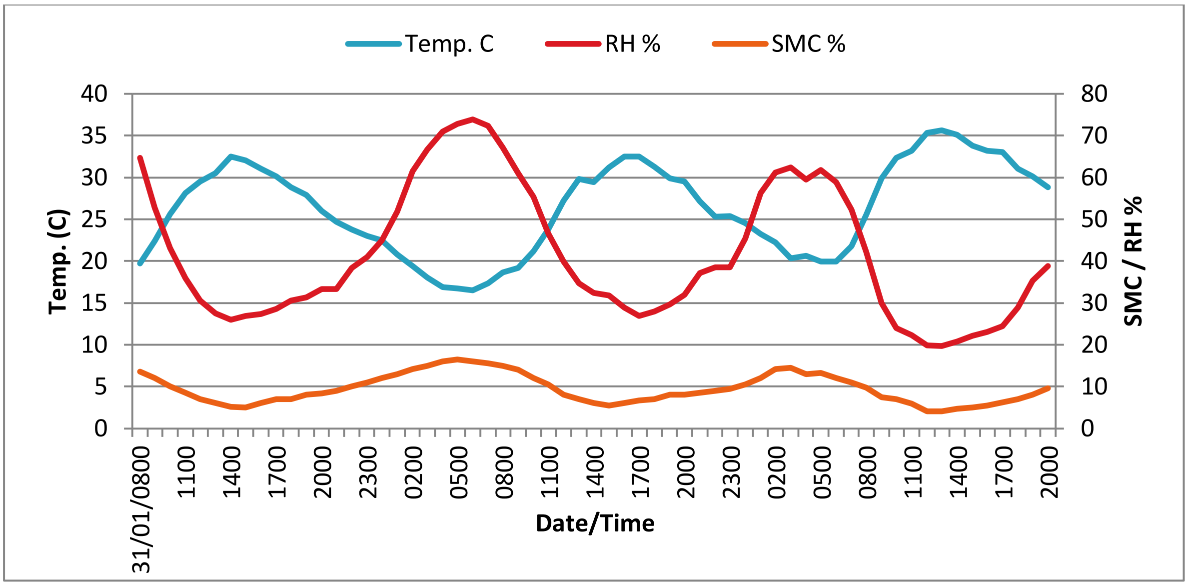


Figure 11: Temperature, RH and calculated (Vesta) fine surface fuel moisture content (SMC) during Phase 1 (fig - 0800/31/01/2015 – 2000/02/02/2015) of the Lower Hotham fire (DAFWA Marradong AWS).

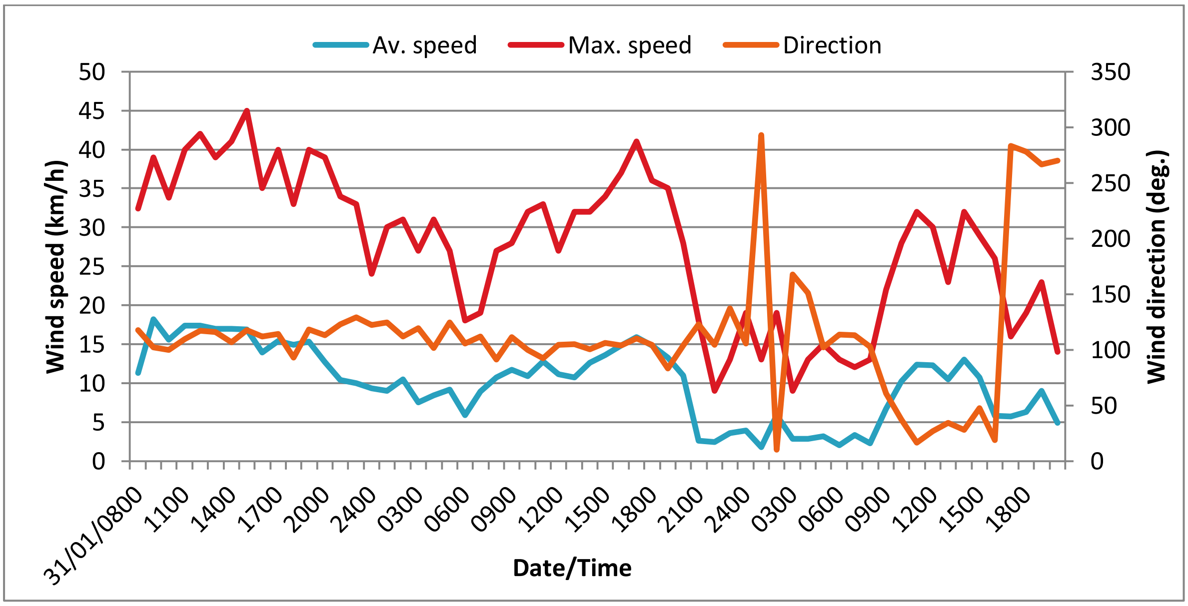


Figure 12: 10 m open wind speeds and direction during Phase 1 (0800/31/01/2015 – 2000/02/02/2015) of the Lower Hotham fire. Data are from the DAFWA Marradong AWS. A correction factor of x 1.3 has been applied to the AWS 3 m wind speeds to approximate 10 m open wind speeds.

Forecast weather is shown in Table 2. Generally, the forecast temperature and RH are similar to those recorded at the Marradong AWS, but forecast wind speeds are about double those observed (at Marradong) and forecast directions are consistently slightly more easterly and northerly than observed. While not detected at Marradong, the aerological diagram (Fig. 7) shows strong ENE winds near the surface (800 m -1000 m) and the synoptic chart also suggests ENE winds (Fig. 6). However, the wind direction on the fire ground, based on the direction of head fire travel, was ESE. There are no reliable wind speed measurements on the fire ground, but fire fighters estimated wind speed in the afternoon of 31/1 to be around 20-25 km, which is less than forecast but higher than recorded at Marradong.

Time (hrs)	Temp (C)		RH%		Wind speed (km/h)		Wind drtn	
	Obs	For	Obs	For	Obs	For	Obs	For
1700	30	30	28	27	15	30	ESE	E
2000	28	26	32	32	13	30	ESE	E
2300	23	21	41	49	10	30	ESE	ENE
0200	19	16	61	68	11	30	ESE	ENE
0500	16	14	73	82	9	30	ESE	NE
0800	19	19	67	56	11	30	E	NE
1100	24	24	46	38	11	25	E	NE
1400	29	27	32	28	13	25	ESE	E
1700	32	30	27	22	16	30	ESE	E

Table 2: Observed (DAFWA Marradong AWS) and forecast weather for the period 1700/31/01/2015 to 1700/01/02/2015. Spot forecast issued by BoM at 1700/31/01/2015.

With the exception of 3 yo fuels in Hakea forest block, which stopped the westerly progress of the head fire, the native vegetation involved in phase 1 was long unburnt. Fuel in bushland on private property north of the conveyor belt is estimated to have been 40+ years old and fuels in George forest block (classed as eastern jarrah) were 15 and 26 years old (Fig. 3). Total available fuel load is estimated (Vesta) to have been in the range 19-22 t/ha. Consequently, Vesta flammability ratings for the various fuel strata ranged from High to Very High.

Topography, particularly the hilly terrain and associated steep slopes, was an important factor influencing fire behaviour and suppression difficulty during this phase. After crossing the Hotham River, the fire spread rapidly up a steep slope aligned with the wind. Once the head fire reached the plateau, the terrain was undulating with 5-6^{o} slopes on a variety of aspects. The progress of the flanks of the fire was initially slowed as they burnt down moderately steep (6-8^{o}) slopes, causing the fire's shape to be slightly more elongated than would be expected for low to moderate winds.

Fire behaviour

Fire behaviour during this phase is summarised in Table 3, which includes fire behaviour determined from ground observations of the fire's perimeter at various known times. After crossing the Hotham River, the fire burnt ~400 m up a steep (~+12^{o}) slope to the plateau. There are no reliable observations of its behaviour during this short run, but its rate of spread was estimated by a fire fighter to have been about 3,000 m/h with 10-20 m flames. Defoliation of the forest canopy indicates sustained crown fire. On reaching the plateau, fire behaviour moderated but the fire continued to crown.

The rates of spread observed during the fire's initial run to 1830 hrs are surprisingly high given the relatively low FFDI as a result of the low wind speeds recorded at the Marradong AWS, which are about 50% less than the spot forecast winds (Table 2) (note: average wind speeds recorded at Collie East were 1-3 km/h higher than Marradong). As can be seen from Table 3, for periods of most active fire behaviour, the observed rates of spread are significantly higher than predicted using observed weather inputs. For the first three time periods in Table 3, predictions using spot forecast weather are similar to observed, but after that, the predictions are significantly higher than observed due to the high spot forecast wind speeds (Table 2). Possible explanations for the under-prediction of rate of spread include the influence of mass spotting and sustained crown fire on extending the head fire, phenomena that are not accounted for in fire behaviour prediction models. Another explanation is that the wind speed on the fire ground was higher than recorded at the AWS, which is located 12 km to the north-east and ~100 m lower in the landscape (see above assumptions for predicting rate of spread). Fire fighters observed that it was 'quite windy', with an experienced observer estimating wind speed on the fire ground to be 20-25 km/h, with stronger gusts, higher than the mean wind speed recorded at the AWS. If a wind speed of 25 km/h is used in the first three time periods, then the predicted rate of spread increase to within 12-15% of observed. The steep terrain may have significantly influenced wind speeds on the fire ground.

The c-Haines Index for 31/1 was 11.6, which is relatively high. The aerological diagram for the 31/2 (Fig. 7) shows a shallow slot of very dry air and associated strong (~40 knot) ENE wind at ~800-1000 m. It is possible that the strong convection column generated by the high intensity surface fire (~10,000-30,000 kW/m) induced mixing of this air and accompanying dry winds to the surface, influencing fire behaviour during this period.

Weather conditions moderated considerably overnight and wind speed reduced from about 2100 hrs through to about 1200 hrs the following day (Fig. 10) as reflected by the reduction in the observed rates of spread (Table 3), which are similar to predictions made using observed weather inputs.

Date/Time	Vesta fuel model	Total fuel load (t/ha)	Obs. ROS (m/h)	[1]Pred. ROS (m/h)	[2]Pred. ROS (m/h)	[1]Pred. Flame ht (m)	[3]Intensity (kW/m)	[4]Sev.	FFDI
31/1 1525-1620	Jarrah east 20+yrs	22	2,640	1,340	2,744	4.8	29,040	D	20
1620-1710	Jarrah east 20+yrs	22	1,538	1,038	1,820	4.1	16,918	D	17
1710-1830	Jarrah east 20+yrs	22	939	621	1,175	2.8	10,329	D	14
1830-2140	Jarrah east 10-12yrs	19.4	236	273	962	1.5	2,289	FS	13
31/1-1/2 2140-0800	Jarrah east 10-20 yrs	19.4	145	104	525	0.8	1,406	PS	5
1/2 0800-1500	Jarrah east 10-20yrs	19.4	150	169	619	1.1	1,455	FS	16

Table 3: Summary of observed and predicted (Vesta) fire behaviour and McArthur Forest Fire Danger Index (FFDI) based on observed and forecast weather. [1]Pred. = prediction using observed weather and predicted SMC (Figs 11 & 12) averaged over the prediction period. [2]Pred. = prediction using spot forecast weather (Table 2). [3]Intensity = calculated using observed ROS. [4]Sev. = overstorey canopy damage; D = defoliated; FS = full scorch; PS = partial scorch or unscorched.

6. Phase 2: 1400hrs/3/2 – 1900hrs/3/2

By morning of 3/2/2015, the fire perimeter was contained (tracked) and virtually controlled – burning out and mop-up was proceeding. However, in the early afternoon, unstable conditions and thunderstorm cells associated with a re-developing west coast trough caused gusty winds, with gusts on the fire ground estimated by a fire fighter to be up to 50 km/h. Maximum wind speeds (gusts) recorded at the Marradong and Harvey AWSs were 30-40 km/h, and at Collie East, 25-30 km/h. At ~1450 hrs, at least two hop-overs occurred on the south-west sector ~1-1.5 km north of the Murray River (~DL7928) (Fig. 9). Under hot, dry NE winds, and burning in flammable old forest fuels, the hop-overs developed quickly, coalseced, and spread rapidly to the south-west. On crossing the Murray River, the fire spread rapidly up a steep slope (~12^{o}), across the H-Q Road, reaching the Bibbulmun Track some 7.5 km to the south-west by about 1700 hrs. By 1900 hrs, it had travelled a further ~3 km, crossing the Murray River again, burning Long Gully Bridge and crossing the Worsely Coveyor belt south of the H-Q Road and east of Chalk Road (Figs. 9 & 10).

Weather, fuels, topography

On the 3/2, a NE wind associated with the trough dragged hot, dry air from the interior, with the temperature peaking at 41.1^{o}C and RH dropping to 12% at about 1600 hrs (Fig. 13). It remained warm and dry into the evening - at 1900 hrs it was 33^{o} C and the RH was 21%. Calculated (Vesta) minimum SMC was 4% at about 1500 hrs and remained below 6% until about 1900 hrs. In the morning of 3/2, the NE wind was relatively light (5-10 km/h) but increased in strength to 15-20 km/h with gusts to 42 km/hr from about 1300-1900 hrs (Fig. 14a).

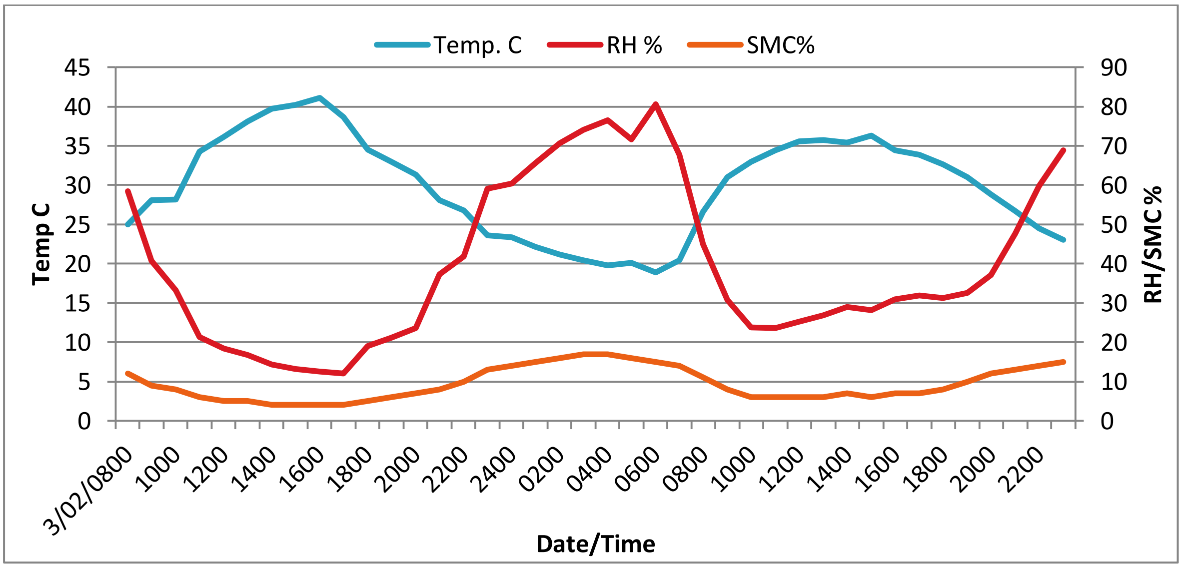


Figure 13: Temperature, RH and calculated (Vesta) fine surface fuel moisture content (SMC) during Phases 2 and 3 of the Lower Hotham fire (DAFWA Marradong AWS).

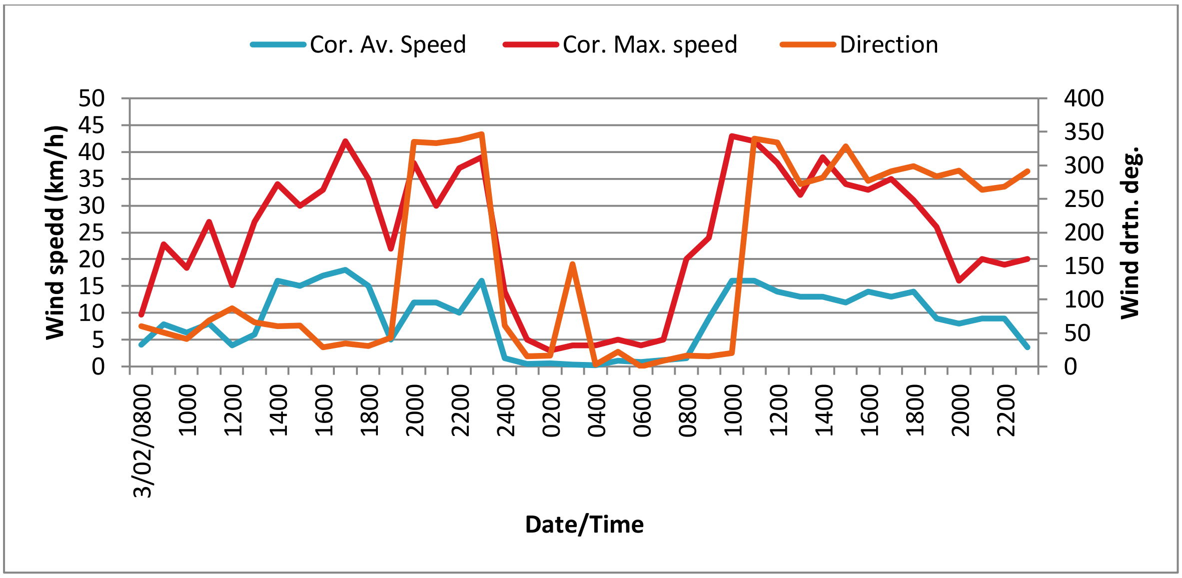


Figure 14a: 10 m open wind speeds and direction during phases 2 and 3 of the Lower Hotham fire recorded at the DAFWA Marradong AWS. A correction factor of x 1.3 has been applied to the AWS 3 m wind speeds to estimate 10 m open wind speeds. Mean av. = 8.8 km/h; mean max. = 24.4 km/h.

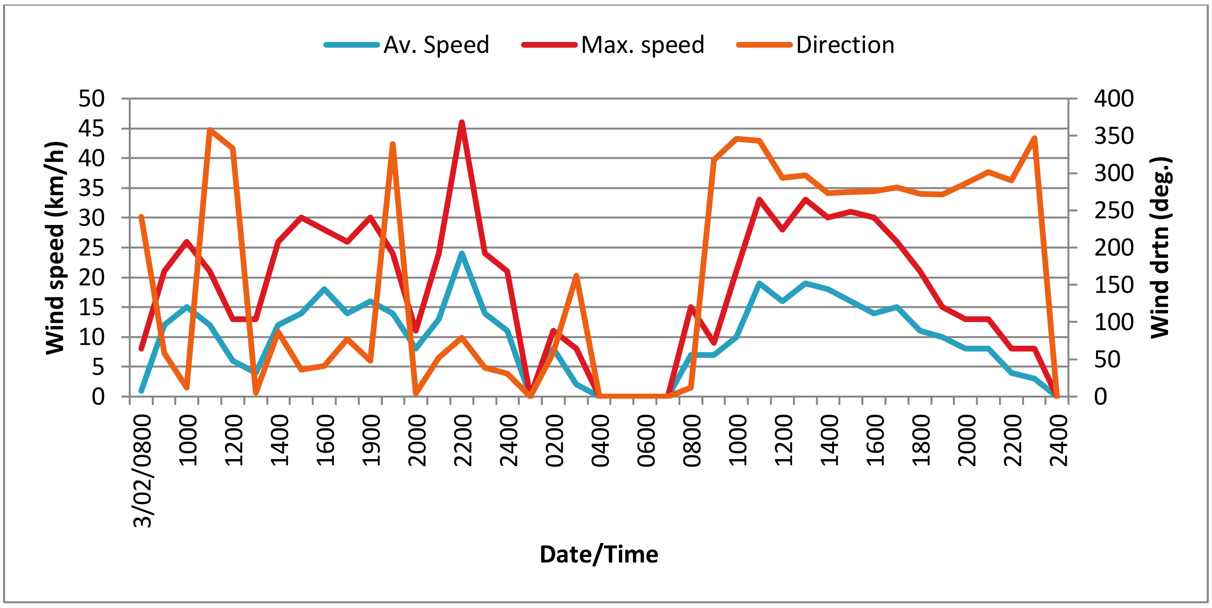


Figure 14b: 10 m open wind speeds and direction during phases 2 and 3 of the Lower Hotham fire recorded at the BoM Collie East AWS. Mean av. = 9.4 km/h; mean max. = 16.6 km/h.

Forecast weather for this phase is shown in Table 4. Generally, the forecast temperature and RH are similar to those recorded at the Marradong AWS, except for peak conditions when the observed maximum temperature exceeded that forecast by about 6°, and the observed minimum RH was 8% below forecast. Forecast wind speeds were almost double observations except for the 1600 hrs and 2200 hrs forecasts, which are similar to observed. However, both observed and forecast wind speeds are light to moderate. Forecast and observed wind directions are similar.

Time (hrs)	Temp (C)		RH%		10m wind speed (km/h)		Wind drtn	
	Obs	For	Obs	For	Obs	For	Obs	For
0700	20	23	80	41	4	10	NNE	ENE
1000	28	29	33	23	6	15	NE	NE
1300	38	34	17	20	6	20	NE	NE
1600	41	35	12	23	18	20	NE	NE
1900	33	32	21	28	5	15	NE	NE
2200	27	27	42	37	10	10	NNW	NE

Table 4: Observed (DAFWA Marradong AWS) and spot forecast weather for the period 0700/03/02/2015 to 2200/03/02/2015. Spot forecast issued 0620/03/02/2015

The fuels involved in this phase were mostly long unburnt jarrah forest (Vesta model - jarrah north west) ranging up to an estimated 40+ yo on private property bushland. Fuels in Pascoe forest block were mostly 23 yo and in Tumlo, mostly 19 yo (Table 1, Figs. 4 & 10). Total available fuel load is estimated (Vesta) to have been ~22-25 t/ha. Vesta flammability ratings for the various fuel layers ranged from High to Very High. As with phase 1, the terrain was hilly with some very steep slopes (to 12^{o}) on a variety of aspects. Steep slopes are generally over short distances before aspect changes, so the terrain is variable at a relatively fine scale.

Fire behaviour

Some of the most severe fire behaviour experienced in jarrah forest in recent times was displayed during this phase. Based on the extent of defoliation, the ~1.5 km wide head fire was a sustained crown fire. There are also indications in the scorch and defoliation patterns (Fig. 3) that flank fire also crowned. In addition to long unburnt, flammable and very dry fuels, as with phase 1, complex and often steep topography was an important factor influencing fire behaviour and suppression difficulty. After crossing the power line and the Murray River, the fire spread rapidly up a ~+12^{o} slope (aligned with the wind). From the Murray River south-west to the Bibbulmun Track and Chalk Road, the terrain is very hilly with steep slopes on a variety of aspects, so the fire burnt up, down and along 5-12^{o} slopes. However, the net slope from when it breached containment lines at ~1450 hrs to when it crossed the Bibbulmun Track some 7 km to the south-west, was about +1^{o}. As to be expected given the long unburnt, dry fuels, significant spotting was observed with the longest recorded spot fire being ~5 km downwind of the head fire.

As with the initial stages of phase 1, the observed rates of spread were 60-70% higher than predicted. Both observed and forecast wind speeds were light to moderate strength (Table 4), with the FFDI being in the range High to Very High (Table 5) driven up by the high temperature and low humidity. While hourly average wind speeds were light to moderate (15-18 km/h) maximum wind speeds (gusts) averaged about 35 km/h and were consistently above 30 km/h. The observed rates of spread were significantly higher than would be expected for the observed average wind speeds. Based on the Vesta model, winds of about 35-40 km/h are required to generate the spread rate observed between 1450 and 1700 hrs on 3/2, which is closer to the maximum wind speeds observed. This raises the question of the significance of wind gusts on fire behaviour. The often acute angle (45^{o}-60^{o}) of vegetation freeze also suggests stronger winds associated with the head fire than observed at any of the AWSs, or forecast, for this period.

Being 1.5 km wide, the head fire likely experienced a wind gust somewhere along its length at regular intervals. It is possible that this acted to significantly increase the overall rate of spread across the entire length of the head fire and had a stronger influence on fire behaviour than the average wind speed. There is no evidence by way of scorch or defoliation patterns that the fire slowed appreciably on downhill runs – appearing to maintain its energy and momentum up and downslope, defoliating the forest. The head fire being in excess of 1.5 km wide, is larger than the distance scales at which the topography (slope and aspect) change in these landscapes (~300 m- 500 m). As with wind gusts, in this landscape, some part of the head fire was almost always burning up a steep slope – this may have the effect of increasing fire behaviour along the entire length of the head fire, regardless of its position in the landscape. These scale effects of wind and topography on fire behaviour are poorly understood as fire behaviour models are developed at much smaller scales in relation to the landscape and small head fires are contained to uniform conditions at any point in time.

Alternatively, it is possible that the intense fire may have quickly developed into a 'plume- driven' fire, also a poorly understood phenomenon when the fire becomes coupled with the atmosphere, generates its own fire weather, and displays extreme behaviour. There appears to be nothing unusual in the aerological diagram (Fig. 8) such as dry slots or strong winds aloft, and the upper atmosphere is neutral to stable, although the c-Haines was 9.8, which is not exceptionally high (the September to April 95th percentile c-Haines for the region = 8.8). As discussed above, mass spotting and subsequent fires ahead of the main fire may have contributed significant energy to the convection column, increasing fire winds and fire behaviour.

Date/Time	Vesta fuel model	Total fuel load (t/ha)	Obs. ROS (m/h)	[1]Pred. ROS (m/h)	[2]Pred. ROS (m/h)	[1]Pred. Flame ht (m)	[3]Intensity (kW/m)	[4]Sev.	FFDI
3/2 1450-1700	Jarrah north west 20+yrs	24.5	3,692	2,205	2,114	6.9	45,227	D	42
1700-1900	Jarrah north west 10-20yrs	22	1,550	1,050	1,483	4.1	17,050	D	30

Table 5: Summary of observed and predicted (Vesta) fire behaviour and McArthur Forest Fire Danger Index (FFDI) based on observed and forecast weather. [1]Pred. = prediction made using observed weather and predicted SMC (Figs 13& 14) averages for the prediction period.[2]Pred. = prediction made using spot forecast weather (Table 4). [3]Intensity = calculated using observed ROS. [4]Sev. = overstorey canopy damage; D = defoliated; FS = full scorch; PS = partial scorch or unscorched.

7. Phase 3: 1900hrs/3/2-1100hrs/4/2

Weather, fuels, topography

At about 1900 hrs on 3/2, the wind backed to the NNW at 10-15 km/h (Fig. 14). On the wind shift, the ~10 km southern flank became ~6 km wide head fire burning in a southerly direction. Under the influence of a northerly wind, conditions remained relatively warm and dry during the early evening, with the temperature and RH at 2000 hrs being about 31^{o}C and 24% respectively (Fig. 15). Subsequently, fine surface fuels were relatively dry (~7% at 2000 hrs). There are no observations of the fire's location over this time (night) but the scorch and defoliation patterns visible on the aerial photography show a green band of unscorched or partially scorched overstorey canopy up to several hundred meters deep in parts (see Figs. 3 & 9) as fire intensity abated. It was calm from ~2400 hrs to ~0800 hrs on 4/2, when the fire became active again as it warmed and the wind speed increased. In addition to a drop in wind speed at ~2400 hrs, temperature decreased and RH and SMC increased, with the latter peaking at ~17% (predicted - Fig. 13), further reducing fire behaviour.

During this phase, the fire burnt mostly in Chalk forest block (6 yo fuels) but small areas of Bell (9 yo fuels), Bednall (5 yo fuels) and Surface (7 yo fuels), as well as some private property bush, were also involved. Total available fuels in Chalk were about 18 t/ha (Vesta – jarrah north west 5-9 yo) with a Vesta hazard rating of Moderate to High for most layers. In the northern section of this phase, topography was hilly with steep slopes (up to 12^{o}) on a variety of aspects (similar to phases 1 and 2). However, south of Opossum Spring Road, the topography was more subdued and could be characterised as undulating with longer 2-4^{o} slopes on a variety of aspects.

Fire Behaviour

Again, the severity of fire behaviour and impact on the forest (defoliation) during this night time period is surprisingly high given the low wind speeds recorded at Marradong and Moderate FFDI (Table 6), although the Collie East AWS, at 2200 hrs, recorded a spike in average wind speed to ~25 km/h, gusting to 45 (Fig. 13b). On the wind shift soon after 1900 hrs, and up to about 2400 hrs, the fire behaviour was sufficiently active to defoliate most of the forest canopy on the night time run (Figs. 3 & 9), suggesting sustained crowning fire, even though the fuels were mostly 6 yo and winds were mostly light to moderate (Marradong - 10-15 km/h gusting to 38 km/h; Collie East 8-24, gust to 45 km/h). The green band (Fig. 3) indicating the fire's position when it 'went to sleep' at about 2400 hrs (winds < 5 km/h), runs south from the conveyor belt and about 0.5 – 1.0 km east of the power line, crossing the power line near the Dee Vee Road intersection. It then runs about 0.5 km south of Dee Vee Road for 1.5- 2 km before running back to the north, east of Chalk Road (see also Fig. 9). There is a section of defoliation on Dee Vee Road just west of the power line in which the vegetation freeze indicates a brief period when the wind veered to the NNE late in the evening. Spot fires recorded at 2400 hrs near Asquith Road (DV7542, DV7598 and DU7540) were probably launched during this period. Other than being able to link the scorch patterns with timing of a reduction in wind speed, there are no reliable observations of the fire's location during this phase.

Assuming the fire's position at 2400 hrs is as shown in Figs. 9 & 10, then the mean rate of spread over this period (1900-2400 hrs) was ~1,600 m/h, which, given the average conditions of fuel moisture and weather, is surprisingly high and about three times higher than predicted. As discussed above, this rate of spread, extent of defoliation and angle of freeze suggests that winds on the fire front were stronger than recorded at the AWSs (Marradong and Collie East). While the mean hourly wind speeds were light to moderate, the gusts were up to 38 km/h (Marradong - Fig. 14) and, as indicated above, may have had a greater influence on fire behaviour than the mean wind speed (scale effects). Based on the Vesta model, to generate this rate of spread under these conditions, the wind speed would need to average around 35-40 km/h, which is in the range of the maximum wind speeds recorded. Alternatively, and as discussed for phase 2, this suggests the fire may have been 'plume driven', generating sufficient energy through its size, high fuel consumption, including involvement of overstorey canopy fuels, and dry fuel. The topography, scale effects and spotting (discussed above) may have played a role in sustaining the kinetic energy of the convection column.

Following a drop in wind speed (< 5 km/h) and an associated drop in fire behaviour from about 2400 hrs to 0800 hrs on 4/2, fire behaviour then increased with the rising hazard. From 0800-1100 hrs, SMC fell to ~6%. The position of the fire at 1100/4/2 was estimated from (crude) MODIS imagery (App. 1) and field evidence, so is an approximation only. Based on this location at 1100 hrs, mean rate of spread from about 0800-1100hrs was ~ 1,000 m/h, which again is surprisingly high given the Moderate FFDI (11). Average hourly winds over this period were northerly at 12-15 km/h, gusting to 40 km/h (Marradong) and 7-19 km/h, gusting to 33 km/h at Collie East.

Date/Time	Vesta fuel model	Total fuel load (t/ha)	Obs. ROS (m/h)	[1]Pred. ROS (m/h)	[2]Pred. ROS (m/h)	[1]Pred. Flame ht (m)	[3]Intensity (kW/m)	[4]Sev.	FFDI
3/2 1900-2400	Jarrah north west 5-9yrs	18	1,580	833	833	3.4	14,220	D	11
3/2-4/2 2400-0800	Jarrah north west 5-9yrs	18	80	75	75	0.6	900	PS	3

Table 6: Summary of observed and predicted (Vesta) fire behaviour and McArthur Forest Fire Danger Index (FFDI) based on observed and forecast weather. [1]Pred. = prediction made using observed weather and predicted SMC (Figs 13 & 14) averaged over the prediction period.[2]Pred. = prediction made using spot forecast weather (Table 4). [3]Intensity = calculated using observed ROS. [4]Sev. = overstorey canopy damage; D = defoliated; FS = full scorch; PS = partial scorch or unscorched.

Plate 5: Defoliated forest indicative of crown fire south of the Worsley Conveyor that burnt during phase 3 between 1930 hrs and 2130 hrs on 3 February. The FFDR during this period was 14 (High); predicted rate of spread 833 m/h, actual rate of spread~1,580 m/h (photo courtesy Peter Gibson DPaW).

8. Phase 4: 1100hrs/4/2-2000hrs/5/2

Weather, fuels, topography

Around 1100 hrs on 4/2, the wind backed from the north-west to the west at 16-19 km/h, gusting to 33 km/h (Fig. 15). From 1700 to 2400, winds remained westerly, but speed steadily decreased to calm conditions by 2400 hrs and remained calm through to ~0700 hrs 5/2. By Mid-morning, wind had increased to ~15km/h and remained at this strength until 1800 hrs when it backed to the south and reduced to less than 10 km/h. Maximum temperature and minimum RH during this phase was

36°C and 22%, with calculated (Vesta) SMC ranging from a daytime minimum of 6% to an overnight maximum of 18% (Fig. 16). Note: An SMC of 18% is close to the moisture content of extinction for jarrah litter (~21%). There is evidence that the SMC model may over-predict night time SMC by 3-5% in some circumstances (L. McCaw pers. com).

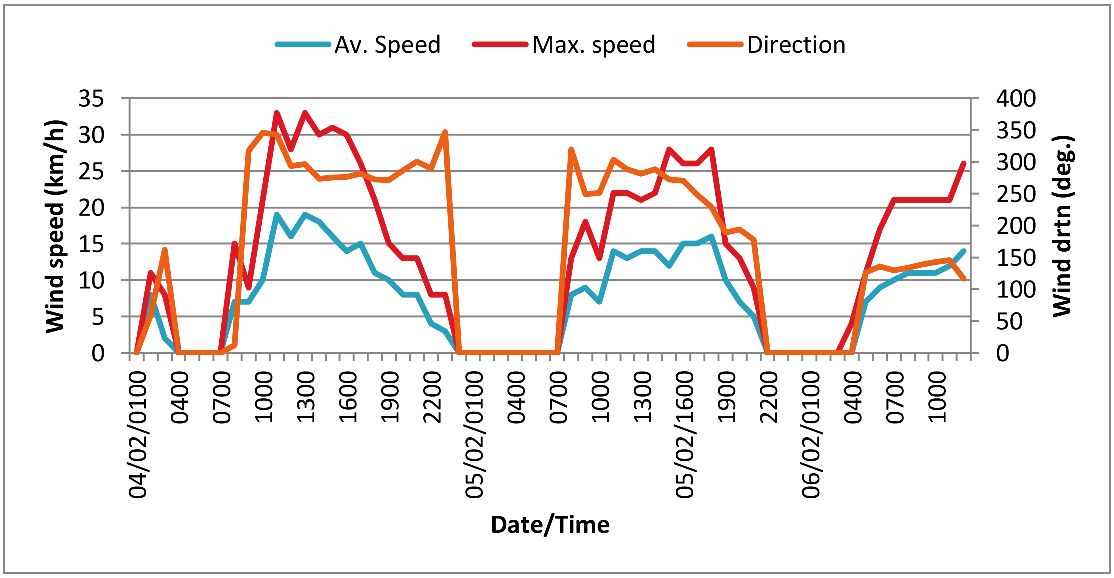


Figure 15: 10 m open wind speeds and direction during phases 4 and 5 of the Lower Hotham fire (BoM Collie East AWS). Note the calm (zero wind speed) conditions overnight responding to the 'green' bands (unscorched canopy) evident in Figure 2.

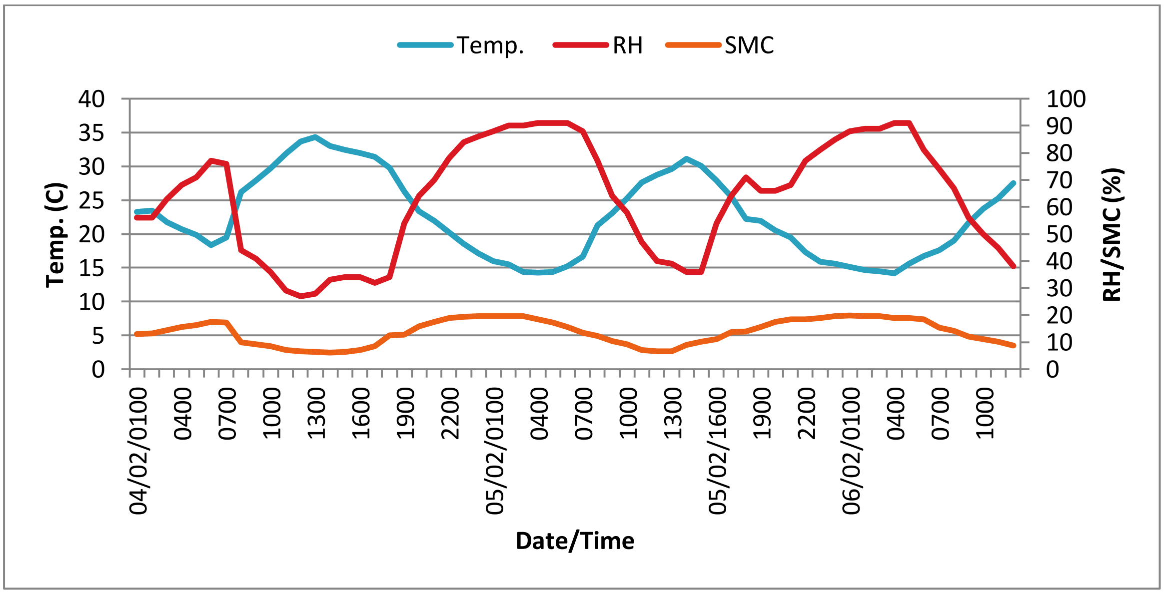


Figure 16: Temperature, RH and calculated (Vesta) fine surface fuel moisture content (SMC) during Phases 4 and 5 of the Lower Hotham fire (BoM Collie East AWS).

On the wind shift from north to west, the ~30 km flank fire became a ~30 km head fire, burning eastward, east of the power line through Bell (9 yo fuel), Bednall (5 yo fuel), Surface (7 yo fuel) , Nalyerin (11 yo fuel), Stockyard (8 yo fuel) and Morgan (9 yo fuel) forest blocks (Figs 9 & 10). For the reconstruction, these forests are considered as jarrah east (Vesta fuel model), with total available fuel loads ranging from 15-19 t/ha and Vesta fuel hazard rating Moderate to High for the various fuel layers.

The topography east of the power line and south of Dee Vee road is flat to undulating but more irregular and hilly north of Dee Vee Road with slopes ranging from 5-10^{o} on a variety of aspects. There are a number of incised drainages with short steep slopes in Bednall and Bell forest blocks including Bell Brook and Opossum Spring Gully. Wandoo woodlands occur in the valley floors and adjoining lower slopes.

Fire behaviour

As with phase 3, there are few reliable records of the location of the fire at various times, largely because of poor visibility due to thick smoke. Reconstructing this phase relied on indicators of the fire's position at various time, including scorch and defoliation patterns visible on the aerial photography and associating this with weather conditions, MODIS satellite imagery (App. 1), BoM's Serpentine Radar (App. 2), which detected the smoke plume and gave a crude indication of fire activity, and field indicators particularly vegetation freeze as an indicator of wind direction. With one exception (see below) a comparison of observed and predicted fire behaviour is not made in this phase or later phases due to the level of uncertainty of the fire's location.

Based on available evidence, the mean rate of head fire spread from 1100 – 1900 hrs on 4/2 was about 750 m/h with an intensity of ~7,700 kW/m in the older, heavier fuels of Nalyerin and Bell Blocks, but was only about 250 m/h with an intensity of ~ 2,250 kW/m in 5 yo fuels in Bednall. Curiously, fire behaviour during the day on 4/2 was less than during the night of 3/2, even though the night time FFDI was ~11 compared with the daytime FFDI of ~19. The subdued terrain, the lower fuel hazards associated with eastern jarrah and wandoo forests and the noticeable reduction in the strength of wind gusts may explain this (reduced scale effect). Further evidence of this reduction in fire intensity can be seen in the scorch and defoliation patterns; while there are patches of defoliation during the day time run on the 4/2, more of the forest burnt during this period is fully scorched, interspersed with patches of defoliation.

From 1900 hrs to 2400 hrs on the 4/2, rate of spread reduced further to about 600 m/h in the older fuels and to ~ 120m/h in younger fuels as the FFDI declined to ~6 and wind speed dropped to 5-8 km/h, gusting to 15 km/h (Fig. 15). As has been the case throughout, fire behaviour was surprisingly active given the generally low to moderate wind speeds. From 2400 hrs to 0800 hrs on the 5/2, the FFDI and fire behaviour moderated considerably with the mean rate of spread over this period being <100 m/h. Mean wind speed over this period reduced to <5 km/h with gusts <10 km/h. This reduction in fire intensity is clearly evident on the aerial photography (Fig. 3) as a green band of unscorched or lightly scorched canopy in the south-east of the fire ground – the western and eastern edges of the band marking the approximate location of the fire at 2400 and 0800 hrs respectively. The extensive area of green canopy in the western part of Bednall forest block further illustrates the significant reduction in fire intensity associated with a reduced FFDI and reduced fuel loads in Bednall.

From 0800 to 1400 hrs on 5/2, fire behaviour increased during the day with increasing FFDI (21). Wind speed increased to 10-15 km/h gusting to 35 km/h, and minimum SMC was ~7%. Mean rate of spread during this period is estimated at ~500 m/h in older fuels of Stockyard forest and ~170 m/h in younger fuels in Bednall. A valuable source of fire behaviour information came from trail cameras located in Stene forest block as part of the DPaW's Western Shield fauna recovery program. Of the thirty cameras in Stene forest, only three (memory cards) survived the fire and we were able to be downloaded, revealing the time the fire arrived at the cameras (note: the year and day on camera #3 was incorrect; time was correct). The surviving cameras were in locations where fire behaviour moderated briefly, enabling the cameras to survive. We became aware of the existence of the cameras after we had completed the reconstruction of the fire and just before finalising this report so the data on the cameras enabled us to independently validate and correct our reconstruction for this (small) part of the fire. Cameras 3 and 8 were ~3.32 km apart and closely aligned with the direction of head fire travel and camera 17 was ~2.51 km south-south-east of camera 8.

Based on the time the fire reached the cameras, and assuming it was the main fire and not a spot fire, the fire's rate of spread between the cameras (1218 – 1453 hrs 5/2) was 1,285 m/h (see Plate 6). This compares with a predicted rate of spread of 528 m/h. Wind speed at the Collie East AWS over this period was ~15 km/h, but based on the movement of small understorey trees and other vegetation evident in the trail camera photos, the wind speed increased as the fire approached and appeared to be stronger than 15 km/h – this may have been fire-induced wind. Soon after 1500 hrs to 2000 hrs, rate of spread in older fuels reduced to as low as ~250 m/h as the FFDI declined to 13.

Knowing the location of the cameras and the time the fire reached the cameras, we were able to check our initial reconstruction of the fire's location with the camera record. This revealed that our reconstruction was about 1 hour out – i.e., over the ~48 hours since the last known location of the fire, the actual head fire was about 1 hour in advance of where we had reconstructed it to be using the techniques described above.

Plate 6: The fire reaches Western Shield camera #3 in Stene forest block ~1218 hrs on 5/2/2015 (date is incorrect on camera, time is correct). The camera's memory card survived because fire behaviour had briefly moderated/lulled. Of the thirty cameras in Stene forest, only three survived.

Plate 7: The fire reaches Western Shield camera #8 in Stene forest block ~1453 hrs 5/2/2015.

As mentioned above, fire behaviour (rates of spread and intensity) during this phase was significantly less, even in the older fuels, than previous phases burning under similar, or lower, FFDI. This is likely due to the fire burning in eastern jarrah forest (less fuel, lower hazard rating) on a more subdued (flatter) terrain during this phase. Another noticeable feature of fire behaviour during this phase was the significantly reduced rates of spread, intensity and canopy damage in the younger, 5 yo fuels in Bednall forest.

9. Phase 5: 2000hrs/5/2 – 1100hrs/6/2

Weather, fuels, topography

Weather conditions moderated as the trough moved east and a cold front approached from the Southern Ocean (Figs. 15 & 16). Winds gradually backed from the west to the south bringing cooler, more humid conditions to the fire ground. Winds were light (5-13 km/h, gusting to 25 km/h). Observed and forecast conditions are shown in Table 7. Observed temperatures during the day were slightly higher than forecast but there is close agreement between observed and forecast wind direction. As has been the case throughout this reconstruction, forecast wind speeds were generally higher than observed, but both indicate light to moderate winds throughout this period.

During this phase, the fire was mostly burning in Stene (12 yo) and Morgan (9 yo) forest blocks (jarrah east), with a smaller part of the northern perimeter in Bednall and Bell. Total available fuel load ranged from 11-19 t/ha with a Vesta hazard rating range from Moderate to High.

On the gradual wind shift from west to south, the northern flank of the fire became the head fire and its rate of spread through Morgan forest from 2000-2400 hrs is estimated at 600-700 m/h and 200-250 m/h in the 5 yo fuels in Bednall forest. The FFDI during this period was 3-4 (Low) and as has been the case throughout much of this incident, significant fire behaviour has been observed under relatively low FFDI (low wind) conditions. Over period from 2400 hrs to 1100 hrs on 6/3/2, when the fire shape stabilised to its final shape, mean rate of spread in Morgan forest is estimated at 250-300 m/h.

Time (hrs)	Temp (C)		RH%		10m wind speed (km/h)		Wind drtn	
	Obs	For	Obs	For	Obs	For	Obs	For
1300	30	29	39	37	14	15	W	W
1600	29	28	54	48	15	20	WSW	WSW
1900	23	24	66	69	10	15	W	SSW
2200	18	21	77	73	0	10	S	S
0100	16	18	88	73	0	10	SSE	SSE
0400	15	16	90	82	0	10	SE	SSE
0700	17	17	74	77	10	15	SSE	SE
1000	23	23	50	57	11	15	SE	SE
1300	29	30	32	38	14	10	SE	SE

Table 7: Observed (BoM Collie East AWS) and spot forecast (fire ground) weather for the period 1300/05/02/2015 to 1300/06/02/2015. Spot forecast issued 1223/05/02/2015

10. Accuracy of weather forecasts

Twenty four- hour spot weather forecasts were issued regularly by the BoM during the fire (see Tables 2, 4 and 7 above). Typically a forecast consisted of 3 hourly predictions of temperature, dewpoint, relative humidity (RH), 10 m open average wind speed, wind gusts and 1000 m AGL wind speed and direction. Wind direction forecasts were given as one of 16 secondary inter-cardinal directions (e.g., N, NW, NNW, etc), there being 22.5° between each secondary inter-cardinal. Wind direction at the weather stations was recorded in degrees, which, for this analysis, were converted to the nearest one of 16 secondary inter-cardinals. For the purpose of this analysis, the spot forecast (surface conditions) were compared with actual weather recorded at the nearest weather station (see Tables above). Accuracy of wind direction forecasts was assessed by examining the number of forecasts that were 'spot on', the number that were one secondary inter-cardinal out (out by 22.5°), the number that were 2 secondary inter-cardinals out (out by 45°) and so on.

The temperature forecasts could be characterised as 'accurate', with the correlation coefficient (R^2) between actual and forecast values being 0.92 (Figure 17). Forecast RH was less accurate with an R^2 value of 0.78. Generally, daytime forecasts of RH were more accurate than night time forecasts, which tended to under-predict. There was no bias in temperature forecasts.

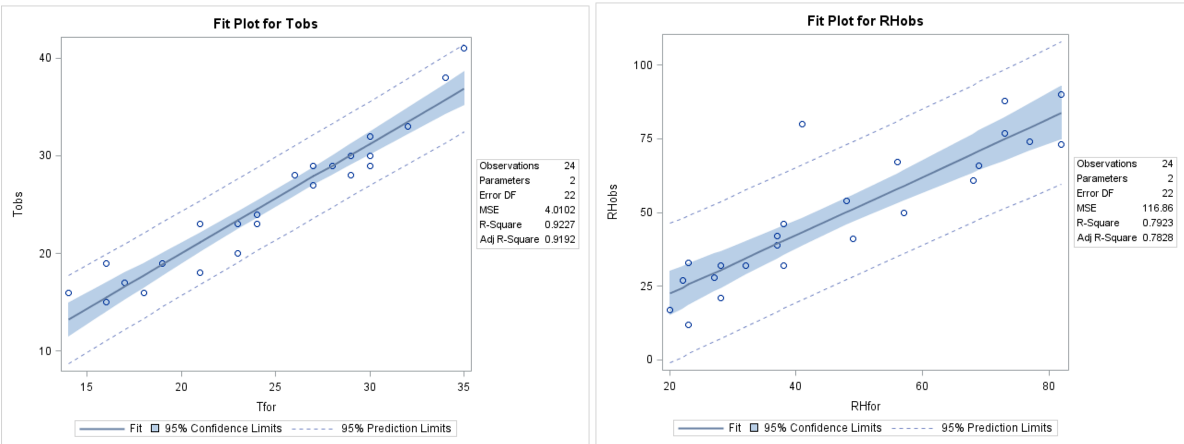


Figure 17: Observed and forecast temperature (L) and RH (R).

The accuracy of forecast wind speed could be characterised as low, with an R^2 of 0.26 (Figure 18). Forecasts were biased towards over-prediction, which is probably a more prudent approach than under-prediction given the importance of wind speed on fire behaviour. For fire behaviour prediction purposes, the wind direction forecasts could be characterised as accurate, with 46% of forecasts being 'spot on', 29% being within 1 secondary inter-cardinal (22.5° or almost spot on), 22% being within 2 secondary inter-cardinals (45°) and only 3% being within 3 secondary inter-cardinals (67.5°) (Figure 18).

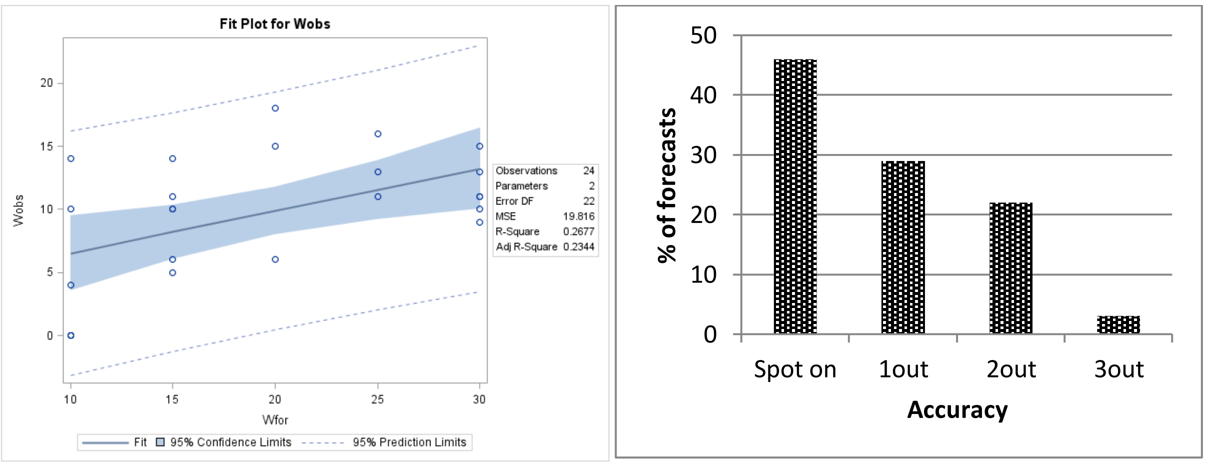


Figure 18: Observed and forecast wind speeds (L) and accuracy of wind direction forecasts (R), where 'spot on'is perfect agreement with observed, 1out = 22.5° out, 2out = 45° out, 3out = 67.5° out.

11. Accuracy of fire behaviour (rate of spread) predictions

Fire rate of spread observations were compared with a) predictions made using observed weather and b) predictions made using forecast weather. During an incident such as the Lower Hotham fire, and as part of the IMT, fire behaviour analysts are required to make regular predictions of the fire's location, shape, rate of head fire spread and perimeter growth. These predictions inform decision-making about suppression strategies, tactics and priorities, what assets are at risk, and predictions help to develop 'trigger points' with respect to when, where and what public alerts are issued. Analysts use a fire behaviour model relevant to the vegetation in which the fire is burning; in this case, the Vesta model was used. Forecast temperature and RH are used to estimate fine fuel moisture content (a model input); forecast wind speed is a model input in its own right, and wind speed and wind direction determine head fire direction and overall fire shape and growth rate. Terrain slope and aspect are also used to predict fire behaviour and shape. A number of assumptions must be made about the influence of suppression actions on fire behaviour and shape, but generally, worst case scenarios are predicted, which assumes no effective suppression action on the fire.

Accuracy of predictions is limited by the inherent inaccuracy of fire behaviour models, which at best explain about 70-80% of the variation in fire behaviour. Couple this with inherent inaccuracies in weather forecasts (see above) and it is clear that expecting accurate predictions of fire behaviour is unrealistic. However, predictions that are within ~20% of the actual fire behaviour are sufficiently accurate in most cases to adequately inform fire fighters and assist with decision making. On the other hand, highly inaccurate predictions can lead to poor decision making with undesirable outcomes.

A comparison of predicted and observed rates of spread was made using the data summarised in Tables 3, 5 and 6 above. Raw data (observed vs predicted rate of spread) are shown graphed in Figure 19. Figures 20 and 21 show the relationship between observed rate of spread (ROSobs) and a) predictions made using observed weather (ROSpred1) and using forecast weather (ROSpred2). Expressed as equations, these relationships are:

Equation 1: ROSobs = 1.74 x (ROSpred1) -46 (R^2 = 0.96).

Equation 2. ROSobs = 1.18 x (ROSpred2) – 133 (R^2 = 0.67).

Equations 1 and 2 are graphed below (Figure 20).

Predictions made using observed weather were reasonably accurate at lower rates of spread, but significantly under-predicted at higher rates of spread. Equation 1 indicates that the observed rates of spread were consistently about ~1.7 times faster than predicted by the model using actual observed weather to make the predictions. Equation 2 indicates that the predictions made using forecast weather were similar to the observed rates of spread but not consistently.

The head fire rates of spread exhibited by this fire at times were significantly higher (almost double) than predicted by the Vesta model (using observed weather inputs). Surprisingly high rates of spread were observed at night and when wind speeds were relatively low (10-15 km/h), which is the main reason why the Vesta model under-predicted rates of spread using observed wind speeds. The model performed better when forecast wind speeds were used because these wind speeds were generally significantly higher than observed (Fig. 18). As discussed above, there may be a number of explanations for the unexpected high rates of spread under generally low to moderate ambient wind speeds including that the weather conditions at the AWSs may not have been similar to those on the fire ground. Because the two AWSs recorded similar data over the 6 days, we are not convinced that this was the case. Other possible explanations include fire-induced mixing down of dry slots, ‘scaling effects’ of wind gusts and steep terrain, at time, intense spotting and spot fire development, and the ‘plume-driven’ fire phenomenon.

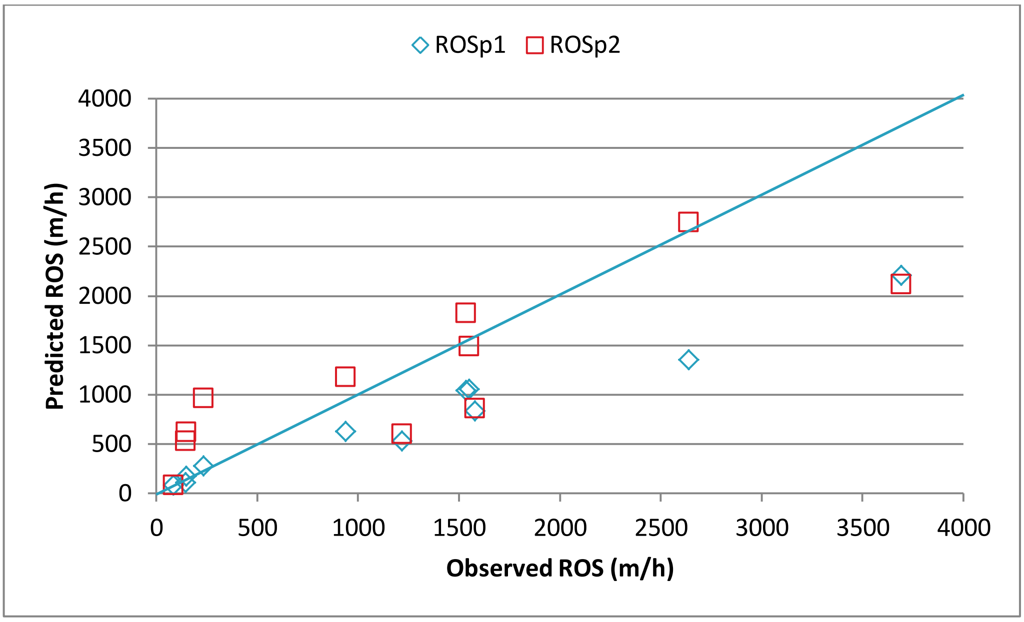


Figure 19: Observed rate of spread with predictions where ROSp1 = predictions made using observed weather and ROSp2 = predictions made using forecast weather. Blue line is perfect agreement between observed and predicted ROS.

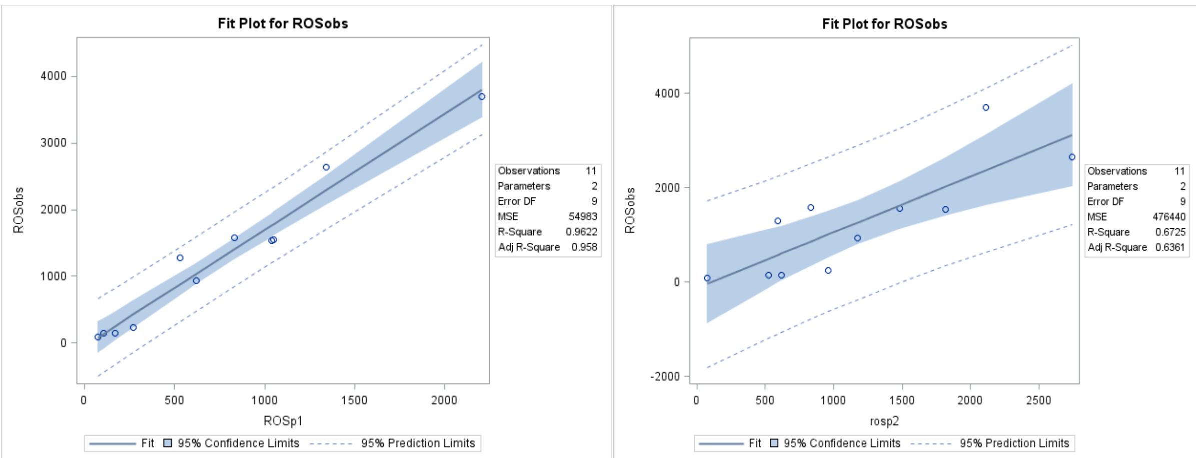


Figure 20: The relationship between observed and predicted rate of spread where ROSpred1 = predictions made using observed weather (Equation 1. Above) and ROSpred2 = predictions made using forecast weather (Equation 2 above).

There have been a number of well documented cases of plume driven fires, variously called ‘extreme fires’ or ‘coupled fire atmosphere’ events. Essentially these are fires that transition from being reasonably predictable surface driven fires (influenced by surface burning conditions - weather, fuel and topography), to ‘three dimensional’ fires that, through strong convection development (formation of Pyro-Cumulonimbus cloud)and interactions with the upper atmosphere, effectively increase wind speed at the fire front via poorly understood thermo-circulation processes. Our understanding of, and ability to predict transition to extreme fire behaviour is poor.

As well as being potentially damaging and dangerous to the community, extreme or 'plume driven' fires are dangerous and costly to control. McCrae and Sharples (2015) have recently produced a very useful 'Extreme Fire Handbook' that summarises current understanding of these events and provides some guidance to assist with anticipating extreme fires.

12. Conclusions

Caused by a lightning strike on private property, the Lower Hotham fire became a large, intense and a potentially damaging forest fire that was costly and dangerous to suppress. Even though the Forest Fire Danger Rating was mostly only Moderate to High during most of the fire's run, it became large because:

- It broke containment lines twice (hop overs/breakouts); once when it was very small (<2 ha) on 31 January and a second time on 3 February when it was ~2,450 ha.
- It displayed extreme fire behaviour, largely due to:
  - Warm to hot, dry weather.
  - Dry fuels; the SDI was ~1700 (170); the McArthur Drought Index was 10; grass was 100% cured; day time forest surface fuel moisture contents were <10% and as low as 4%.
  - Long unburnt forest/bushland fuels (5-40+ yrs). The Vesta hazard rating was Very High in older fuels.
  - Terrain was often steep and complex.
  - Periods of intense spotting.
  - Changing wind direction.

At times, the fire spread rapidly, up to double the speed predicted by the Vesta model. Surprisingly high rates of spread were maintained down slope, during periods of low wind speed and into the evening when the FFDR was falling, suggesting the fire was at times 'plume-driven'. While poorly understood, plume-driven fires essentially create their own fire weather, especially wind. They are usually associated with large fires burning under the fuel and weather conditions described above, and are characterised by violent convection columns and the formation of pyro-cumulonimbus cloud (Plate 5). Of the environmental factors that contribute to the development of plume-driven fires, which at their peak, are uncontrollable, management can only control the fuel hazard. This is best achieved by regular prescribed burning.

Plate 5: Pyro-cumulonimbus cloud, Lower Hotham fire 1118hrs 04/02/2015 (photo courtesy Steve Carnaby DPaW).

Acknowledgements

We wish to acknowledge the efforts of fire fighters in bringing this dangerous fire under control without serious injury. These include volunteer brigades from WA and inter-state, fire fighters from the Department of Parks and Wildlife, Department of Fire and Emergency Services, and from interstate fire and emergency services and land management agencies. We also thank the following people who in various ways, contributed to this reconstruction. Apologies to those we may have missed.

Shire of Boddington: Greg Day, Bob Jones (Marradong Volunteer Fire Brigade)

Department of Parks and Wildlife: Ross Mead, Ian Freeman, Brett Beecham, Michael Pasotti, Greg Mair, Cassidy Newland, Leigh Sage, Steve Carnaby, Lachie McCaw, Brad Johnson, Brad Bourke, Bryce Touchstone, Gareth Watkins, Michael Cirrilo, Glen Daniel, Cindy Miller, Drew Griffith, Anna Macdonald, Peter Gibson, Leon Price, Owen Donovan, Alf Lorkiewicz.

Department of Fire and Emergency Services: Michael Parker, John Landwehr, Troy Stubberfield, Tim O'Hara, Phil Graham, Gavin Wornes, David Horsey

Department of Agriculture and Food WA: Ian Foster

Forest Products Commission: Laurie Capill, Todd Britain

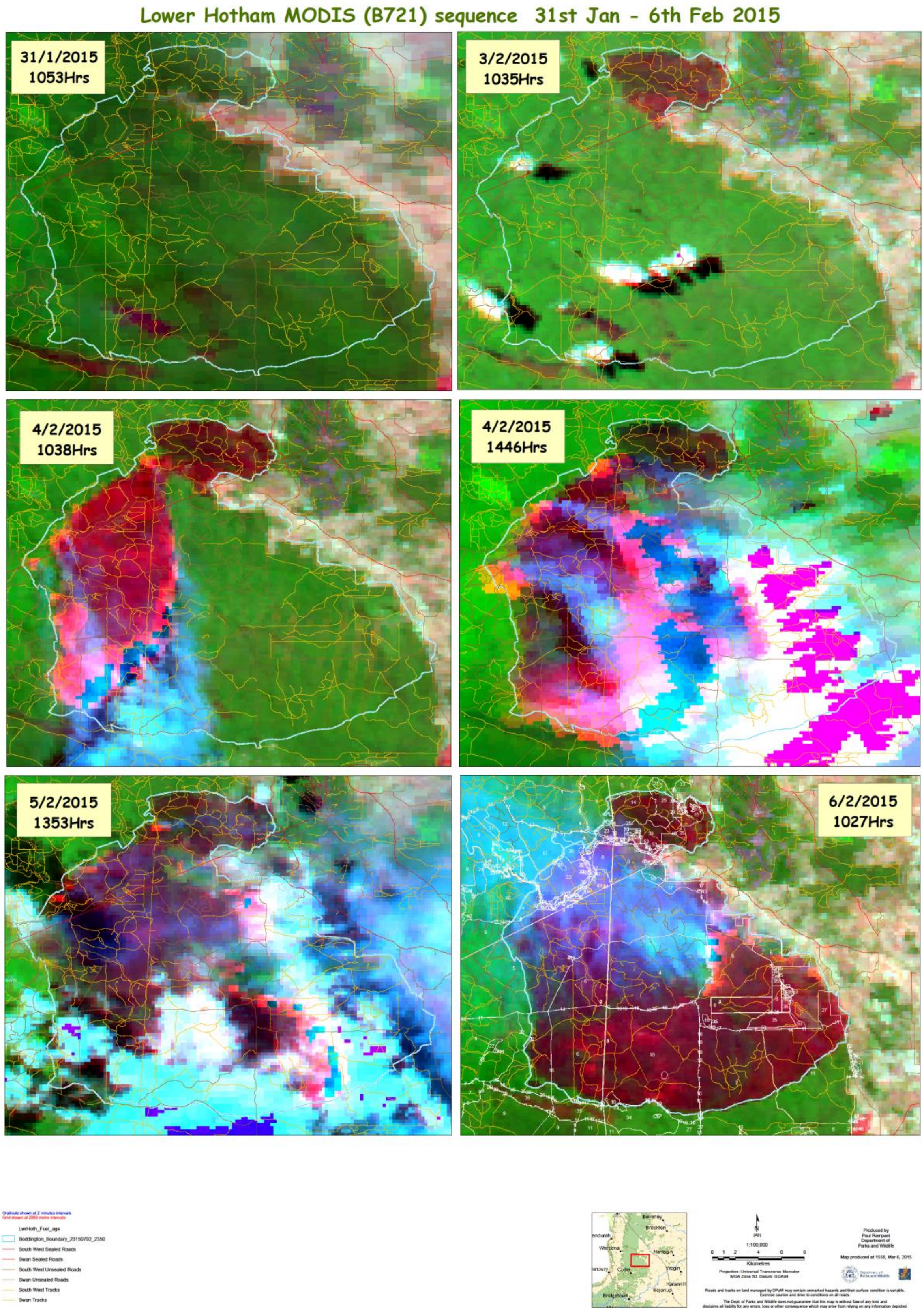
Bureau of Meteorology: Brad Santos, Graham Mills

WA Police: Alf Fordham

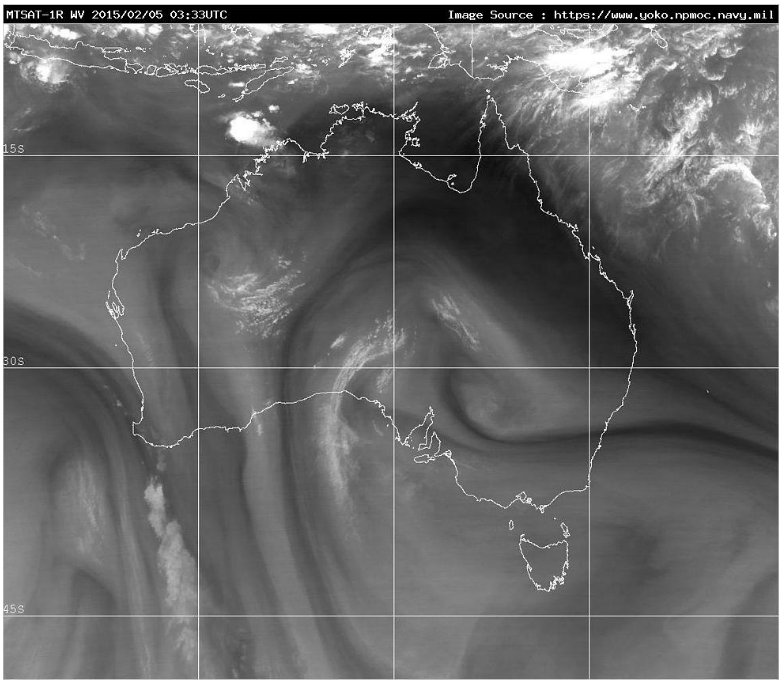
ACT Emergency Services: Rick McRae

Appendix 1

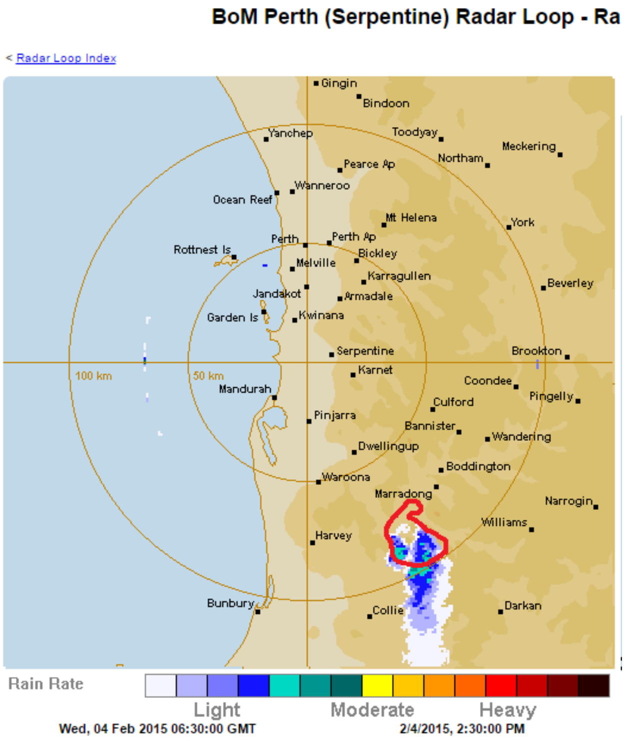
MODIS satellite imagery Lower Hotham fire



Appendix 2



Satellite imagery of atmospheric water vapour 05/02/2015. Dark bands associated with dry air.



Source: BoM via Brett Beecham