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DEVELOPMENT, BEHAVIOUR, THREAT AND METEOROLOGICAL ASPECTS OF A PLUME-DRIVEN BUSHFIRE IN WEST-CENTRAL VICTORIA: BERRINGA FIRE FEBRUARY 25-26, 1995

Research Report No. 48
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CFTT was commissioned to complete this project by Fire Management, Department of Natural Resources and Environment. The Bureau of Meteorology supported both Tony Leggett and Andrew Treloar in the undertaking of their reports.

SUMMARY

This report has been compiled to assist interested parties to better understand the more unusual aspects of the Berringa Fire (25 February 1995). The fire, and the monitoring that occurred during its development, provided a useful opportunity to describe the conditions leading to the development of its plume-driven phase. The report focuses on the conditions leading to the development of the plume-driven fire and the identification of possible early warning signs of impending danger to firefighters as a result of the convection column behaviour. Each of the three parts of this report is complete within itself (and can be read separately). However it is recommended that the report be read in its entirety.

Part one ("*Behaviour and Threat of a Plume-Driven Bushfire in West-Central Victoria*" by Kevin Tolhurst and Karen Chatto) examines the fire behaviour of the Berringa fire, and the threat posed to the safety of both firefighters and nearby residents' lives following the development of the convection column. The second and third parts of this report were written by Tony Leggett and Andrew Treloar (both from the Severe Weather Section, Bureau of Meteorology). "*Meteorological Aspects of the Berringa Fire of 25-26 February 1995*" by Tony Leggett describes in detail the overall meteorological aspects of the fire, whilst "*Meteorology of the Berringa Bushfire Smoke Plume*" by Andrew Treloar discusses the development of the plume and associated convective cloud. Parts two and three of the report provide important additional background information relevant to an understanding of the behaviour of this fire.

The data collection, data analysis and scientific writing was funded and supported by the Department of Natural Resources and Environment and the Bureau of Meteorology.

All three parts of this report were presented at the 13th International Fire and Forest Meteorology Conference held in Lorne, Victoria, Australia in October 1996.

CONTENTS

PART ONE

DEVELOPMENT, BEHAVIOUR AND THREAT OF A PLUME-DRIVEN BUSHFIRE IN WEST-CENTRAL VICTORIA

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CFTT

CENTRE FOR FOREST TREE TECHNOLOGY

SUMMARY

An average of 30 million hectares are burnt in Australia each year by prescribed and unplanned fires. Of this, 3 million hectares is in forests and grasslands of southern Australia and the remainder is in the savanna woodlands of northern Australia. South-eastern and south-western Australia are among the most fire prone areas in the world, and are also the most populated parts of Australia. Therefore the potential for natural disasters in southern Australia is great.

Most large bushfires in Australia are driven by strong winds and occur when conditions are hot and dry. In February 1995 just before 1200 hours (EDT), a bushfire started 25 km south-west of Ballarat, Victoria under extreme fire weather conditions (north-westerly wind of about 35 km/h, temperatures rising to 37°C and relative humidities dropping to 6%). Under these conditions, the fire accelerated to about 4 km/h with a fireline intensity of over 53,000 kW/m. However, late in the afternoon the wind dropped to less than 10 km/h and shifted to the south. Under these conditions the fire still spread at about 3 km/h (with a fireline intensity of 42,000 kW/m) and burnt the majority of the final fire area of 11,000 ha. The late afternoon run of this fire was driven by a convection column which rose directly above the fire. This plume was estimated at one stage to be rising at a vertical velocity of over 600 m/min. It rose to a height of about 10,000 m. The first part of this report discusses the importance of total fine fuel loads, wind speed, fuel moisture contents and short distance spotting in the spread of bushfires generally, and in relation to this fire in particular.

If conditions had been suitable for the convective cloud at the top of this plume to start cooling by the coalescence of ice or moisture, then the column may have collapsed with a downdraft estimated to be about 100 km/h. This may have rapidly spread the fire in all directions with very little notice. Firefighters' and nearby residents' lives may have been at serious risk. Similar situations in North America have resulted in the death of firefighters. This report concludes by identifying a need to be able to identify the conditions resulting in plume fire development and to better understand the possible downbursts that can result.

INTRODUCTION

The annual average area burnt by planned and unplanned fires in Australia is 30 million hectares (Tolhurst 1994). Victoria has one of the most fire prone environments in the world and whilst the average annual area burnt is only about 278,000 ha per annum, this can vary by a factor of ten in bad fire years (Department of Natural Resources and Environment, Victoria, Annual Reports 1982-1992). Of the 467 deaths caused by bushfires in Australia since 1900, 336 or 72% have occurred in Victoria (Hickman and Tarrant 1986) and of the insurance payouts for loss to private property by bushfires in Australia between 1970 and 1989, 69% of the $384 million was paid out in Victoria (Joy 1991).

On Saturday, 25th February 1995, a major bushfire which resulted from an escaped campfire, occurred near Berringa, 25 km south of Ballarat (Figure 1) in western Victoria. The forecast weather conditions were for Very High to Extreme Forest Fire Danger (McArthur 1967), so the day was declared a Total Fire Ban day. The fire started on private property in partially cleared native forest, entered Enfield State Park, and proceeded to burn over 80% of the western section of the Park. The fire threatened the small township of Enfield and destroyed seven homes, seven cars and other private assets, but no human life was lost.

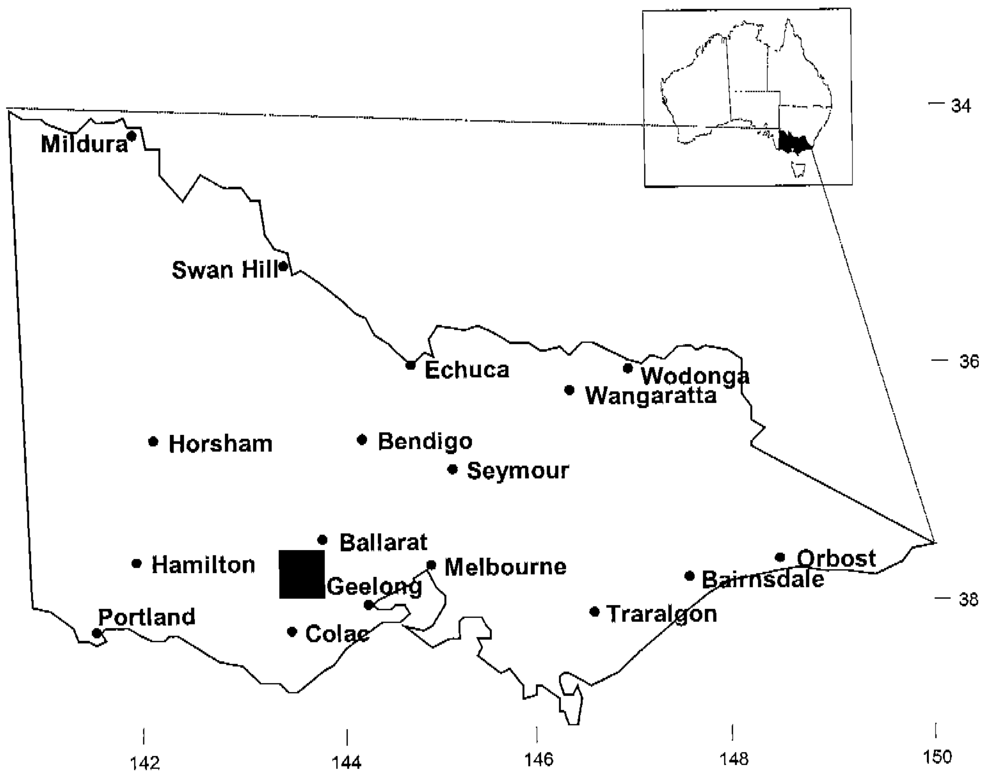

Figure 1. Location of the Berringa fire in west-central Victoria.

The Berringa fire had a significant convection driven phase (plume fire) during which time it had the potential to unexpectedly threaten the lives and property of those in the vicinity of the fire. The aim of this report is to document the observed fire behaviour, and to describe the conditions leading to the development of the plume-driven phase. The fire behaviour predictions from both the McArthur Forest Fire Danger Meter MkV (FFDM) (1973) and the Western Australian Forest Fire Behaviour Tables (FFBT), commonly known as the "Red

Book", (Sneeuwjagt and Peet 1985) were compared with observed fire behaviour. This study was aimed to identify the conditions leading to the development of a plume (driven) fire and to identify possible early warning signs of impending danger to firefighters from sudden changes in rates of spread resulting from a downburst of wind from the convection column.

METHODS

Site description

The majority of the area burnt in the Berringa fire was in the Enfield State Park. The Park is bounded by partially cleared private property with houses scattered through the private forest. Enfield State Park is located about 25 km south-west of Ballarat and 105 km west of Melbourne. The Park contains the headwaters of the Mount Misery Creek and is consequently dissected by hills and ridges with slopes ranging between 5° and 20°. The elevation at the southern end of the fire is as low as 260 m and gradually rises to 460 m at the northern end of the fire 16 km away. The northern end of the Park is less hilly than the southern end near the origin of the fire. Vehicular access is good with few areas more than one kilometre away from the nearest road or vehicular track.

Climate in the fire area is characterised by an average annual rainfall of around 720 mm which is spread throughout the year but with a clear peak in winter. Daily mean maximum temperatures in summer are about 26°C and in winter are about 10°C (Anon 1980). However, summer temperatures can reach 40°C and brief snowfalls occur in most winters. Extreme fire danger weather does not occur every year, but between 5 and 10 days can occur in dry years.

There were three major forest types in the area burnt (Anon 1980), all classified as Open Forest (30 to 70% foliage projective cover) and ranging in height from 15 to 28 m. Trees in the south were closer to 15 m in height and in the north were closer to 28 m, with the average tree height around 20 m. The predominant forest type in the south of the area was characterised by *Eucalyptus macrorrhyncha* (red stringybark), *E. dives* (broad-leaf peppermint) and *E. aromaphloia* (scent-bark) with an understorey of low shrubs such as *Pultenea* spp. (bush-peas), *Daviesia mimosoides* (narrow-leaf bitter pea), *Epacris impressa* (common heath), *Acacia paradoxa* (hedge wattle), *Xanthorrhoea minor* (small grass-tree), *Poa* spp. (tussock grass). The predominant forest type in the north of the area burnt was dominated by *Eucalyptus obliqua* (messmate) and *E. baxteri* (brown stringybark) in association with *E. dives*, *E. radiata* (narrow-leaf peppermint), *E. aromaphloia* (scent-bark), *E. macrorhyncha* (red stringybark), *E. ovata* (swamp gum) and *E. rubida* (candlebark) with an understorey of small shrubs and grasses. The third forest type is dominated by *E. ovata* (swamp gum), *E. aromaphloia* (scent-bark) and *E. radiata* (narrow-leaf peppermint) distributed in swampy areas along the northern and eastern boundaries of the Park, with an open understorey of *A. melanoxylon* (blackwood), *A. mearnsii* (black wattle), *Leptospermum continentale* (prickly tea-tree) and *Poa* spp. (tussock grass). Areas of grassland and open woodland occurred on private land outside the Park.

Data Collection

Weather data was collected before and during the fire from a Bureau of Meteorology automatic weather station (AWS) at Sheoaks, 48 km southeast of Berringa. This was supplemented by a portable AWS set up at Staffordshire Reef (about 1 km northeast of the origin of the fire) and a second portable weather station set up at Napoleons (about 15 km northeast of the origin of the fire and about 6 km east of the final fire boundary). Details of each weather station are given in Table 1.

Table 1. Details of the three weather stations used to collect data at the time of the Berringa fire.

	Sheoaks	*Staffordshire Reef*	*Napoleons*
Operator	Bureau of Meteorology permanent AWS	Authors portable AWS	Country Fire Authority portable AWS
Latitude / Longitude	37°55' 144°08'	37°45' 143°43'	37°41' 143°50'
Location	48 km SE of fire origin, open paddock	1 km NE of fire origin, open paddock with some trees to East	15 km NE of fire origin and 6 km E of final fire boundary, football ground
Elevation (m asl)	237	440	385
Anemomenter Height (m)	10	2	10
Wind Measurement Periods		5 minute average 5 second gusts	1 minute average
Air Temperature Sensor Height (m)	1.5	1.2	1.2
Frequency of Records	hourly	10 minutes	30 minutes
Duration of Records	continuous	1740 hrs 25/02/95 onwards	2000 hrs 25/02 to 0000 hrs 26/02/95, and 0600 hrs 26/02/95 onwards

Fine fuel moisture data was collected by taking litter-bed samples periodically throughout the fire. Approximately 100 g of litter was collected and placed in airtight tins which were then taken to the laboratory for weighing, drying at 105°C for at least 24 hours or until no further weight loss was measured, and reweighing to determine the moisture content of the samples. The litter-beds were quite shallow so the whole of the litter profile was taken in the sample. Estimates of variation in the surface fine fuel moisture were made using Pook's (1993) LITTER1 model and the two models in McArthur (1962, 1967) as expressed in equations in Viney (1991) and Viney and Hatton (1989).

Fire behaviour observations were made from various vantage points around the perimeter of the fire. Isochrones were drawn using the record of the radio traffic which included times and observations of when the fire had passed particular landmarks such as roads. The radio log was recorded to the nearest minute, so reports of fire positions should be accurate to within about ±10 minutes. After the fire, measurements of the freeze angle of leaves and small twigs scorched but unburnt by the fire were used to determine the fire direction at given points in the fire area. These were related back to the record of wind direction recorded at the Staffordshire Reef AWS and this was used to check the on-ground observations of fire position recorded in the radio log. It was assumed that the direction of the headfire spread and the wind direction when the fire was travelling on flat terrain. Observations of fire behaviour including spotting distances were made from the air by Hayden Biggs[1], an experienced aerial observer and firebombing commander. His observations started within the first two hours of the fire's ignition and continued through the main run of the fire.

Fuel assessment was carried out after the fire at five locations, three in unburnt forest adjacent to the burnt area and two within the burnt area. Surface fine fuel was assessed by taking 12, 0.1 m^2 litter samples and 12 measurements of litter-bed depth at the same sites. The surface fine fuels were oven dried, sorted into litter and humus fractions, and weighed. Humus was defined as the fragmented component of the surface fine fuel which passes through a 5 mm sieve, and litter was defined as the dead leaf, bark and twig material on the forest floor which was less than 6 mm in thickness and the live grass, herb and shrub material within 30 cm of the forest floor less than 2 mm in thickness. Elevated and bark fuels were assessed and classified according to the scheme proposed by Wilson (1992, 1993). The overall fuel (a combination of influences of bark, elevated and surface fine fuels) was determined using Wilson (1993). The amount of fine fuel burnt was taken to be the difference between the average of the unburnt area fuel loads and the burnt area fuel loads.

Each elevated and bark fuel class was assigned an equivalent fuel loading for the purpose of applying the FFDM (McArthur 1973) and FFBT (Sneeuwjagt & Peet 1985) fire behaviour models. Table 2 gives the equivalent fuel loads for each fuel class in the elevated and bark assessments. These estimates of fuel loads for elevated fuels are extrapolated from Fogarty's (1993) measurement of available fine fuel load in wiregrass fuels in a Very High hazard elevated fuel of 6 t/ha and estimates for available bark fine fuels are based on Tolhurst *et al*.s' (1992) measurements of 7 t/ha for Extreme bark fuel hazard. The total bark and elevated biomass is greater than these amounts, but only the potentially available fine fuels were assessed here.

Table 2. Equivalent fuel loads (t/ha) for the elevated and bark fuel classes (McCarthy *et al.* 1998).

	Hazard Level				
	Low	*Moderate*	*High*	*Very High*	*Extreme*
Elevated	0	0	2	6	10
Bark	0	0	2	5	7

[1] Hayden Biggs, Air Attack Supervisor, Dept. Natural Resources & Environment, Ballarat, Victoria

In addition to the surface, elevated and bark fine fuel, the available fine fuel in the tree canopies was also estimated because the crowns were also burning in the fire front for much of the time. Two studies of canopy leaf and twig biomass in dry sclerophyll forest in Victoria found the biomass to average 12.7 t/ha (Loyn 1980) and 12.1 t/ha (Stewart *et al.* 1979) respectively. A further study by Stewart and Flinn (1985) in similar forest found 9.8 t/ha of leaf and twig material was lost through slash burning, so an average of 10 t/ha of fine fuels was used as an estimate of the available fine fuel in the live canopies of the trees in the Berringa fire.

Data Analysis
Two fire behaviour models were tested - FFDM (McArthur 1967, 1973) and FFBT (Sneeuwjagt and Peet 1985). Input parameters to each model were predicted on the basis of the estimated values as made by functions or assumptions in the models as well as by direct measurements of the parameters. The relative performance of the models in predicting the observed input parameters as well as predicting the observed fire behaviour were evaluated. Comparisons were made between the observed and predicted forward rates of spread each hour between 1200 and 2000 hours[2]. A comparison was also made between the predicted and observed average rate of spread of the fire between 1200 and 1600 hours, and 1600 and 2000 hours. The fire was split into these two periods based on the changed weather conditions and forces driving the fire. Between 1200 and 1600 hours the fire was driven by winds of 30 to 35 km/h from the northwest and between 1600 and 2000 hours the fire was driven by the convection of the smoke plume.

For McArthur's model, the Drought Factor, an estimate of fuel availability, was used as estimated on the FFDM (McArthur 1967, 1973) by the number of days since rain and the amount of rainfall as well as being fixed at the observed level. The observed fuel availability factor was calculated by measuring the total fine fuel before and after the fire to determine the proportion actually burnt. Next the fine fuel moisture content as estimated by the FFDM using observed inputs of air temperature and relative humidity was used, and compared with moisture contents measured from field samples. Next, the effect of altering the wind ratio function which estimates the wind speed at the fire front in the forest from the wind speed in the open at 10 m above the ground was tested. The effect of incorporating ground slope in the fire behaviour prediction once the fire had developed was investigated. Finally, the effect of altering the fine fuel load to incorporate additional amounts of fuel from the forest profile as the fire developed was examined.

Inputs to the FFBT (Sneeuwjagt and Peet 1985) were adjusted to investigate which variables needed alteration to give the best correlation between the observed and predicted fire behaviour. Input variables tested were the surface fine fuel moisture content, surface fine fuel load, fine fuel availability, air temperature, relative humidity, ground slope and wind ratio factor.

Measurements of the smoke plume height were made from photographs taken at about 20 km north of the fire. The distance from the smoke plume and the focal length of the camera were used to calculate the scale of the photograph and hence scale the height of the plume.

[2] All times referred to are Eastern Daylight Savings Times (that is EST minus one hour).

RESULTS

The fire began just before noon under extreme fire weather conditions. By 1330 hours the wind was nor-nor-westerly with a strength of about 35 km/h, air temperature was 37°C and relative humidity was 6%. By late afternoon on the 25th, the wind speed had dropped to less than 10 km/h and changed direction to southwesterly, whilst temperature and relative humidity moderated only slightly. At this time the fire changed from being a wind driven fire to one driven by the convection column vertically above the fire. It was during this time that the majority of the final area of 11,000 ha was burnt.

A detailed description of the weather conditions before and during the fire is given in Leggett (1996), Leggett (1998) and Leggett *et al.* (in press.). Figures 2a and 2b show the temperature, relative humidity, wind speed and wind direction recorded at Staffordshire Reef near the origin of the fire. When the fire started, the temperature was about 34°C and rose to 37°C where it stayed for the period of the wind driven phase of the fire. Soon after 1800 hours, the temperature dropped about 5°C in an hour and continued to decline until it reached 25°C by midnight. Relative humidity was only 33% at 0700 hours on the morning of the fire and had dropped quickly to 10% by the time the fire started. It continued to decline to a low of 6% where it remained for most of the afternoon until about 1600 hours when it gradually started to rise again, but it only increased slowly until 1800 hours and then rose more quickly until it had reached 35% by 2000 hours and 40% by midnight. The wind had gradually strengthened during the morning of the fire until it averaged about 30 km/h when the fire started. It rose to about 33 km/h by 1400 hours with gusts reaching 57 km/h. After 1400 hours, the wind gradually abated until by 1600 hours it was averaging 10 km/h or less. When the fire started, the wind was coming from the nor-nor-west and gradually moved more westerly until 1800 hours when it suddenly changed to be southerly and then gradually moved to the southeast by 2000 hours. The Forest Fire Danger was Extreme during the early afternoon and continued to be Very High until about 1800 hours.

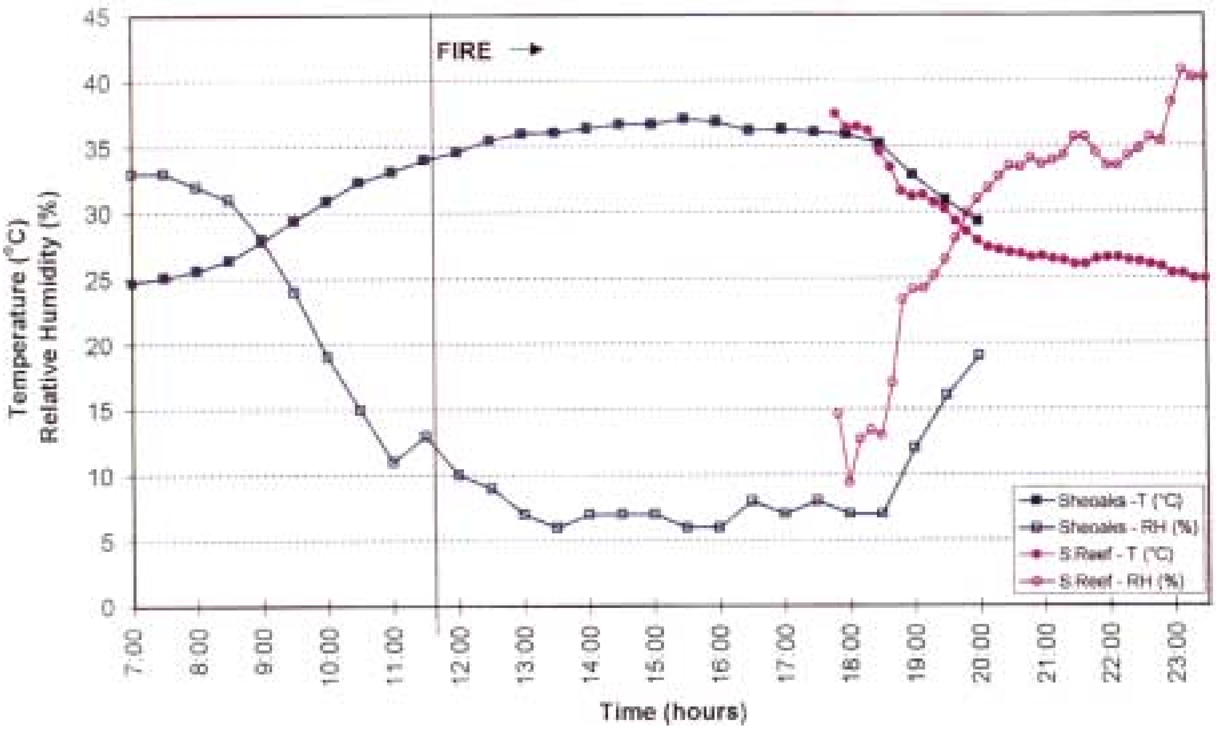

Figure 2a. **Ambient air temperature and relative humidity measured at Sheoaks AWS until 2000 hours and Staffordshire Reef AWS after 1740 hours on 25th February 1995.**

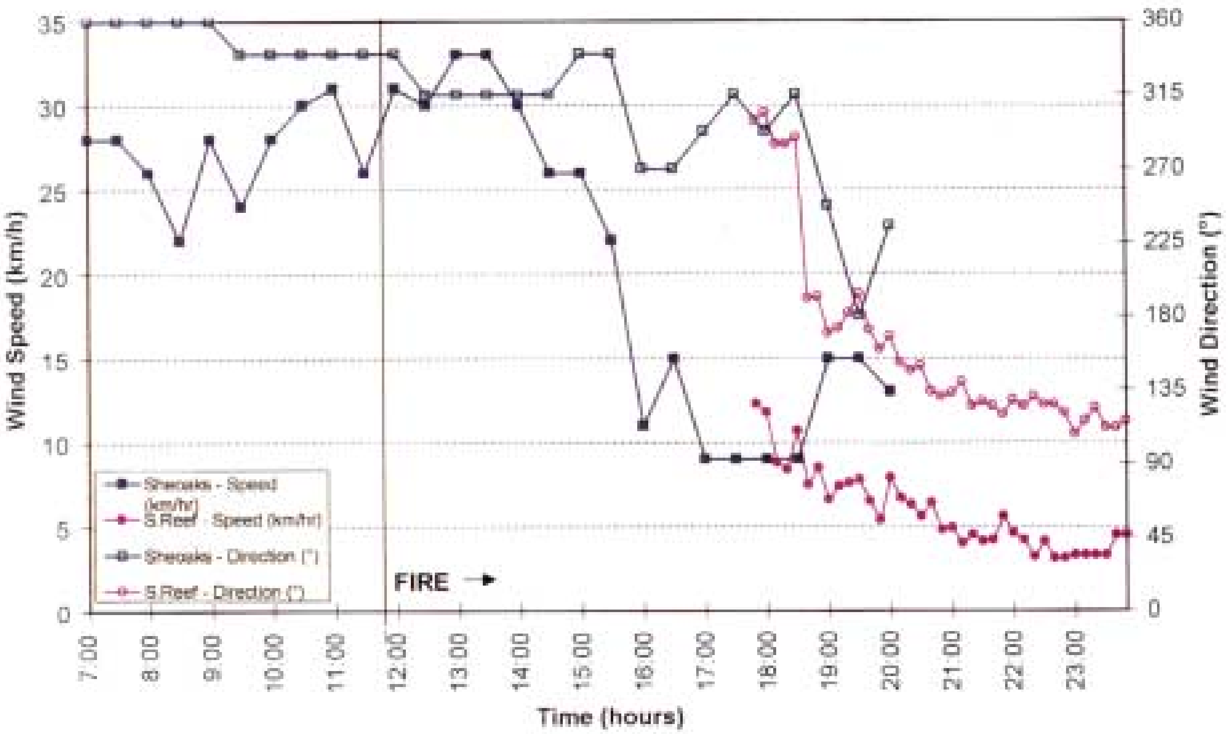

Figure 2b. **Wind speed and wind direction measured at 2 m height at Sheoaks AWS until 2000 hours and Staffordshire Reef AWS after 1740 hours on 25th February 1995.**

Observed surface fine fuel moisture contents ranged between 6.6 and 12.7% oven dry weight, however no fuel moisture samples were taken during the early afternoon of the 25th February when the fuel moistures would have been at their lowest. Figure 3 shows the predicted fuel moisture contents using the models in McArthur's Control Burning Guide (1962), McArthur's Forest Fire Danger Meter (1967) and Pook's (1993) LITTER1 model. McArthur's Control Burning Guide (CBG) fuel moisture model showed the best agreement with the observed readings, especially when a local calibration factor of 1.5 is added to the model as suggested by Pook (1993). Pook's LITTER1 model fluctuates much more widely than was observed in the field and McArthur's Forest Fire Danger Meter (FFDM) model showed little diurnal variation and underestimated the surface fine fuel moisture content by about 5%. The fine fuel moisture content during the early afternoon was therefore probably as low as 3.0% and did not rise significantly until about 1800 hours. Both of McArthur's fine fuel moisture models agree between about 1200 and 1800 hours.

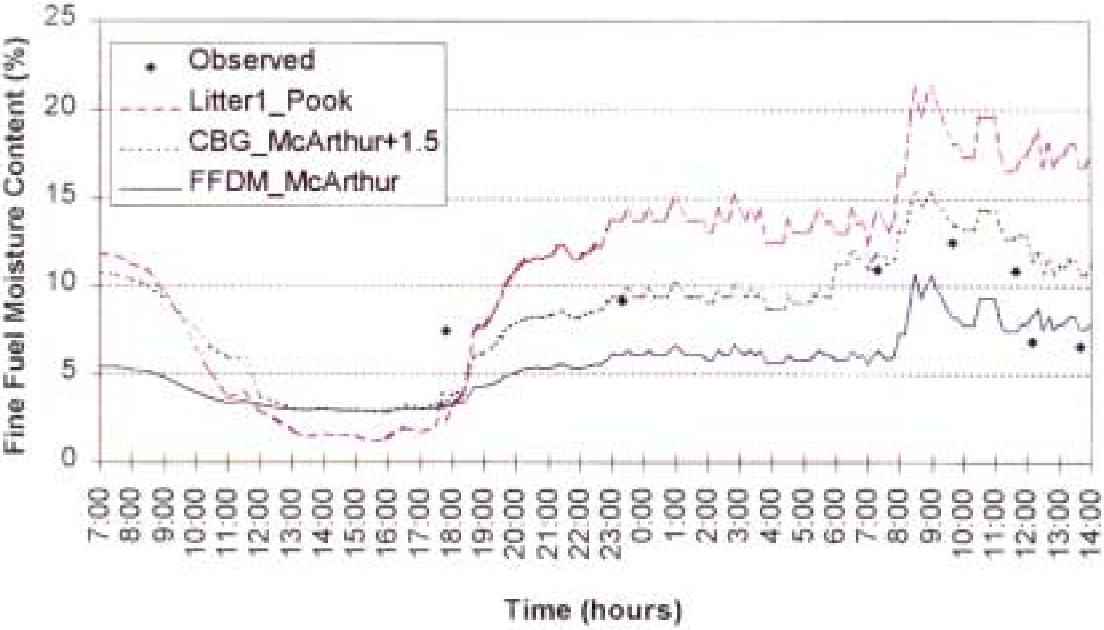

Figure 3. Observed surface fuel moisture content compared with the predicted moisture content from the LITTER1 model of Pook (1993), control burning guide (CBG) (McArthur 1962) +1.5 and the FFDM (McArthur 1967) on the 25th and 26th February, 1995 at the Berringa fire.

Due to the low surface fuel moisture contents, spotting was prevalent throughout the duration of the fire. Spotting was estimated to be 300-500 m ahead of the main fire front according to H. Biggs (pers.comm.). At 1510 hours, a spot fire was reported to the southeast of the main fire front, which most likely led to the forward rate of spread of 4 km/h of the fire between 1500 and 1600 hours. Spotting continued, carrying the fire from ridge to ridge. The transmission line was lost due to increased spotting across the line.

Surface fine fuel loads ranged between 10.4 t/ha and 14.1 t/ha in the unburnt adjoining forest. Within the burnt area, 3.1 t/ha of predominantly fragmented "humus" material remained in a crown scorched area and 1.5 t/ha of totally fragmented material remained in an area burnt by crown fire. A summary of the surface fine fuel loads at the five sites assessed is given in Table 3.

Table 3. Surface fine fuel loads within the burnt area and in adjacent unburnt areas at the Berringa fire.

	Humus (t/ha)	*Litter (t/ha)*	*Total (t/ha)*	*Depth (mm)*	*Packing Ratio (t/ha/mm)*
Unburnt - Fire Origin	2.0	8.3	10.4	29	0.372
Unburnt - Enfield	2.9	11.0	14.1	40	0.372
Unburnt - Doctors Rd	3.1	8.4	11.5	33	0.362
Crown Scorch - Doctors Rd	2.5	0.7	3.2	9	0.396
Crown Fire - Mt Misery	1.5	0.0	1.5	6	0.264

The average overall fuel rating for the Berringa fire area was Very High. The main contributing factor to this was the presence of Very High bark fuel due to the presence of stringybark trees in the overstorey. Table 4 shows the fuel assessment at three representative sites. The Enfield site was chosen because it had one of the most important fuel types and the Fire Origin site was chosen because of its importance to the whole fire history and because it was considered to be of low fire hazard within the Berringa Fire. There was surprisingly very little variation in the overall fuel across the fire area. For the purposes of predicting fire behaviour, a surface fine fuel load of 12 t/ha was used, an overall fine fuel load in the understorey was taken to be 17 t/ha, and the amount of available fine fuel in the tree canopy was taken to be 10 t/ha. The total amount of fine fuel available for the crown fire was therefore estimated as 27 t/ha.

Table 4. Pre-fire Overall Fuel Class Ratings for the Berringa fire area and the equivalent fuel loads (t/ha) in parentheses.

	Surface Fine Fuel	*Elevated Fuel*	*Bark Fuel*	*Overall Fuel*
Fire Origin	High (10)	Moderate (0)	Very High (5)	Very High (15)
Enfield	Very High (14)	High (2)	Very High (5)	Very High (21)
Doctors Rd	High (12)	Moderate (0)	Very High (5)	Very High (17)

The fireline shown by isochrones in Figure 4 may indeed show where the fireline was at a particular point in time, however it is unknown whether this is the fireline of the main fire, or the fireline of a spot fire. It was therefore assumed that the firelines shown are actually the firelines of the main fire. Forward rates of spread were calculated from the isochrones. These forward rates of spread are the average forward rates of spread for a particular time period. As only the average rate of spread for any particular time period was calculated, it is likely that the actual rate of spread was faster or slower. Gaps in the timeline indicate a lack of information available. The northwest sector of the fire was being managed by the Country Fire Authority, and their radio log lacked the detailed information used previously from 2000 hours onwards.

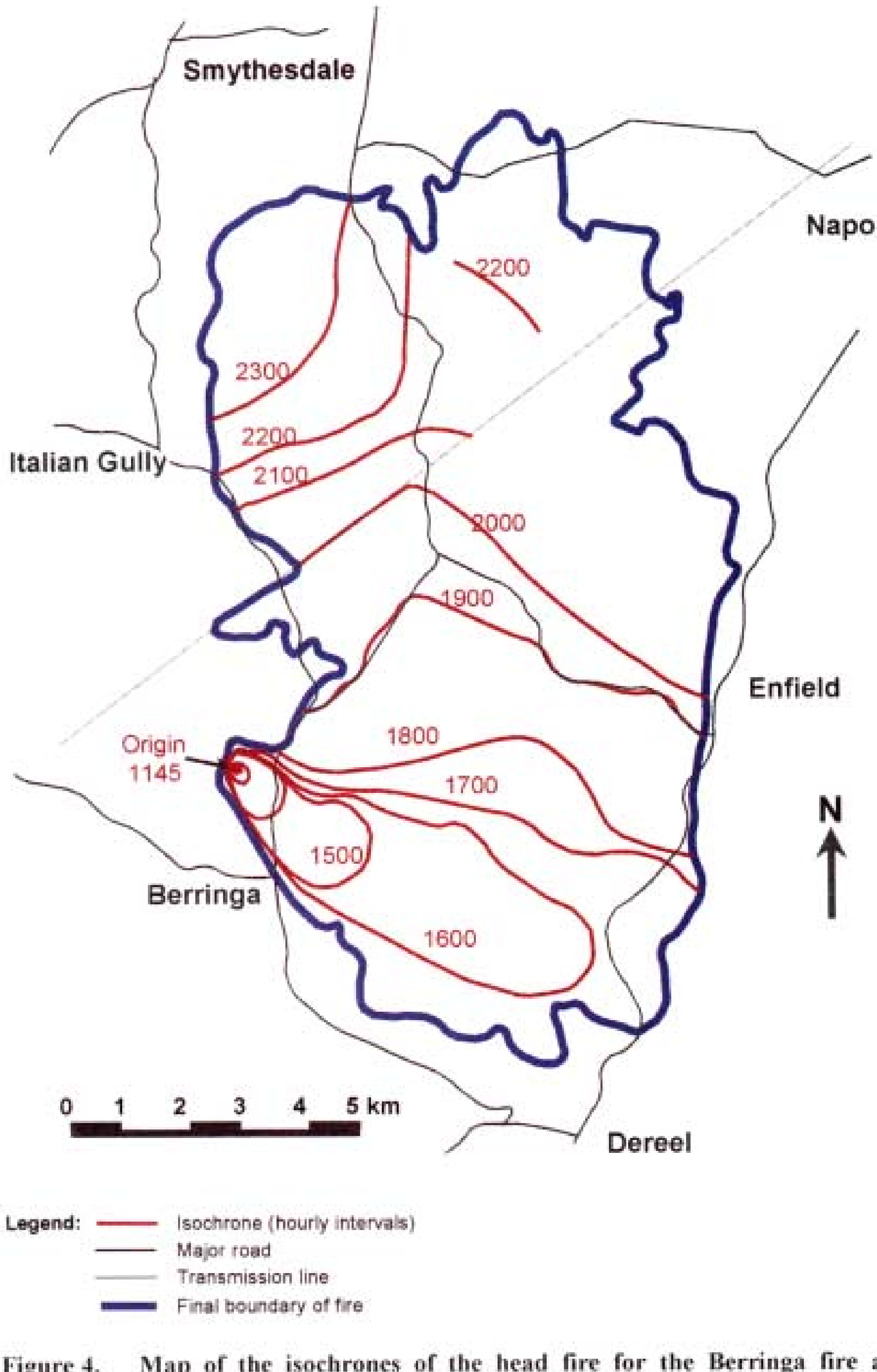

Figure 4. **Map of the isochrones of the head fire for the Berringa fire at hourly intervals on 25th February 1995.**

McArthur's (1967, 1973) FFDM when used in the standard fashion, underpredicted the average rate of spread of the wind-driven component of the fire (1200 to 1600 hours) by a factor of about 2.0. In Figure 5, the rate of spread predicted with standard inputs is shown by the line labelled "No-slope". McArthur (1967) says that once the fire has had a chance to develop (about 2 hours), then slope is not important as the effect of spotting carries the fire from ridge to ridge and nullifies its effect. The predicted rates of spread, however, were much closer to matching those observed when slopes were included (Figure 5, "Slope") assuming all slopes are uphill and ignoring the downhill component. The wind ratio between 10 m in the open and that expected in the forest at 1.5 m was estimated to be 3.0 (McArthur 1967), but "Wind_2" shows the effect of using a wind ratio factor of 2.0 instead. Adjusting this ratio improved the rate of spread predictions but this change could not be justified on the basis of the tree height, cover and density in this forest. McArthur's model predicted that 70% of the fine fuel should be available for consumption in the fire front, but 10 out of 12 t/ha , or about 80%, was in fact available. In Figure 5, the line "DF8" shows the effect of correcting this input, but the effect is not great. The available fine fuel loads were increased to include the elevated and bark components as shown in Table 3. The rate of spread predictions made using this value for fine fuel load is shown in Figure 5 by the line labelled "17 t/ha". This improved the predicted rate of spread estimates, but on average it was still about 25% less than was observed for the fire up until 1600 hours. The best estimate of fire spread rates were when the fine fuel load was adjusted to include all the components involved in the flaming front of the fire. Initially, it was observed only the surface fine fuel was involved in the fire, by about 1200 hours, the surface fine fuel, the elevated fuels and the bark fuels were all involved, and by 1400 hours the crown fine fuels were involved as well. Using this changing fine fuel load information, the line "Overall_FF" showed relatively close agreement with the observed rate of spread. By 1600 hours, the observed and predicted rates of spread only differed by about 10%. Between 1600 and 2000 hours when the fire was in the convection driven phase, McArthur's model was a factor of two out in its prediction of rate of spread even when the overall fine fuel load was used.

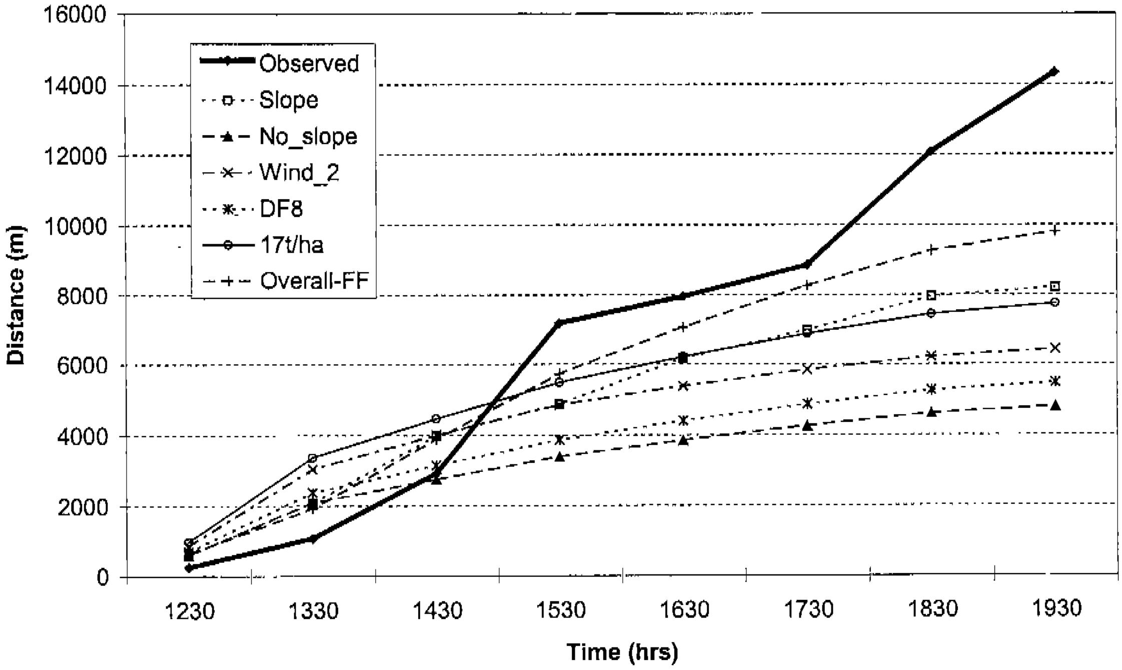

Figure 5. Comparisons between the observed cumulative forward rate of spread ("Observed") in the Berringa fire and those predicted by the McArthur (1973) FFDM; predicted rates of spread when slopes are included in the calculations ("Slope"), slopes are only included for the first two hours as recommended by McArthur (1973) ("No_Slope"),a wind ratio between 10 m wind speed and 1.5 m wind spedd is 2.0 instead of 3.0 ("Wind_2"), the observed drought factor of 8 is used instead of the predicted 7 ("DF8"), fine fuel load includes surface fine fuel as well as elevated and bark fuel loads ("17t/ha"), fine fuel load includes surface fine fuel, elevated, bark and canopy fuel loads ("Overall_FF"). Rates of spread are expressed as the cumulative distance travelled from 1200 hours on the 25th February 1995.

The FFBT (Sneeuwjagt and Peet 1985) was developed for a different forest, but is based on extensive empirical data, so it was evaluated as well. The average rate of spread up until 1600 hours showed close agreement with what was observed, but the shape of the curves were quite different (Figure 6). The FFBT overestimated the forward rate of spread by a factor of about two earlier in the fire development. Altering the fuel moisture content from 8% to 3% did not significantly change the predicted rates of spread. The predictions from the FFBT were very sensitive to the wind ratio factor used. Changing the wind ratio from 2.5 to 2.6 made a 20% change in the predicted rate of spread, and changing the wind ratio from 3.0 to 2.5 more than doubled the predicted rate of spread. The FFBT's prediction of forward rate of spread, after the wind dropped (and the fire was plume-driven), was out by more than an order of magnitude.

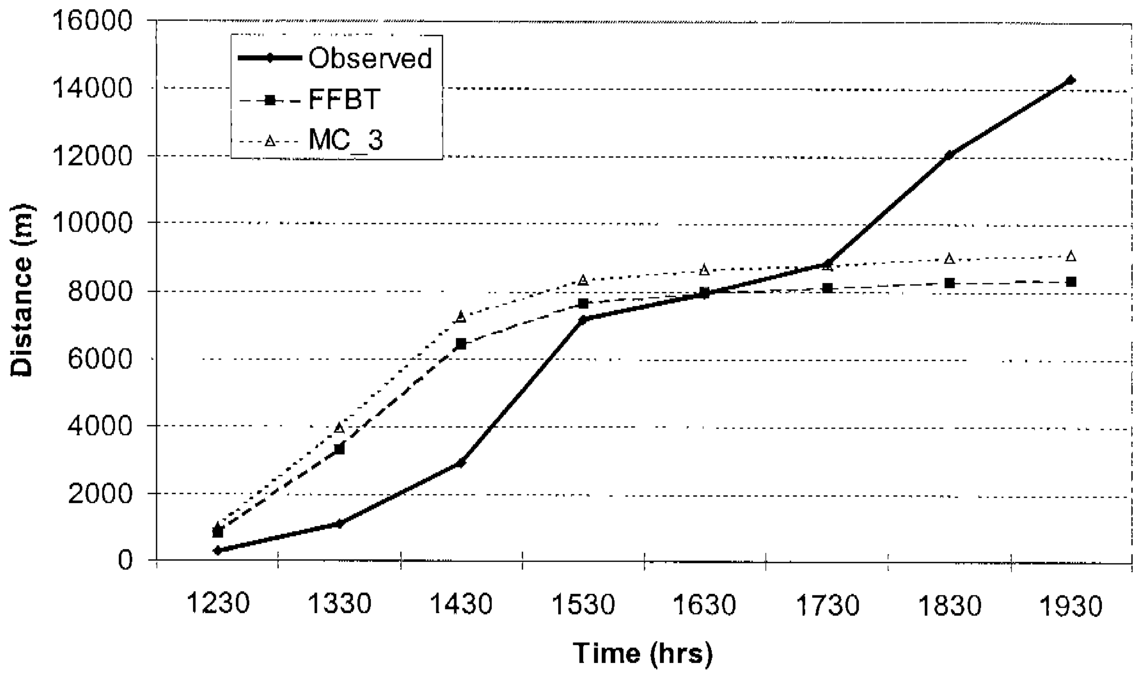

Figure 6. Comparisons between the observed cumulative forward rate of spread ("Observed") in the Berringa fire and those predicted by the FFBT (Sneeuwjagt & Peet 1985); predicted rate of spread using the FFBTs in the standard fashion ("FFBT"), using 3% as the minimum surface moisture content instead of 8% ("MC_3"). Rates of spread are expressed as the cumulative distance travelled from 1200 hours on the 25th February 1995.

Plume height was estimated from three photographs and is recorded in Table 5. Throughout most of the afternoon, the plume rose to about 6,000 m, but at about 1830 hours the plume began to climb rapidly. By 2000 hours, the plume had risen to about 10,000 m following the entrainment of moister air from the cooler change from the south. The vertical velocity of the plume at this time was estimated to be at least 39.6 km/h, or around 11 m/s (Treloar 1996).

Table 5. Plume height of the Berringa fire, 25th February 1996.

Viewing point	Time (hours)	Height (m)
Mt Rowan	1566	6,100 ± 670
Smythes Creek	1819	5,700 ± 620
Ballarat Airport	1957	9,800 ± 1,100

DISCUSSION

Although the weather conditions experienced on the 25th February 1995 were forecast to be hot and dry, the air was in fact much drier than forecast. The forecast relative humidity was 20% whereas it actually fell to 6%. Meteorologists find it difficult to accurately forecast such dry conditions, yet it is these very dry conditions which lead to the severe fire behaviour and the development of the plume driven fire. The very dry conditions lead to rapid rates of spread and the increased chance of fire brands starting spot fires ahead of the fire front. McArthur (1967) reported that the heat release of fuel at 3% moisture content is four times that of fuel at 10% moisture content and Luke and McArthur (1978) state that below 7%, rates of spread will double for each 2% drop in fuel moisture. The conditions at the Berringa fire were such that the predicted minimum moisture content was 3% (according to McArthur (1967)).

A feature of the weather during the development of this fire was the formation of the pre-frontal trough where the northwesterly and southwesterly winds converged. This trough was over the area of the fire between approximately 1830 hours and 2000 hours. It was during this time that the fire burnt almost half the total area finally burnt. This situation was akin to that existing during the Hellgate fire in western Virginia (Taylor and Williams 1968). Taylor and Williams (1968) found that the large-scale negative divergence and cyclonic vorticity of the surface wind appeared to contribute to the vertical development of the fire. These are the same features present in the development of thunderstorms, so meteorologists could use the same methods for forecasting areas of possible unusual fire behaviour as they do for forecasting areas of possible thunderstorms.

The moist air which arrived with the southwesterly airstream was probably responsible for the increased fire behaviour between 1830 and 2000 hours. Vines (1973) noted that as a large amount of moist air was entrained into the smoke plume, there was a large increase in the convective activity of the plume. The moisture from the entrained air, in addition to the smaller amounts produced by the fires themselves, rose to the level of condensation at which point the latent-heat of vaporisation was released, increasing the convective activity of the plume. Vines (1973) found that the amount of latent heat released in a large fire was almost as great at that produced by the burning fuel and therefore doubling the convective activity. This may explain why the predicted rates of spread between 1600 and 2000 hours were almost exactly half that observed. This effect on the convective activity was most pronounced between 1830 and 2000 hours when a sudden increase in height of the convection column from about 6,000 m to 10,000 m occurred. After a period of about two hours, the moisture in the air had had time to increase the surface fuel moisture content from around 3% to about 8% which is sufficient to reduce the rate of fire spread by a factor of four (Luke and McArthur 1978).

Only a few large convection driven fires have ever been documented. In Australia, Taylor *et al.* (1968) reported on the meso-meteorological conditions of five large-scale prescribed fires in the south-western part of Western Australia. These fires exhibited a significant degree of convective activity due to the mass ignition methods used. They serve as a useful base for understanding the development of plumes and the effect they have on fire behaviour. Rothermel (1991) reviewed the North American literature and cites the Butte fire in 1985, the Mack Lake fire in 1980, the Dude fire of 1990 and the Shoshone fire in Yellowstone National Park in 1988 as examples of plume driven fires. A feature of these fires was the unexpected fire behaviour which resulted in six fatalities in the Dude fire, one fatality in the Mack Lake fire and a near miss for 73 firefighters at the Butte fire. The rapid spread rates of these fires were equivalent to wind driven fires, but the sudden increase in fire behaviour was not predicted by those at the fires.

A feature of convection driven fires is their ability to produce unexpected gale-force downbursts. As with a thunder cloud, the rising moisture in the convection column eventually condenses. When the droplets of moisture coalesce to form large drops, they begin to fall into the column and cool the air in it. When enough water coalesces, it will cool the column sufficiently for it to reverse and result in a sudden downburst as in a thunderstorm. Because in a plume driven fire the column is directly over the fire area, this downburst increases horizontal wind speeds resulting in markedly increased rates of spread, potentially catching firefighters unaware. Rothermel (1991) reports on two instances where this has happened in North America resulting in the loss of lives, and he cites another instance where a team of firefighters were seriously threatened by a downburst. Fortunately there was no downburst in the Berringa fire. It was estimated by Treloar (pers. comm.) using meteorological models available to him, that had the Berringa convection column collapsed, the resultant downburst would have had a surface wind speed of around 100 km/h and a duration of a few minutes. This would have seriously threatened the lives of firefighters. However, we have no way at present of predicting the occurrence of such a downburst. Rothermel (1991) suggested that one indicator is the occurrence of precipitation below the plume, and another is an unusual calm which develops before a downburst. Firefighters on the perimeter of the fire must be aware of these signs and respond quickly. Another indication that a downburst may occur is the presence of virga, but this can only be observed at a distance from the fire. Therefore, there is a need to have an observer watching for these signs that the column may collapse and so warn firefighters near the fire..

During the wind driven phase of the fire between 1200 and 1600 hours, the rates of spread were reasonably well predicted by the McArthur Forest Fire Danger Meter for about the first two hours, but then underpredicted by a factor of three or more. This underestimation by a factor of three has been observed elsewhere by Cheney[3] (pers. comm.) and by McArthur himself (1967). McArthur attributed this underestimation to the fire being spread predominantly via spotting. Spotting overcomes any physical barriers to the spread of fire and it also creates small fires ahead of the main fire front which may either draw the fire front forward by the additional convective forces or form a new fire front and hence advance the fire spread rate. Cheney (1991) discounted the idea of new fronts forming from spot fires because most of them are drawn back into the main fire front. However, in this study, where spotting was also prevalent, McArthur's Forest Fire Danger Meter predicted the observed rates of spread between 1200 and 1600 hours providing all the fine fuel in the flaming zone was included. McArthur (1967) provides a conceptual model of fires accelerating in stages as first the surface fuels, then the shrub fuels and finally the tree crowns become incorporated into the flaming front. In this study we have included the estimated fuel load contributed by each fuel stratum as the fire developed. This provided a very good average rate of spread for this time period even if the hour by hour estimates were out by up to a factor of two. It was therefore concluded that the main reason for the poor performance of the model was because the definition of fine fuel is generally viewed too narrowly and should include the elevated, bark and tree canopy fuels.

[3] Cheney, N.P. Bushfire Unit, Division of Forestry, CSIRO, PO Box 4008, Queen Victoria Terrace, ACT 2600

Factors affecting the McArthur predictions of rates of spread were found to be of relatively minor importance in this case as the forest and weather conditions experienced here were similar to those to where the meter was developed. The predicted fine fuel moisture content, the fine fuel availability factor and the wind ratio factor were all accurately predicted for this fire. Such agreement is not always to be found.

The average rate of spread predictions made by the FFBT (Sneeuwjagt and Peet 1985) were generally accurate for the wind-driven phase of the fire. However, the FFBT overestimated the rate of spread by a factor of about two for the first two hours and then severely underestimated the rate of spread from then on. It was found that the estimates of rate of spread were very sensitive to the wind ratio factor used. This indicated that great care should be taken in determining this factor if the predicted rates of spread are to be reliable and several factors may need to be used in large fires. The FFBT's predicted rates of spread deviated significantly from the observed rates of spread in this instance, and is probably not suited to the forests and climates of south-eastern Australia.

CONCLUSIONS

McArthur's Forest Fire Danger Meter provided an estimate of forward rate of spread when it is wind driven provided the fuel load (based on the amount of consumed fuels) was used for the model. Other inputs such as fine fuel moisture content, wind reduction factor, and drought factor all need to be measured directly if possible to improve the performance of the fire behaviour estimates. The overall fuel must be assessed and expressed in terms of a fuel load if the model is to be used effectively.

Further observations and research are needed to determine the importance of increased convective activity as a result of masses of spotfires ahead of the main fire front. Comparisons need to be made between forest types with strong spotting characteristics and those less prone to spotting.

Weather forecasts should note the location of troughs along which thunderstorms could develop and where fires, if they occur could display unexpected fire behaviour. If a fire does occur in the vicinity of a trough, the convection column should be regularly monitored to determine if the fire is being driven by the convection column or the prevailing winds.

If a fire is plume driven, then fire behaviour can be expected to increase when a parcel of moist air is entrained into the column. Heightened convective activity can then be expected for a period of about two hours.

An observer should be made available as part of an Incident Management Team to monitor the convection column of the plume driven fire. Their role would be to alert firefighters of an imminent downburst.

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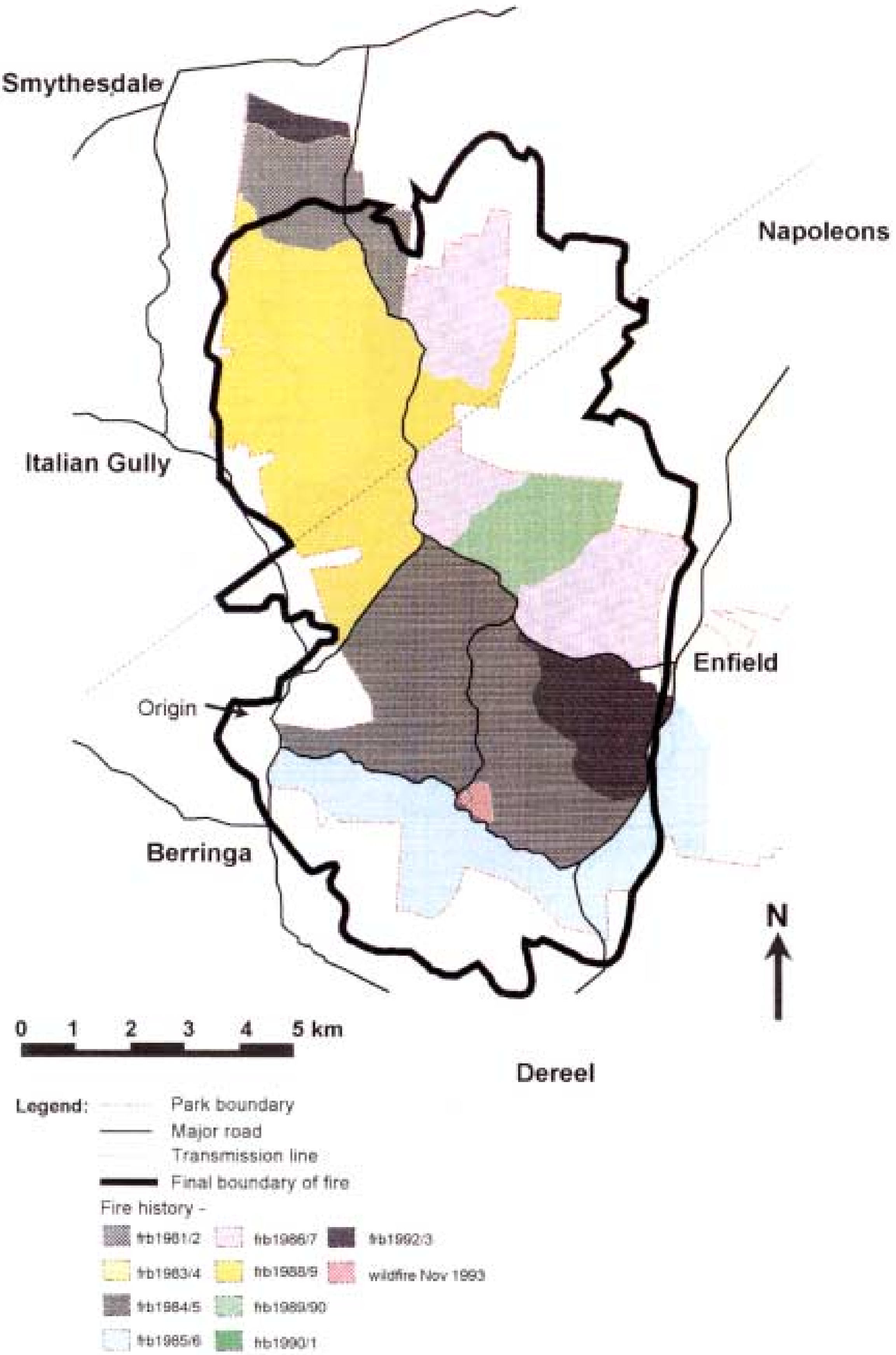
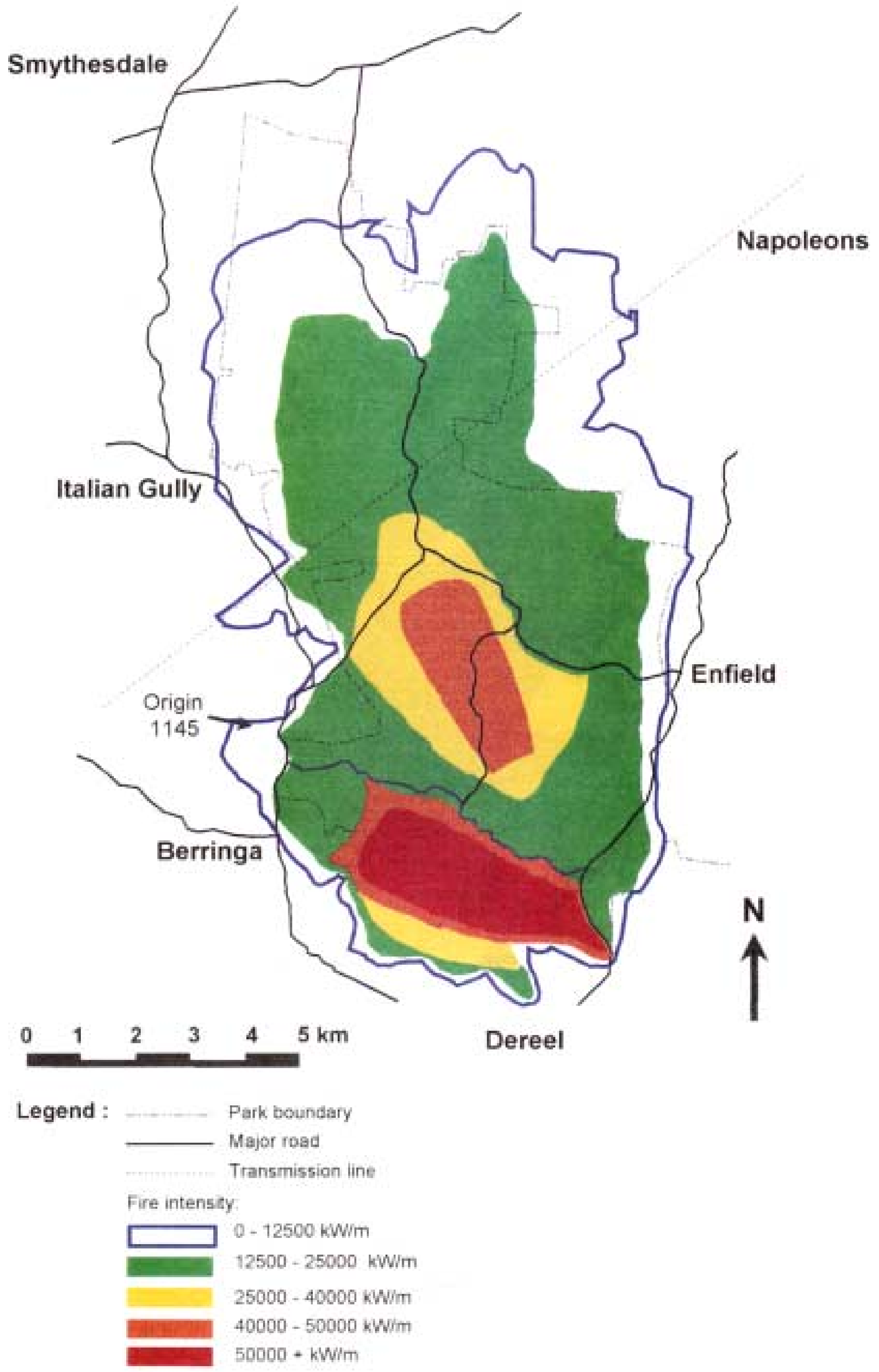
APPENDIX 1. Map showing the fire history of the Enfield State Park. Dates shown are date of last fire in area.



APPENDIX 2. Map showing the fireline intensity of the Berringa fire.



PART TWO

METEOROLOGICAL ASPECTS OF THE BERRINGA FIRE OF 25-26 FEBRUARY 1995

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BUREAU OF METEOROLOGY

INTRODUCTION

The Berringa fire (sometimes referred to as the Enfield fire) occurred about 30 km southwest of the city of Ballarat, reaching a final size of around 11,000 hectares. The fire started from a campfire on private property northwest of Berringa at around 1230 hours on 25th February 1995, spreading rapidly southeastwards into the Enfield State Forest driven by a hot gusty northwesterly wind. By 1830 hours the fire had reached a size of about 1000 hectares. A sudden south to southwesterly wind change then pushed the fire initially northeastwards, then northwards until it reached 10,000 hectares by early morning on the 26th. Weather conditions on the 26th initially led to light winds within a few kilometres radius of the fire, dominated by local effects such as the heat generated by the fire and topographic effects. Cooler southerly winds eventually extended across the fire area by the afternoon of the 26th February improving fire weather conditions.

Additional observational data for this report was supplied by officers from both the Victorian Department of Natural Resources and Environment (NRE) and the Victorian Country Fire Authority (CFA) who recorded local weather conditions at the fire using portable automatic weather stations (AWS). Times used throughout the report are given in local time (Eastern Daylight Savings Time), i.e. UTC+11 hours.

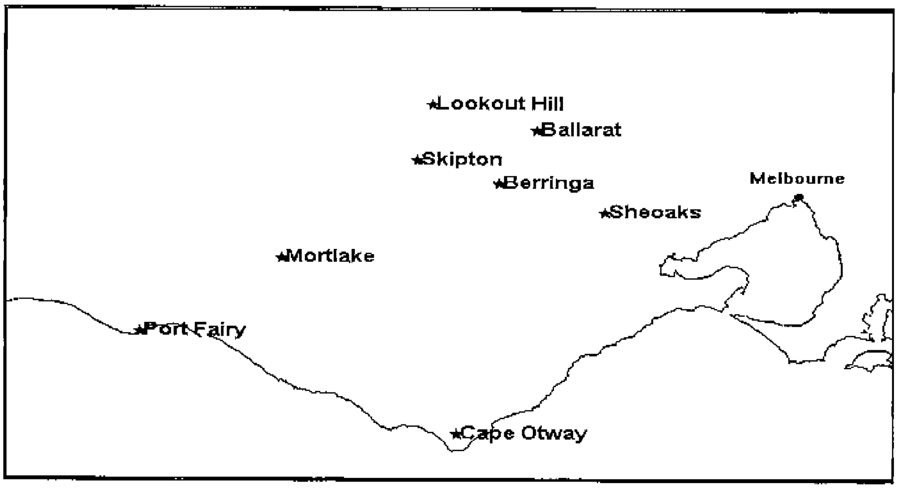


Figure 1. **Map of southwestern Victoria showing places mentioned in text.**

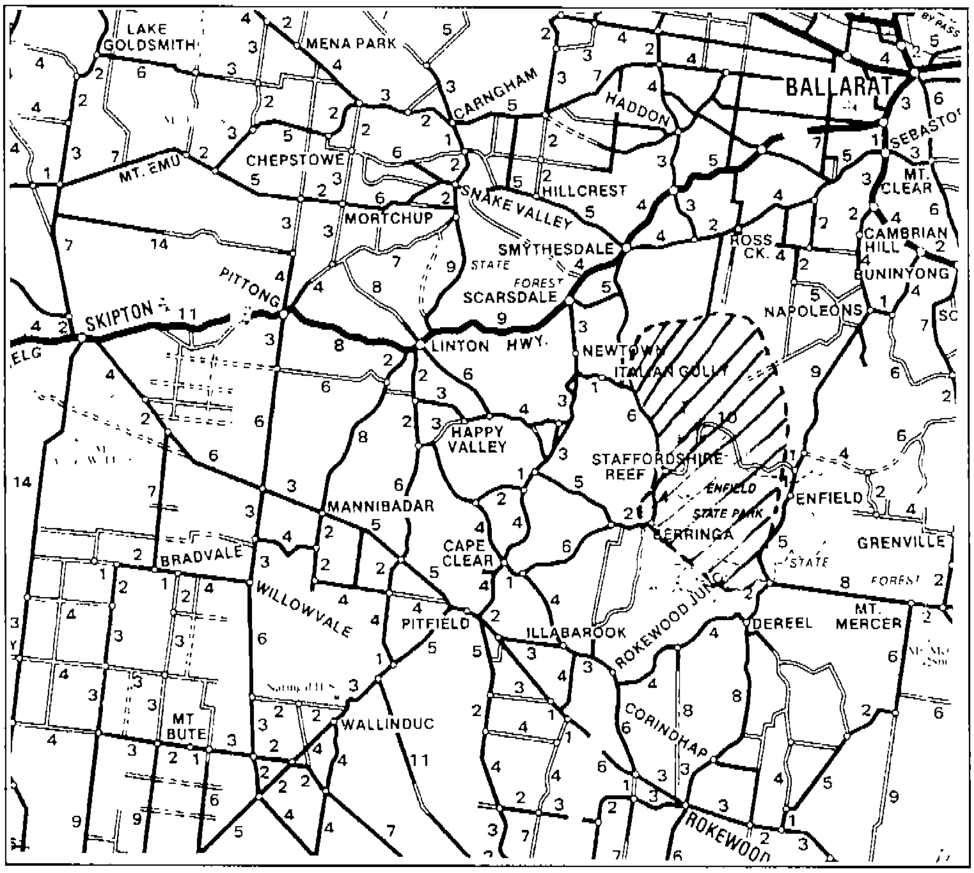


Figure 2. Enlarged view of locations near the fire, shown schematically as the hatched area. Distances are in kilometres.

Antecedent Weather

Table 1 shows the winter, spring and summer rainfall recorded at Rokewood, Skipton and Ballarat Airport.

Table 1. Rainfall recorded at Rokewood, Skipton and Ballarat Airport.

Rainfall	Rokewood		Skipton		Ballarat Airport	
	Total (mm)	Average (mm)	Total (mm)	Average (mm)	Total (mm)	Average (mm)
Winter 1994	122.6	145.9	134.4	177.6	158.8	209.0
Spring 1994	155.4	171.9	142.0*	181.5	153.6	200.0
December 1994	27.2	48.2	18.8	47.9	4.2	53.0
January 1995	66.0	36.1	46.0	35.6	51.0	39.0
February 1995	20.2	31.0	19.4	38.9	39.6	44.0

** Skipton spring 1994 rainfall may be incomplete due to missing data.*

A pronounced El Niño event led to dry conditions across most of Victoria in both the winter and spring of 1994. The dry conditions continued through December 1994 with rainfall totals in the lowest 10-30% of records.

January 1995 was characterised by abnormally persistent low pressure systems affecting western Victoria. These caused wetter conditions than normal, although the rain occurred on only 5 or so days. January rainfall in the Berringa area was in the top 80-90% of records while average rainfall occurred in February 1995. Figure 3 shows the daily rainfall recorded at Rokewood, Skipton and Ballarat Airport for February 1995. No rain was recorded at these locations in the week prior to the fire.

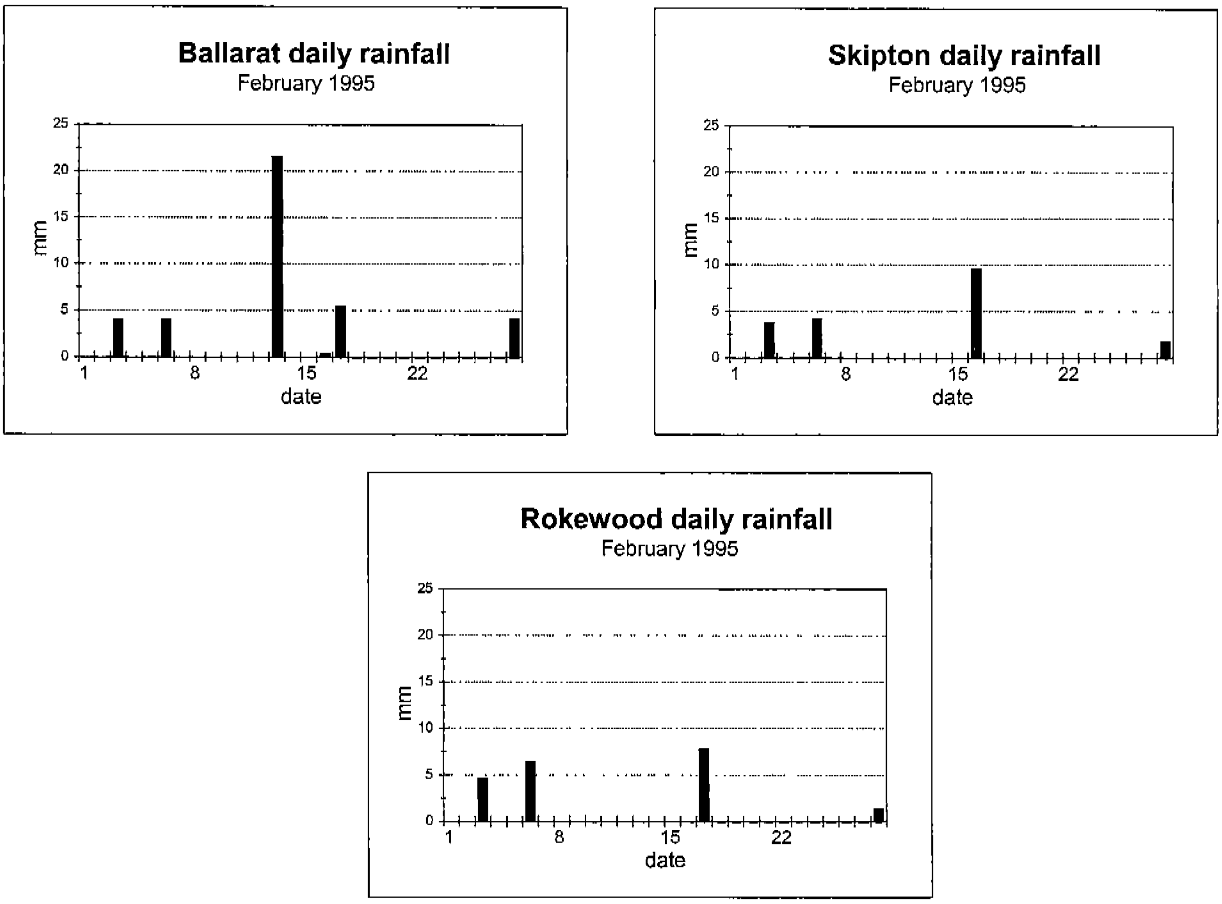


Figure 3. Daily rainfall recorded at sites closest to the Berringa fire during February 1995.

Mean maximum temperatures for the 1994-95 summer were around 1 to 2°C above normal in the Berringa area. Ballarat recorded above average temperatures from 11th to 15th February, briefly cooling for 4 to 5 days before rising to above average conditions from the 23rd onwards. This sequence of a dry winter and spring, followed by a dry December, was critical in priming the forest fuels for a potentially major wildfire. Although the wet January ameliorated conditions slightly, that would have been negated to a large extent by the warm conditions in February 1995 and the dry conditions a week prior to the fire.

The overall effect is shown by the Keetch-Byram Drought Index (KBDI), an index used in Victoria as an input to the McArthur Mark V Forest Fire Danger Meter. The KBDI gives an approximate indication of the dryness of live and coarse (diameter greater than 6 mm) forest fuels. Fine fuel moistures are affected more by relative humidity and recent rainfall events. The KBDI is a cumulative index, adjusted daily from rainfall and maximum temperature observations. When the KBDI reaches an index greater than 75, forest fuels are likely to be highly flammable. Figure 4 shows Ballarat's KBDI rising from a value of 12 in early October 1994 to a value of 86 on 26th February 1995.

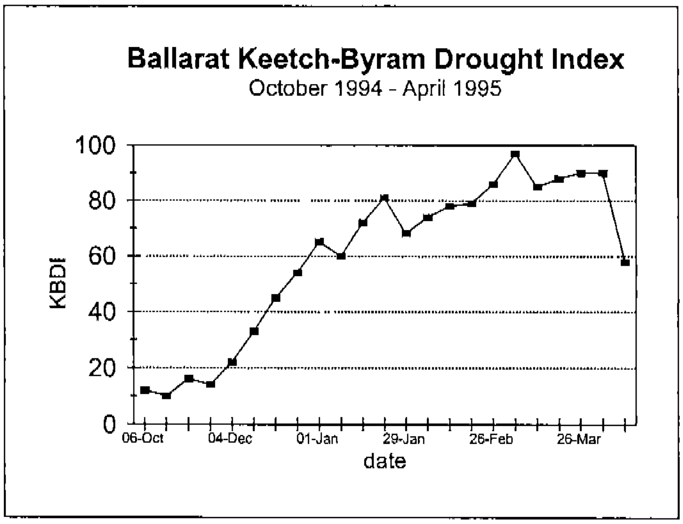


Figure 4. **Ballarat's Keetch-Byram Drought Index for the period October 1994 to April 1995.**

Synoptic scale weather patterns

Figure 5 shows the synoptic scale 0900 hours mean sea level (MSL) pressure analyses from 20th to 27th February 1995. Several days prior to the fire a typical summer pattern existed. A high pressure system over the Great Australian Bight on the 20th February extended a ridge to the Tasman Sea. Apart from an approaching weak cold front and a quasi-stationary low pressure trough over Victoria on the 22nd, the dominant feature was the strengthening high pressure system over the Tasman Sea. The high over the Bight weakened by the 24th ahead of an advancing cold front. A pre-frontal associated with this front is evident on the chart of the 25th. This trough passed through southwestern Victoria and the Berringa area during the morning of the 26th. A cooler southeasterly flow subsequently extended across all of southern Victoria within 24 hours as another high pressure system developed over the Bight.

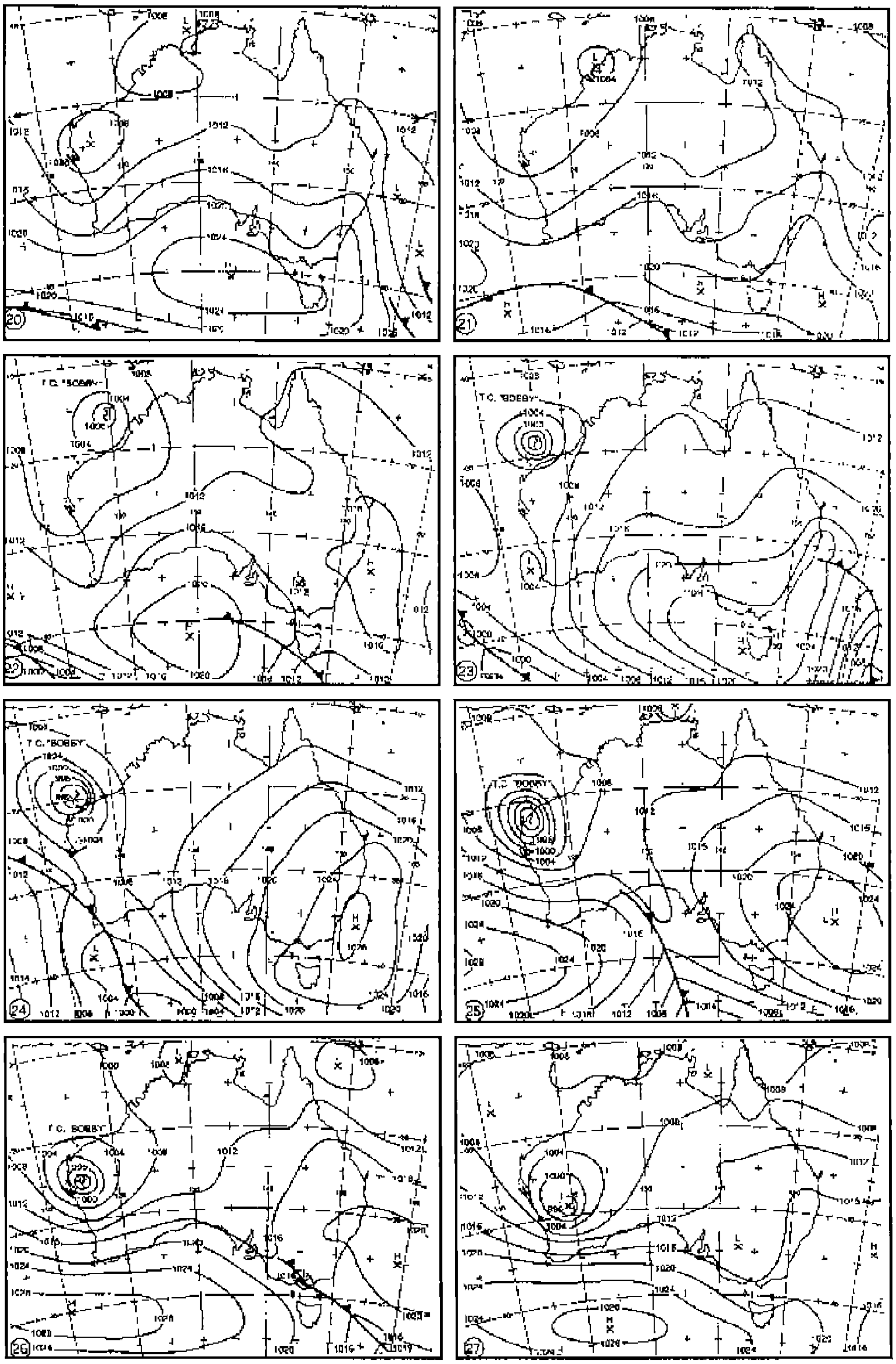


Figure 5. Mean sea level pressure analyses at 0900 hours each day for the periods 20-27 February 1995. (The date is shown by the number in the bottom left hand corner of each chart.)

Further detail on the movement of the pre-frontal trough across Victoria on the 26th is shown by the sequence of synoptic scale MSL pressure analyses in Figure 6. The chart for 1500 hours on the 25th is particularly interesting as there is a “kink” in the isobars over southwestern Victoria, a sub-synoptic scale feature related to the development of a sea breeze that is discussed in more detail in the next section.

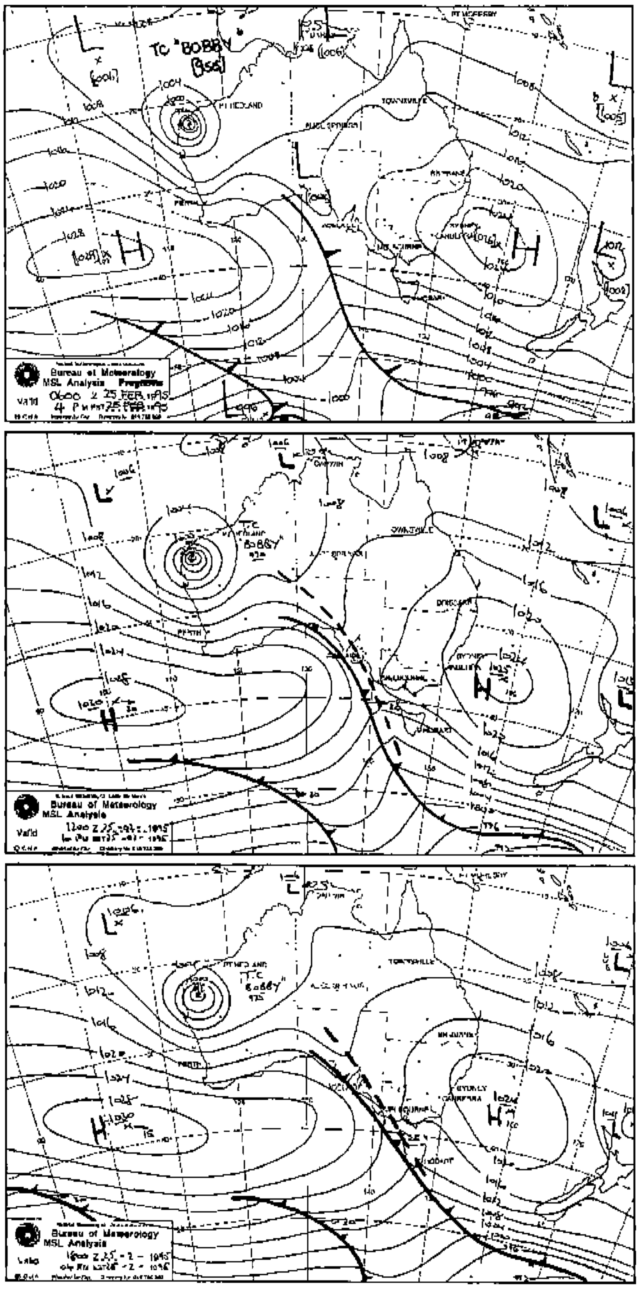


Figure 6. Mean sea level pressure analyses at six-hourly intervals for the period 1500 hours on 25th February to 0900 hours on 26th February 1995.

The pre-frontal trough accelerated eastwards between 2100 hours on the 25th and 0300 hours on the 26th but slowed down over central Victoria in the next 6 to 12 hours. The physics behind the acceleration of the trough are not completely understood, however there is evidence to suggest evaporative cooling may be the reason. Precipitation falling from the cold frontal cloudband to the west of the trough would have been evaporating as it fell into the drier sub-cloud air. As a result of this evaporation, air would have cooled and descended, subsequently moving northeastwards and accelerating the trough further towards the coast. This process is similar to the mechanism in thunderstorms whereby a downdraft can develop a squall line that moves well ahead of the storm.

After the pre-frontal trough crossed southern Victoria, moderate south to southeasterly surface winds developed. As shown in Figure 6, the south to southeasterly winds extended quite slowly northeastwards across Victoria during the afternoon of the 26th. A relatively weak pressure gradient existed across the State as the trough moved northeastward, producing complex local wind conditions in the Berringa area. The trough may have slowed down due to the comparatively weak pressure rises occurring in its wake. It is unlikely the fire would have affected the trough's movement on this synoptic scale, however during the 26th, the fire is likely to have had a significant influence on local winds within a radius of a few kilometres.

Figure 7 shows the infrared satellite picture at 0400 hours on the 26th. The main frontal cloudband lies well offshore. The more diffuse cloud extending from southwestern Victoria to northeast Tasmania appears to be close to the position of the pre-frontal trough.

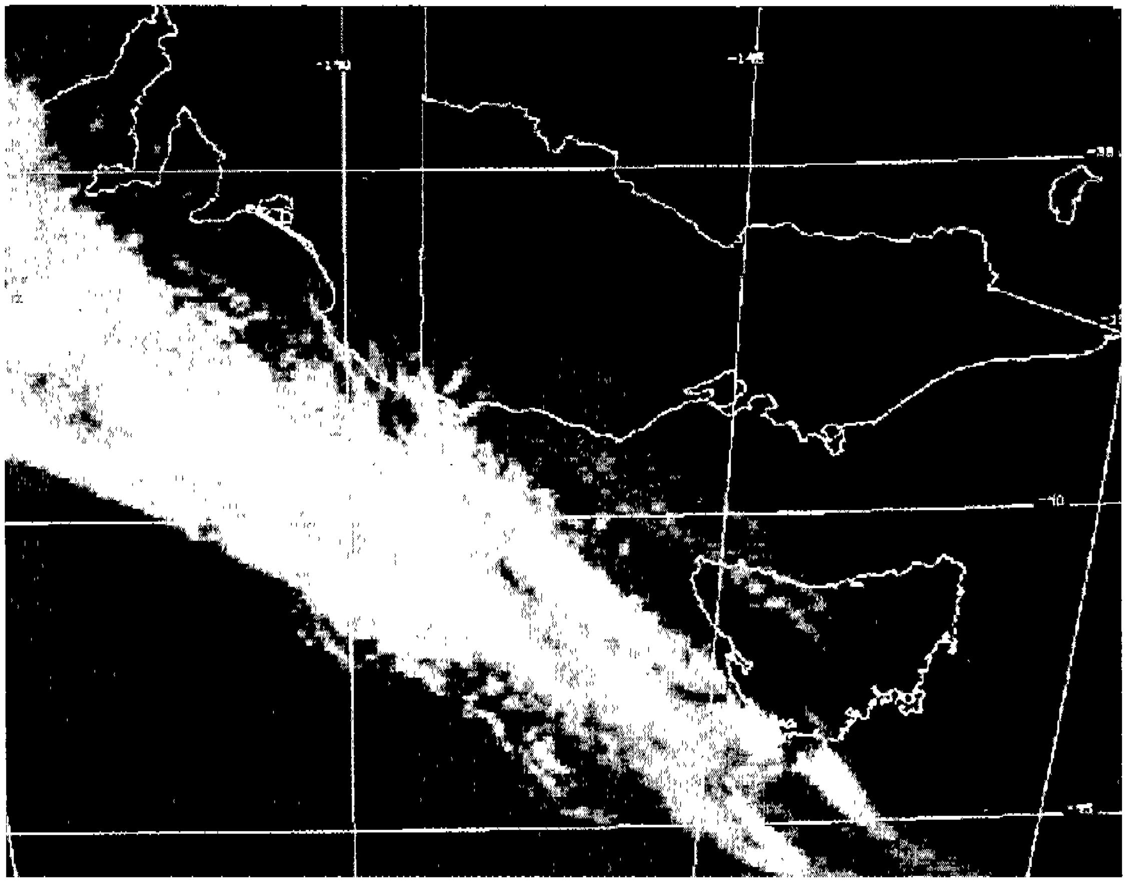
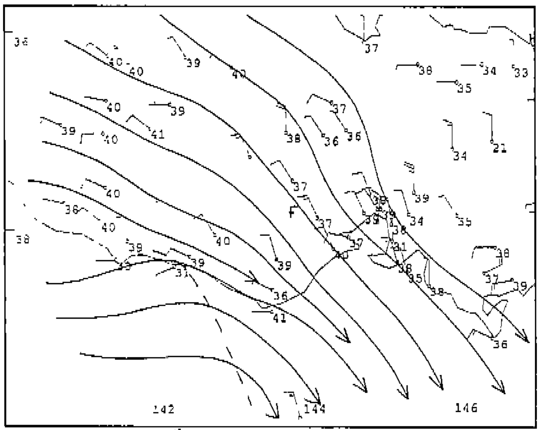


Figure 7. Infrared satellite image at 0400 hours on 26th February 1995.

Local scale weather patterns in the Berringa area

Figure 8 shows a sequence of surface wind streamline analyses, based mainly on the AWS network, starting from the afternoon of the 25th and ending at midday on the 26th. The hot northwesterly winds on the 25th caused fire danger indices to reach the extreme range for several hours. Figure 9 shows the temperature, relative humidity, wind speed, wind direction and Forest Fire Danger Index (FFDI) recorded at Sheoaks, 48 km to the southeast of Berringa. Although Sheoaks recorded its maximum temperature of 37°C at 1530 hours on the 25th, the highest FFDI values were recorded approximately two hours earlier. The maximum recorded

FFDI (using a Drought Factor of 10 with the McArthur Mark 5 Forest Fire Danger Meter) was 77 at 1330 hours when the temperature was 36°C, the relative humidity was 6%, and the wind was northwesterly at 33 km/h, gusting to 50 km/h.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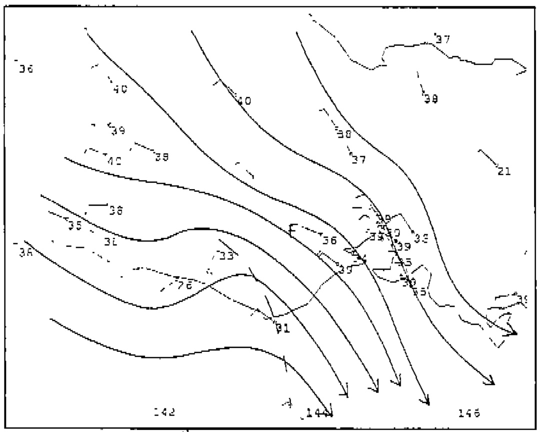
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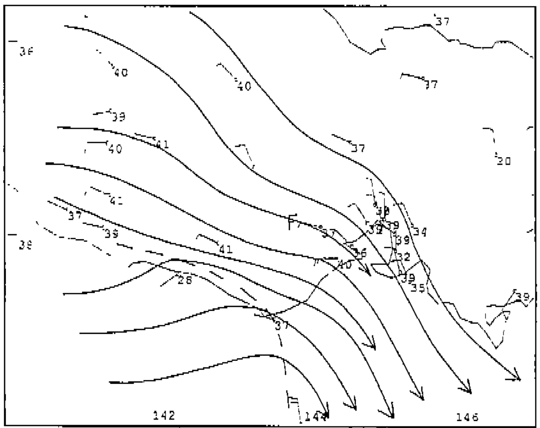
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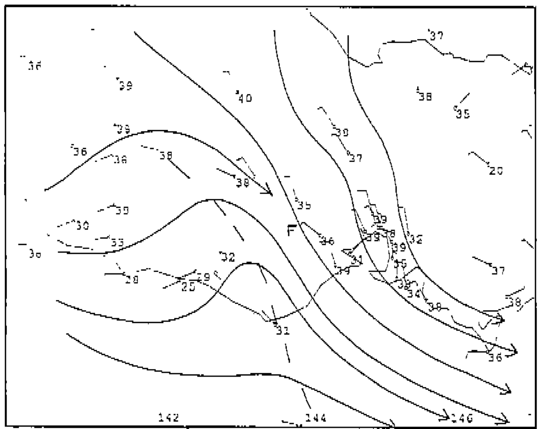
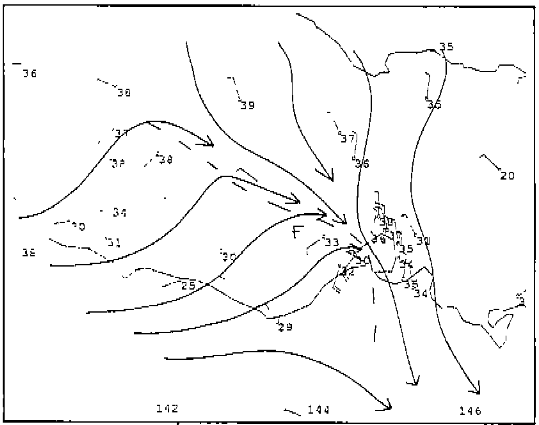

1800 hours 25th February 1995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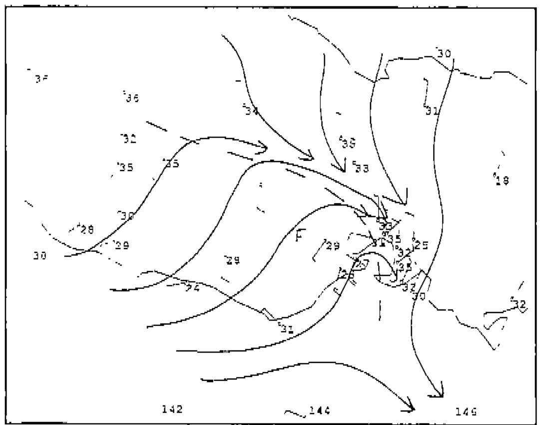
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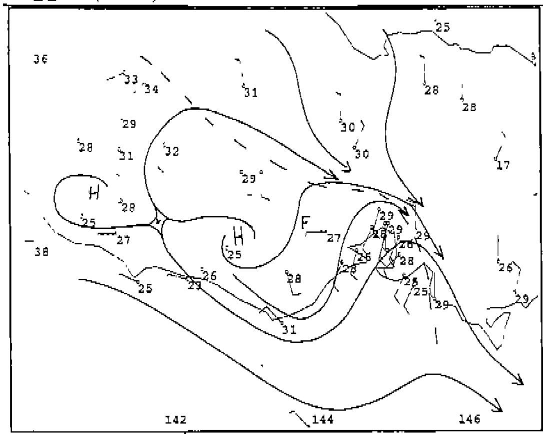

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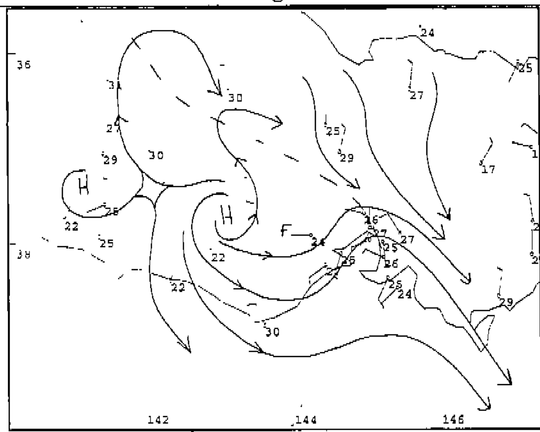
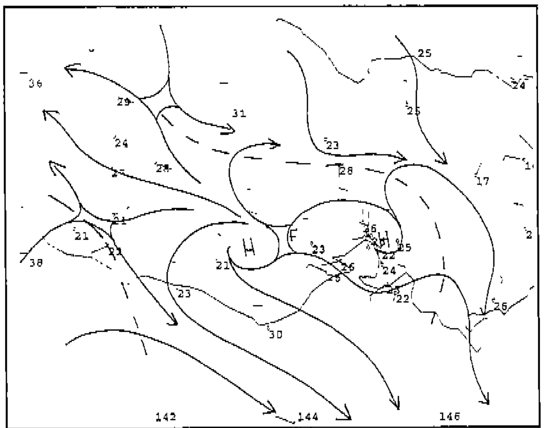


2200 hours 25th February 1995



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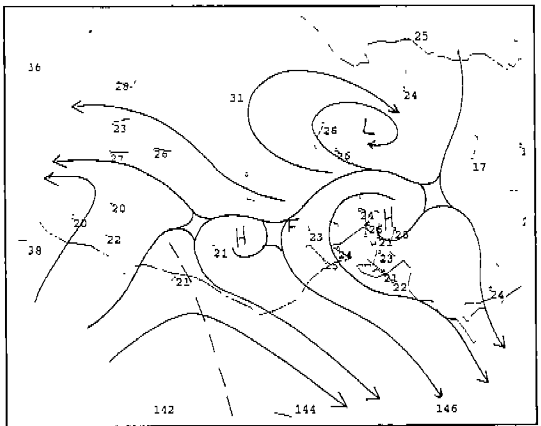
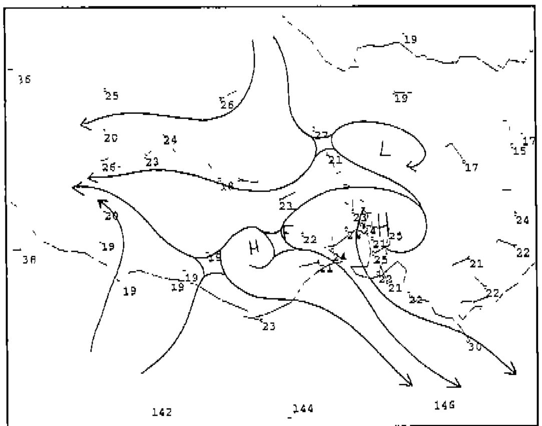
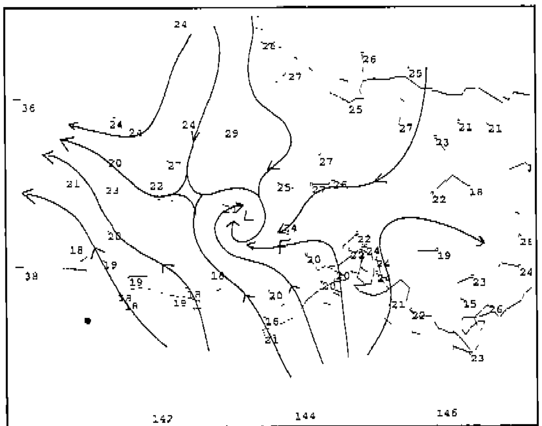


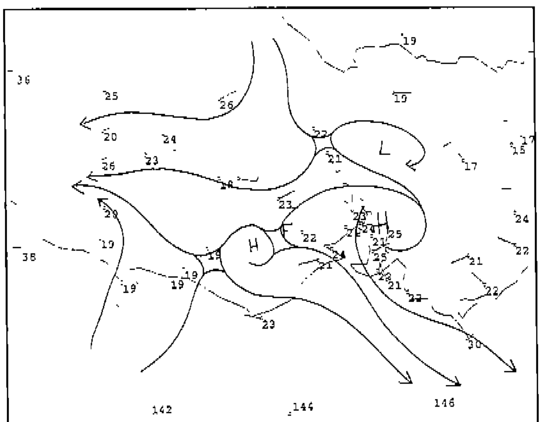
0001 hours 26th February 1995



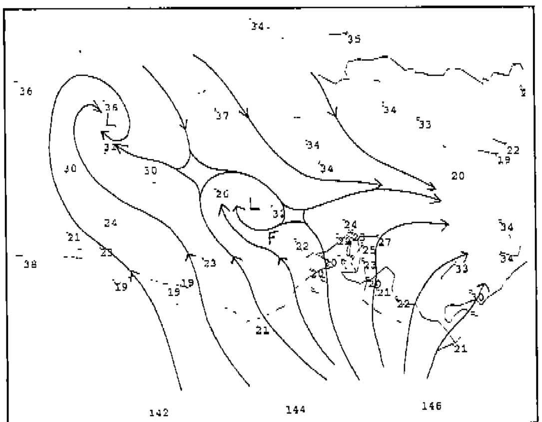
0300 hours 26th February 1995



0600 hours 26th February 1995



0900 hours 26th February 1995



1200 hours 26th February 1995

Figure 8. **Surface wind analyses with the streamlines drawn to represent the approximate surface wind flow. Wind barbs are in knots, a full barb represents 10 knots. Temperatures are given in °C. The letter "F" marks the approximate location of the fire.**

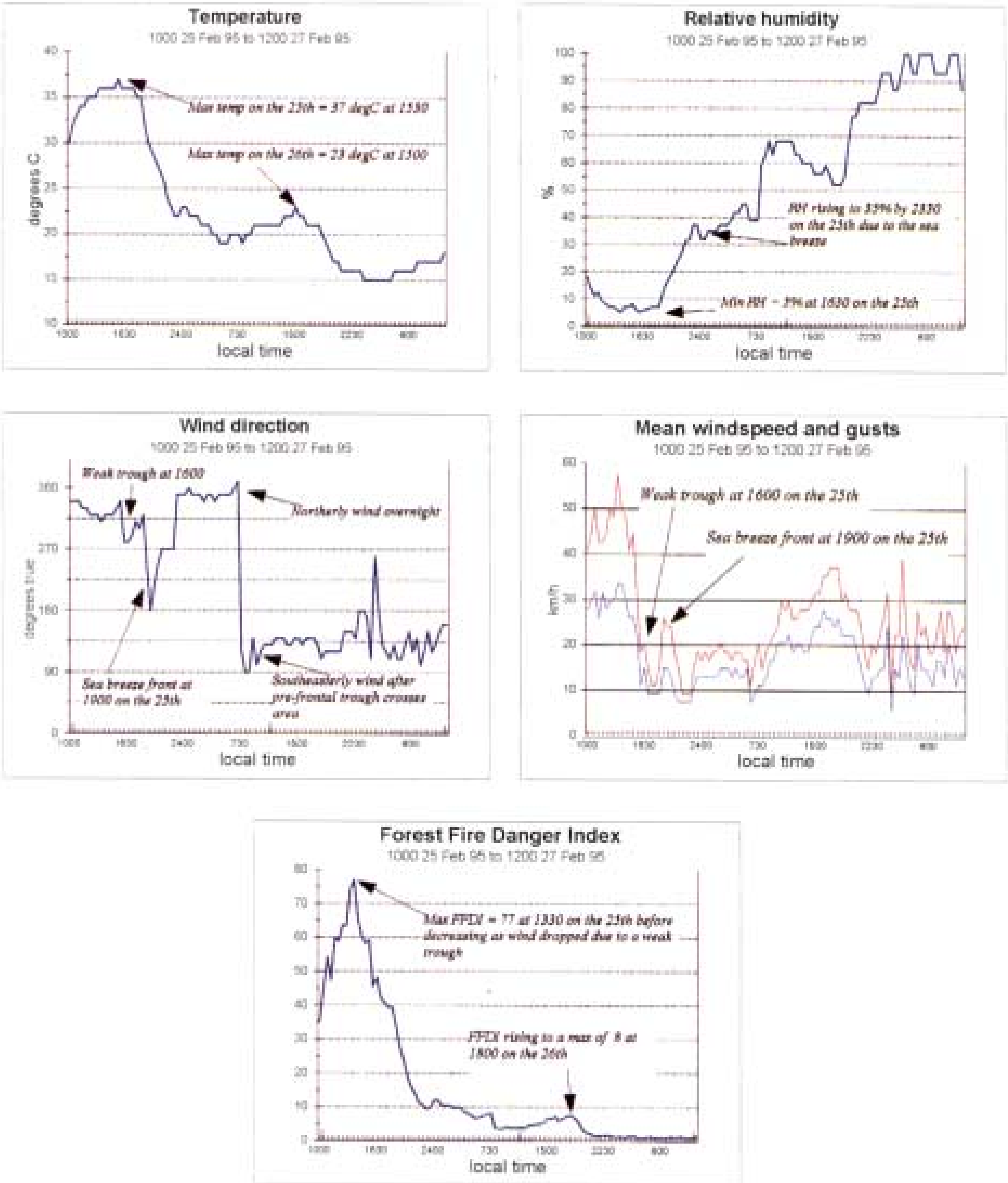


Figure 9. Temperature, relative humidity, wind direction, wind speed and gusts from Sheoaks AWS from 1000 hours February 25th to 1200 hours February 27th, 1998.

Sheoaks wind speeds decreased by about 10 to 20 km/h after 1600 hours. At the same time, the wind direction briefly tended west northwesterly for about one hour before tending more northwesterly again. There was no discernible temperature or relative humidity change associated with this weak trough line.

Of major significance was the development of an afternoon sea breeze in southwestern Victoria that moved east reaching Berringa that evening. A well-defined confluence zone ahead of the sea breeze marks the approximate edge of the hot dry northwesterlies. The cool southwesterly winds associated with the sea breeze reached Port Fairy at 1400 hours resulting in a 5°C temperature drop. The sea breeze reached Mortlake at 1645 hours causing the temperature to drop 6°C in 30 minutes. At about the same time, Cape Otway dropped 4°C although its winds remained northwesterly until 0500 hours the following day. This anomalous northwesterly wind at Cape Otway might be due to the west southwesterly wind behind the sea breeze being deflected by the cliffs to the west of the AWS site. There are records of this anomalous northwesterly occurring on previous occasions.

A NRE officer operating a portable AWS near Staffordshire Reef noted the northwesterly winds decreased from 26 km/h at 1430 hours to 11 km/h at 1600 hours (K.G. Tolhurst[1] pers. comm.). That wind speed decrease was probably due to the weak trough that went through Sheoaks at about the same time, also causing the wind to drop. The Berringa AWS subsequently recorded the main south southwesterly sea breeze arriving at 1830 hours. Initially mean winds[2] were 7 to 10 km/h with gusts subjectively estimated to be 15 to 20 km/h. Figure 10 shows the temperature, relative humidity, wind speed, wind direction and Forest Fire Danger Index recorded by the Staffordshire Reef AWS.

[1] Kevin Tolhurst was a Fire Research Officer with NRE at the time of the fire.

[2] This portable AWS recorded winds at 2 m above ground level and was at an elevation of 440 m.

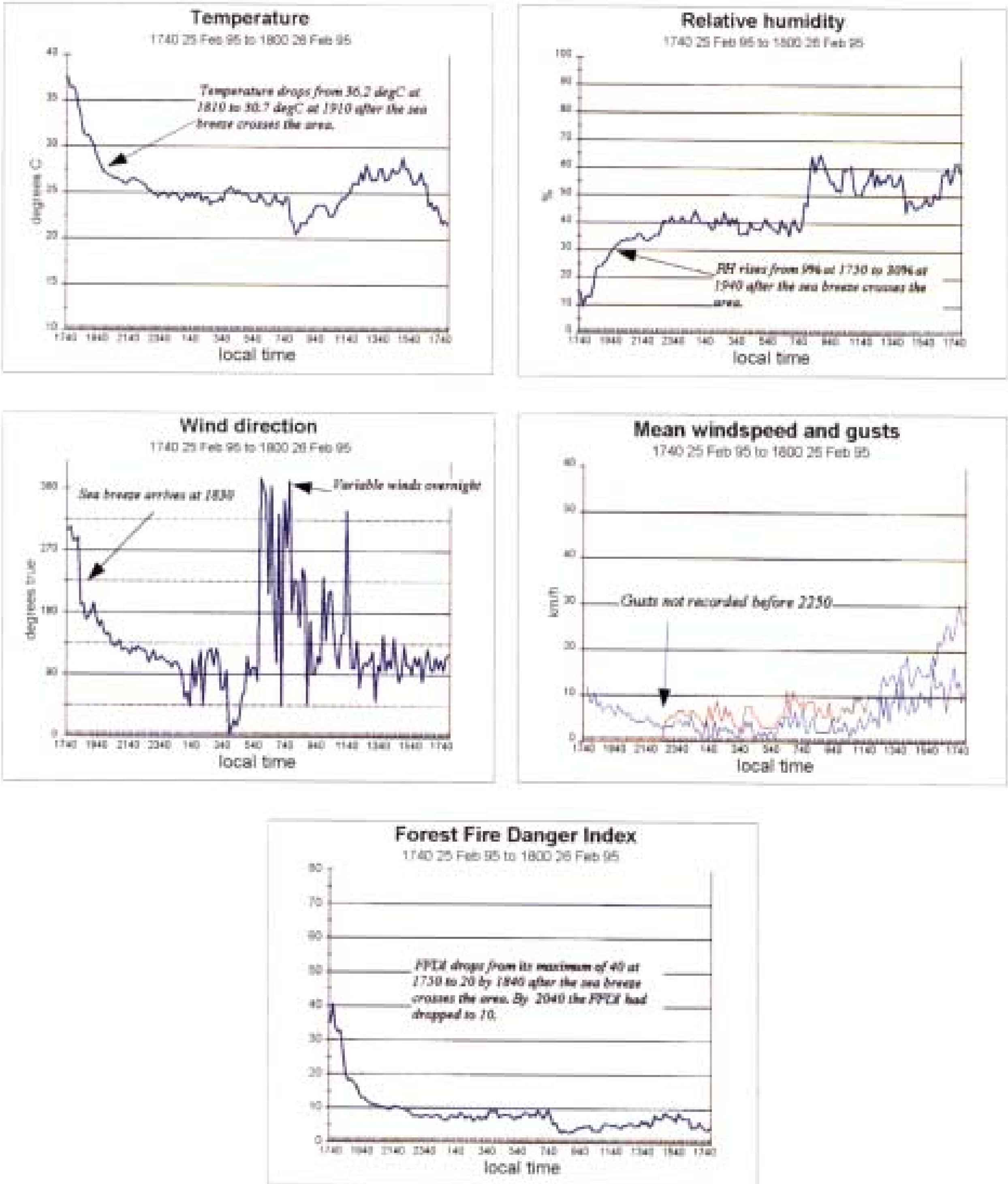


Figure 10. Temperature, relative humidity, wind speed, wind gust and wind direction observations from Staffordshire Reef portable AWS from 1740 hours 25th February to 1740 hours 26th February 1995.

Observations from a fire tower[3] at Cherry Tree Hill (12 km northwest of Berringa) show the west-northwesterly winds decreased from 25 - 45 km/h to 15 – 30 km/h after 1600 hours.

[3] Cherry Tree Hill has an elevation of 480 m compared to Berringa's elevation of 300 m. Also the fire tower records winds at 20 m above ground level using a handheld cup anemometer. Standard Bureau AWS wind speeds are recorded at 10 m above ground level.

wind direction briefly shifted west to southwesterly at around 1655 hours, then veered northwesterly about one hour later before a more persistent south southwesterly wind developed at 1835 hours. Winds briefly reached 30 – 40 km/h for about 20 minutes before easing back to 10 – 20 km/h by 2000 hours. The earlier wind speed decrease and the subsequent wind direction variability might have been due to the weak trough mentioned previously. This is supported by the temperature and relative humidity remaining almost constant until the later wind shift when the temperature dropped 4°C in 30 minutes and the relative humidity rose by 10%.

The strength of the sea breeze at Berringa was less than that recorded at Cherry Tree Hill, most likely because the latter's winds are recorded at a higher elevation. In comparison Sheoaks reported south-southwesterly winds briefly reaching 15 – 25 km/h for one hour before decreasing later that evening.

The arrival of the sea breeze at the fire led to a significant increase in the fire size as the northeastern flank spread first northeastwards then northwards with the prevailing winds. Of interest was the convective column or smoke plume on top of the fire that intensified after the sea breeze arrived. The dramatic smoke plume was also apparent on Melbourne's weather radar.

From about 2000 hours the winds at Berringa began to decrease to 5 – 8 km/h and back around to the southeast. By early morning on the 26th, the winds had decreased to less than 5 km/h, tending northeast to southeasterly in direction. The overnight weakening of the winds is consistent with the weakening of the sea breeze and the overall synoptic pattern. There is some evidence to suggest the existence of a small scale high pressure cell left over from the sea breeze circulation that persisted just southwest of Berringa, slowly weakening after dawn. A CNR officer reported the smoke to the northeast of the fire rising to a couple of hundred metres then spreading out. This suggests a low level inversion formed overnight, at a height of around 200 - 500 m above ground level.

It is doubtful whether current forecasting skills would be able to predict the occurrence of such small-scale circulations. In practice it is perhaps more likely that the forecaster would only be able to recognise the existence of such features in hindsight. With the continued expansion of the Victorian AWS network, it is becoming apparent that there are very localised weather phenomena, particularly near elevated areas. With such a weak synoptic scale pressure gradient, close to the fire there are likely to have been winds influenced both by the heat of the fire and topographic effects such as downslope winds (katabatics) at night and upslope winds (anabatics) during the afternoon.

At 0600 hours on the 26th, light and variable winds existed at Berringa. Further south the advancing pre-frontal trough and associated southerly winds were apparent. Over the next three hours, that southerly flow extended northwards. At the same time, with the onset of daylight, temperatures began to rapidly rise inland. This led to the mixing down to the surface of the stronger north northwesterly winds aloft over areas north of the trough. By 1200 hours on the 26th, there is a marked low pressure region located close to Berringa. This low pressure region marks the boundary between the warm fresh northwesterlies over northern Victoria and the cooler south southeasterlies to the south. The opposing winds meant that the subsequent northward movement of the southerly flow was significantly retarded.

In the early afternoon of the 26th, Berringa's winds were essentially east southeasterly and strengthened slightly due to the increased mixing with the upper winds. As mentioned previously the pre-frontal trough became slow moving over central Victoria allowing temperatures to rise at the fire. However by mid afternoon the pre-frontal trough appears to have pushed sufficiently northwards· to dominate weather conditions at Berringa with east southeasterly winds averaging 10 – 15 km/h, gusting to 30 km/h. Consistent with the passage of the pre-frontal trough, Berringa's temperature fell from a maximum of 28.9°C at 1510 hours to 23°C at 1730 hours. At the same time the relative humidity rose from 45% to 57%. Temperatures continued to drop that evening due both to the normal diurnal variation and the advection of cooler air in the wake of the trough.

Table 2 shows the upper winds recorded at Laverton during this event, indicating the south southwesterly sea breeze extended to a height of between 900 and 1500 metres at 2100 on the 25th. Within six hours, the flow had shifted back to the north northeast as the sea breeze weakened overnight. The pre-frontal trough reached Laverton around 0830 hours on the 26th. The northwesterly that persisted at 1500 m at 1500 hours on the 26th illustrates the relative shallowness of the pre-frontal trough.

Table 2. Upper winds recorded at Laverton from 0900 hours on 25th February to 2100 hours 26th February 1995. (Direction in degrees true and windspeeds in km/h.)

Date	Time (hours)	Altitude (m)			
		300	600	900	1500
25 February	**0900**	340/48	335/59	340/52	300/37
	1500	350/26	345/26	340/30	300/33
	2100	210/48	200/48	190/33	325/11
26 February	**0300**	005/22	070/07	150/07	015/11
	0900	180/22	170/4	315/30	305/37
	1500	190/30	160/26	180/11	320/37
	2100	190/22	130/48	130/70	115/41

Fire Weather Forecasting Performance

The routinely issued fire weather estimates for Ballarat and the corresponding observations are shown in Table 3. Total Fire Bans and Fire Weather Warnings were issued for both the 25th and 26th February 1995 based on these estimates. In general terms the routine estimates for the 25th and the 26th were within expected accuracy standards for this type of forecast.

Table 3. Fire weather estimates issued by the Bureau of Meteorology for Ballarat. The corresponding observations at Ballarat Airport are shown in bold italics below each forecast[4]. The observations at Sheoaks AWS (Figure 10) and at Berringa (Figure 11) during the afternoon of the 25th suggest slightly hotter but significantly drier and windier conditions occurred near the fire. Note particularly the FFDI value of 39 at Ballarat Airport compared to the 77 at Sheoaks.

Forecast Issue Time	Forecast Validity Date	Max Temp (°C)	Relative humidity (%)	Wind Direction & Speed-Gusts (km/h)	FFDI	Wind Change (direction, kph & time)
1700 24 Feb	25 Feb	36	20	N/NW 30-40	41	-
0630 25 Feb	25 Feb	36	20	N/NW 30-40	41	-
Observed 25 Feb		***37.3***	***16***	***NW 19***	***39***	***SSW 15-30* 1900-2000****
1700 25 Feb	26 Feb	37	15	NW 30-45	44	SSW 25 1400-1800
0630 26 Feb	26 Feb	35	20	N 10-20	24	SSW 25 1200-1600
Observed 26 Feb		***33.7***	***20***	***NW 19***	***31***	***SSE 20-40* 1300-1400****

* *estimated*

Due to the expected strength of the northwesterly flow, the distance inland and the elevation of Berringa, an afternoon sea breeze was not forecast on the routine estimates. The ten Spot Forecasts issued for this event (Appendix 1) and the verbal briefings between the Bureau and NRE also omitted any mention of the sea breeze until it had already reached the fire.

Forecasting policy on the 25th (supported by the numerical model guidance) was expecting the synoptic flow to remain essentially northwesterly before a southerly change the next day. South Australian AWS data up until 1700 hours on the 25th confirmed the flow was still northwesterly in that area. The windshift at Mortlake was noted but given the persistent northwesterlies in South Australia and the ambiguous northwesterly at Cape Otway, it was not expected to extend east so as to affect the fire at an elevation of about 300 – 400 m. In hindsight it would have been better if the alternate scenario of a late southwesterly wind change at the fire had been passed on to the fire authorities, even though the likelihood of it occurring was very small.

In future, fire weather forecasters will be encouraged to continue giving the most likely scenario in the Spot Forecast, but will also mention any alternate scenario that is less likely,

[4] Ballarat's 1500 hours' observation on the 25th and the midday observation on the 26th are used for the relative humidity and wind details in this table.

but would be of real significance to the fire. This could be included as a separate comment in the forecast as well as being passed over the phone to the fire authorities. Either this alternate scenario or the forecaster's degree of confidence in the forecast would assist NRE's and CFA's strategic planning.

Other contributing factors to the forecasters not predicting the sea breeze arrival at the fire involve the AWS network. A possibly critical AWS (Aireys Inlet) had been out of service since the afternoon of the 24th and was not reset until the 27th. A routine procedure for checking AWS serviceability has since been set up. There is also a noticeable gap in the AWS network in southwestern Victoria between Mortlake and Grovedale away from the coast. A future AWS location is likely to be somewhere inland between Geelong and Mortlake, perhaps Lismore, Colac or Winchelsea. A lack of confidence in some of the AWS data, particularly Cape Otway, has also been mentioned as a contributing factor.

A comparison between Ballarat's forecast and observed weather conditions (Table 3) and the observations from Sheoaks AWS and Staffordshire Reef (Figures 10 and 11 respectively) highlights the importance of local weather conditions. Fire managers should be cautious in applying the specific location predictions in the Bureau's routine Fire Weather Estimates to large regions. Topographic effects are often the causes of localised weather conditions, such as funnelling through valleys and downslope winds overnight. The spot fire weather forecast provided to the fire agencies on request is tailored to deal with these local effects.

Recently the Bureau has begun trialling a higher resolution numerical model. Initial results for this event have been encouraging, with the model producing a sea breeze, albeit with slight timing and positional errors. Further work to include AWS data into the model is expected to occur in one to two years.

CONCLUSION

The Berringa fire started on a day when extreme weather conditions existed. The development of a southwesterly wind change, associated with a sea breeze, caused the fire to enlarge considerably during the evening of the 25th February 1995. Lighter synoptic winds on the 26th allowed local effects to produce variable winds across the fire until a cooler southerly flow developed later that day.

APPENDICES

Appendix 1. Spot forecasts issued for the Berringa fire

Issued at: *1415 hours Saturday 25/02/95*
Forecast for first 6 hours

Time period (hours)	1400/1600	1600/1800	1800/2000
Temperature (°C)	36/38	38/35	35/32
Relative Humidity (%)	5-10	5-10	5-10
Wind at 10 m (km/h)	NW 30/40	NW 25/35	NW 20/30
1000 m Wind	NW 45/55	NW 45/55	NW 40/50

(a) Details of any major wind change: NIL.
(b) Comments on stability: MAINLY STABLE.
(c) Weather and/or other detail: NIL.

Forecast for subsequent 12 hours: *252000/260800*

(a) Temperature: MINIMUM 23 BY 0400 THEN RAPIDLY INCR AFTER SUNRISE TO 29 BY 0800.
(b) Humidity: DECR TO 20-30%.
(c) Wind: NORTHWESTERLY WIND OVERNIGHT 15/25 INCR 25/35 KPH BY 0600.
(d) Stability: MAINLY STABLE.
(e) Weather and/or other detail: FINE OVERNIGHT.

Issued at: *1520 hours Saturday 25/02/95*
Forecast for first 6 hours

Time period (hours)	1500/1700	1700/1900	1900/2100
Temperature (°C)	36/38	38/35	35/32
Relative Humidity (%)	5-10	5-10	5-10
Wind at 10 m (km/h)	NW 30/40	NW 25/35	NW 20/30
1000 m Wind	NW 45/55	NW 45/55	NW 40/50

(a) Details of any major wind change: NIL.
(b) Comments on stability: MAINLY STABLE.
(c) Weather and/or other detail: NIL. SMOKE HAZE DETECTABLE ON RADAR RADAR SHOWS TOPS TO 4 KM.

Forecast for subsequent 12 hours: 252100/260900

(a) Temperature: MINIMUM 23 BY 0400 THEN RAPIDLY INCR AFTER SUNRISE TO 29 BY 0800.
(b) Humidity: INCR TO 20-30% THEN DECR TO 10% BY 0900.
(c) Wind: NORTHWESTERLY WIND OVERNIGHT 15/25 INCR 25/35 KPH BY 0600.
(d) Stability: MAINLY STABLE.
(e) Weather and/or other detail: FINE OVERNIGHT.

Issued at: ***1820 hours Saturday 25/02/95***

Forecast for first 6 hours

Time period (hours)	**1900/2100**	**2100/2300**	**2300/0100**
Temperature (°C)	36/38	36/33	33/30
Relative Humidity (%)	10-15	10-20	20-30
Wind at 10 m (km/h)	WNW 25/35	NW 20/30	NW 15/25
1000 m Wind	NW 30/40	NW 30/40	NW 25/35

(a) Details of any major wind change: NIL.
(b) Comments on stability: MAINLY STABLE.
(c) Weather and/or other detail: NIL.

Forecast for subsequent 12 hours: 260100/261200

(a) Temperature: MINIMUM 23 BY 0400 THEN RAPIDLY INCR AFTER SUNRISE TO 35 BY 1200.
(b) Humidity: INCR TO 30-40% THEN DECR TO 20% BY 0900.
(c) Wind: NORTHWESTERLY WIND OVERNIGHT 15/25 INCR 25/35 KPH BY 0600 AHEAD OF SOUTHWEST TO SOUTHERLY CHANGE DURING THE AFTERNOON.
(d) Stability: BECOMING UNSTABLE.
(e) Weather and/or other detail: FINE OVERNIGHT.

Issued at: *2115 hours Saturday 25/02/95*

Forecast for first 6 hours

Time period (hours)	**2100/2300**	**2300/0100**	**0100/0300**
Temperature (°C)	28/27	27/25	25/24
Relative Humidity (%)	30/35	35/40	40/45
Wind at 10 m (km/h)	S 5/15	VBL 5/10	VBL 5/10
1000 m Wind	NW 30/40	NW 30/40	NW 25/35

(a) Details of any major wind change:
(b) Comments on stability: LOW LEVEL INVERSION TO 300M.
(c) Weather and/or other detail: NIL.

Forecast for subsequent 12 hours: 260300/261500

(a) Temperature: MINIMUM 22 BY 0500 THEN RAPIDLY INCR AFTER SUNRISE TO 35 BY 1200.
(b) Humidity: 40/45 THEN DECR TO 20% BY 0900 15% BY 1200.
(c) Wind: NORTHWESTERLY WIND 5/15 AFTER 0300 INCR 25/35 KPH BY 0800 AHEAD OF SOUTHWEST TO SOUTHERLY CHANGE DURING THE AFTERNOON.
(d) Stability: BECOMING UNSTABLE.
(e) Weather and/or other detail: SOUTHWEST CHANGE 25/35 KPH EXPECTED 1500/1800 EST.

Issued at: *0005 hours Sunday 26/02/95*

Forecast for first 6 hours

Time period (hours)	**0001/0200**	**0200/0400**	**0400/0600**
Temperature (°C)	25/24	24/23	23/22
Relative Humidity (%)	35/40	35/40	40/45
Wind at 10 m (km/h)	VBL 5/10	VBL 5/10	N/NW 5/15
1000 m Wind	NW 20/30	NW 20/30	NW 25/35

(a) Details of any major wind change: NIL.
(b) Comments on stability: LOW LEVEL INVERSION TO 300M.
(c) Weather and/or other detail: NIL.

Forecast for subsequent 12 hours: 260600/261800

(a) Temperature: MINIMUM 22 BY 0500 THEN RAPIDLY INCR AFTER SUNRISE TO 35 BY 1200.
(b) Humidity: 40/45 THEN DECR TO 20% BY 0900 15% BY 1200.
(c) Wind: N/NW 5/15 INCR 20/30 KPH BY 0800EST AHEAD OF SOUTHWEST CHANGE 1400/1800EST.
(d) Stability: BECOMING UNSTABLE.
(e) Weather and/or other detail: SOUTHWEST CHANGE 25/35 KPH EXPECTED 1400/1800 EST.

Issued at: *0450 hours Sunday 26/02/95*

Forecast for first 6 hours

Time period (hours)	**0500/0700**	**0700/0900**	**0900/1100**
Temperature (°C)	22	22/28	28/32
Relative Humidity (%)	45	45/30	30/25
Wind at 10 m (km/h)	VBL 5/10	VBL 5/10	NW 10/20
1000 m Wind	N 15/25	N 20/30	NW 25/35

(a) Details of any major wind change: NIL.
(b) Comments on stability: LOW LEVEL INVERSION TO 300M DISSIPATING MID MORNING.
(c) Weather and/or other detail: NIL.

Forecast for subsequent 12 hours: 261100/261700

(a) Temperature: MAXIMUM 32/35 THEN DECREASING 25/22 FOLLOWING WEAK SOUTHERLY CHANGE 1200/1400.
(b) Humidity: 25/20 THEN INCREASING 40/50 FOLLOWING CHANGE.
(c) Wind: N/NW 10/20 SHIFT SW/S 15/25 FOLLOWING CHANGE 1200/1400.
(d) Stability: BECOMING UNSTABLE.
(e) Weather and/or other detail: ISOLATED THUNDERY SHOWERS DEVELOPING WITH CHANGE.

Issued at: *0740 hours Sunday 26/02/95*

Forecast for first 6 hours

Time period (hours)	**0730/0930**	**0930/1130**	**1130/1330**
Temperature (°C)	24/27	27/30	30/23
Relative Humidity (%)	40/35	35/30	30/65
Wind at 10 m (km/h)	VBL 10/15	VBL 10/15	S 25/30
1000 m Wind	N 15/25	N 15/25	N 25/35

(a) Details of any major wind change: S'LY CHANGE 1100/1300. WIND WILL HAVE TENDENCY TO BE MAINLY N JUST AHEAD OF CHANGE.
(b) Comments on stability: LOW LEVEL INVERSION TO 300M DISSIPATING MID MORNING.
(c) Weather and/or other detail: ISOLATED THUNDERY SHOWERS POSSIBLY AROUND CHANGE.

Forecast for subsequent hours: ***261330/270130***
(a) Temperature: TEMPERATURE DECREASING FOLLOWING CHANGE AND FALLING TO 15 DEGREES OVERNIGHT.
(b) Humidity: IN THE RANGE 55/75% FOLLOWING CHANGE.
(c) Wind: S 25/30 GRADUALLY SHIFTING SE AND EASING TO 15/20 IN THE NIGHT.
(d) Stability: STABILISING.
(e) Weather and/or other detail: ISOLATED SHOWERS.

Issued at: *1014 hours Sunday 26/02/95*

Forecast for first 6 hours

Time period (hours)	**1000/1200**	**1200/1400**	**1400/1600**
Temperature (°C)	27/24	24/22	22
Relative Humidity (%)	40/50	60/70	30/65
Wind at 10 m (km/h)	VBL 10/15	SE 20/25	SE 20/30
1000 m Wind	NW 15/25	NW 15/25	S 15/25

(a) Details of any major wind change: WIND WILL PROBABLY TEND EASTERLY AT 10/20 KPH THEN TEND MORE SOUTHEASTERLY AT SIMILAR STRENGTH BETWEEN 1000-1130.
(b) Comments on stability: BECOMING UNSTABLE.
(c) Weather and/or other detail: A SHOWER OR TWO AND THE LOW RISK OF A THUNDERSTORM DEVELOPING NORTH OF THE RANGES BEING STEERED BY UPPER NORTHWESTERLIES ACROSS THE FIRE SITE.

Forecast for subsequent 12 hours: ***261600/270400***
(a) Temperature: TEMPERATURE DECREASING TO 15 DEGREES OVERNIGHT.
(b) Humidity: INCREASING OVERNIGHT TO 70-85%.
(c) Wind: SE 10/20.
(d) Stability: STABILISING OVERNIGHT.
(e) Weather and/or other detail: ISOLATED SHOWERS.

Issued at: *1430 hours Sunday 26/02/95*

Forecast for first 6 hours

Time period (hours)	1500/1700	1700/1900	1900/2100
Temperature (°C)	29/31	27/29	27/25
Relative Humidity (%)	30/45	35/50	50/60
Wind at 10 m (km/h)	S/SE 10/20	SE 10/20	SE 15/25
1000 m Wind	NW 15/25	NW 15/25	S/SW 20/30

(a) Details of any major wind change: WEAK CHANGE PROBABLY STILL PUSHING THROUGH FIRE SITE BUT WIND NEAR THE FIRE WILL BE FLOWING IN TOWARDS THE FIRE. GRADUALLY THE WIND WILL TEND MORE SOUTHEAST OVER THE NEXT 6 HRS.
(b) Comments on stability: UNSTABLE.
(c) Weather and/or other detail: CHANCE OF A SHOWER OR TWO LATE THIS EVENING.

Forecast for subsequent 12 hours: 262100/270900

(a) Temperature: TEMPERATURE DECREASING TO 15 DEGREES OVERNIGHT.
(b) Humidity: INCREASING OVERNIGHT TO 65-75%.
(c) Wind: SE 10/20
(d) Stability: STABILISING OVERNIGHT.
(e) Weather and/or other detail: ISOLATED SHOWERS.

Issued at: *0112 hours Monday 27/02/95*

Forecast for first 6 hours

Time period (hours)	0100/0300	0300/0500	0500/0700
Temperature (°C)	17/15	15/14	14/16
Relative Humidity (%)	80/90	80/90	80/90
Wind at 10 m (km/h)	SE 20/30	SE 20/30	SE 20/30
1000 m Wind	SE 35/45	SE 35/45	SE 35/45

(a) Details of any major wind change: NIL.
(b) Comments on stability: INVERSION AT ABOUT 800M.
(c) Weather and/or other detail: PATCHY LIGHT RAIN. SLIGHT RISK OF A THUNDERSTORM.

Forecast for subsequent 12 hours: 270700/271900

(a) Temperature: MAX = 23.
(b) Humidity: MIN = 50%.
(c) Wind: SE 20/30 INCREASING SE 25/35 DURING DAY.
(d) Stability: NEUTRAL.
(e) Weather and/or other detail: PATCHY LIGHT RAIN GRADUALLY CLEARING. SLIGHT RISK OF STORM.

PART THREE

METEOROLOGY OF THE BERRINGA BUSHFIRE SMOKE PLUME

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BUREAU OF METEOROLOGY

SUMMARY

A bushfire in southeastern Australia burnt a total area of around 11,000 ha on 25 and 26 February 1995. A feature of the fire was a massive smoke plume. This reached its greatest height of over 10,000 m following a shallow wind change during the first evening which introduced relatively cool and moist air to the fire site. The conditions surrounding the development of the plume are found to be similar to those associated with thunderstorms. Convective clouds above fires are known to produce erratic winds and occasionally strong downbursts. The mechanism for downburst formation is presented along with a possible downburst speed for this plume.

INTRODUCTION

A bushfire started in forest area to the north of Berringa, in the southwest of Victoria, at around midday on 25 February 1995. The fire reached a final size of approximately 11,000 ha by the following day. Figure 1 shows the location of the fire and other places mentioned in the text. The bushfire initially burnt under extreme fire danger with hot, dry and unstable conditions fanned by a fresh north to northwest wind. Fire danger reduced somewhat to Very High during the mid-afternoon when the wind backed to the westnorthwest and eased. Fire dangers in this report are calculated using the Forest Fire Danger Meter Mark V (McArthur 1973) with a Drought Factor of 10.

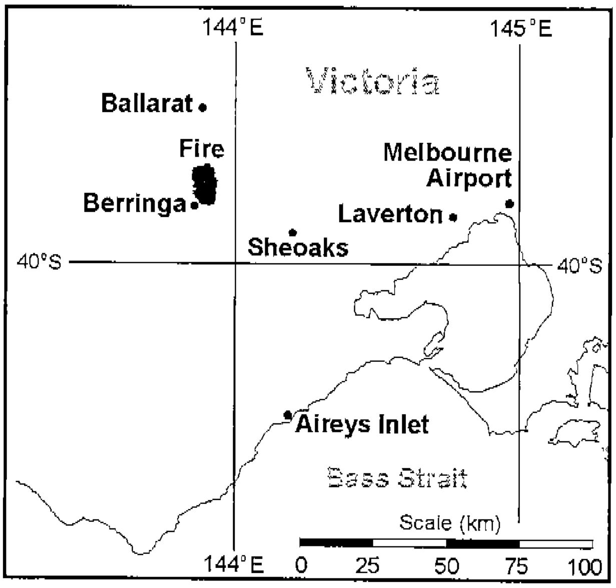

Figure 1. Location of the Berringa fire, Sheoaks Automatic Weather Station (AWS) and the Observing Office at Laverton.

During the early evening a more significant wind change crossed the fire area. This was associated with a sea-breeze initiated circulation, driven by the strong surface temperature gradient between the Victorian landmass and the cooler waters of Bass Strait to the southwest of the fire. The change brought a slight decrease in temperature, an increase in low-level moisture and light southerly winds at the surface. However, although the Fire Danger Index based on surface weather observations reduced further, the fire actually burned more vigorously as a towering convection column rapidly developed above the fire. The convection column remained a feature above the fire for several hours following the change.

A detailed study of the meteorological aspects surrounding the fire has been presented by Leggett (1998) and an analysis of the fire itself by Tolhurst and Chatto (1998). The scope of this report is to examine in detail the upper air conditions over the fire site during the afternoon and evening, and suggest a mechanism for the massive convective development evident during the evening. A one-dimensional plume model, PLUMP, developed by Latham (1994) is used to demonstrate the role of low-level moisture in the convective development. The report also describes radar imagery of the fire during the afternoon and evening of 25 February and compares this to three photographs taken during the evolution of the fire.

METHODOLOGY

Weather conditions near the fire site

The Australian Bureau of Meteorology operates an Observing Office at Laverton (elevation 18 m), approximately 90 km east of the fire, which performs surface and upper air observations. Upper wind soundings are taken every six hours at 0300, 0900, 1500 and 2100 hours local time, and radiosonde soundings of temperature and dewpoint at 0900 and 2100 hours. A 5 cm wavelength WSR74C weather-watch radar is also located at the site, updating radar images every 10 minutes.

Surface observations were available from the Bureau's three-hourly synoptic reporting stations and a network of Automatic Weather Stations (AWS) which report half-hourly, or when specified aviation amendment criteria are met. The closest AWS to the fire site was at Sheoaks (elevation 237 m), approximately 50 kilometres to the southeast of the fire origin. Wind speed and direction at Bureau of Meteorology stations are measured at a height of 10 m above ground level whilst temperature, dewpoint and humidity sensors are mounted 1.5 m above ground level in a white instrument screen. Further valuable observations were taken after 1800 hours from a Department of Conservation and Natural Resources (CNR) portable AWS erected at Staffordshire Reef.

The synoptic-scale mean sea level pressure analysis at 0900 hours[1] on 25 February (Figure 2) show a high pressure centre to the east of Victoria in the Tasman Sea directing a northwest wind flow over the State. A cold front and pre-frontal trough is located over ocean waters to the south of the Australian continent approached Victoria from the west, however the pressure gradient over the State remained relatively weak during the afternoon and evening.

[1] All times referred to are Eastern Daylight Savings Time (that is EST minus one hour).

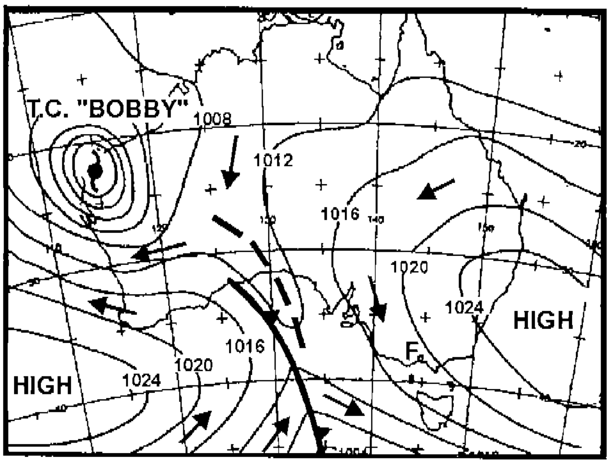

Figure 2. Mean sea level pressure weather chart for 0900 hours on 25 February. A cold front (barbed line) is located over ocean waters to the south of mainland Australia with a pre-frontal trough (dashed line) in the weak pressure gradient eastwards of the front. Arrows represent gradient wind direction. The fire site is marked by the letter "F".

Wind and temperature observations over southwest Victoria at 1500 and 1800 hours (Figure 3) reveal the development of a seabreeze initiated wind change on the southwest coast of Victoria during the mid-afternoon. The change had penetrated inland, almost to the fire area by 1800 hours that evening. The weather conditions and Fire Danger Index at Sheoaks AWS and Staffordshire Reef AWS at various times during the afternoon and evening are given in Table 1.

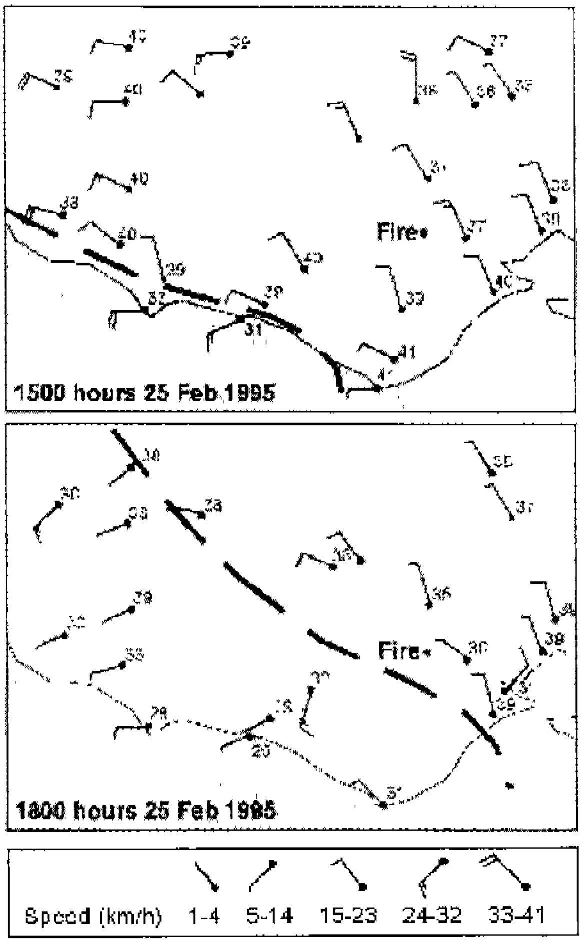

Figure 3. **Weather observations at 1500 hours and 1800 hours on 25 February. The barbed tail of each wind plot indicates the direction the wind is blowing from whilst the barbs themselves represent wind speed as decoded below. Temperature (°C) is shown at the top right corner of the plots. The progress of the southerly seabreeze wind change is marked with a dashed line.**

Table 1. Weather conditions and McArthur Forest Fire Danger Index near the fire site.

Time (hours)	Temp (°C)	RH (%)	Dewpoint (°C)	Wind (km/h) Dir'n / Speed / Gust			Forest Fire Danger Index
1250 (Sheoaks)	35.8	7	-5.1	320	30	26	66
1350 (Sheoaks)	36.4	7	-4.5	320	30	26	66
1500 (Sheoaks)	36.7	7	-3.9	330	26	24	62
1600 (Sheoaks)	36.9	6	-7.0	280	11	10	45
1700 (Sheoaks)	36.3	7	-5.0	290	9	8	41
1800 (Sheoaks)	35.9	7	-5.3	300	9	6	41
1820 (S' Reef)	34.6	13	3.0	289	11		33
1830 (S' Reef)	33.4	17	5	191	7		25
1900 (Sheoaks)	32.8	13	0.7	240	15	14	34
1900 (S' Reef)	31.3	24	8	173	7		18
2000 (Sheoaks)	29.3	20	3.8	220	13	13	22
2000 (S' Reef)	27.3	32	9.0	152	7		12
2100 (Sheoaks)	27.3	24	5.3	270	7	8	16
2100 (S' Reef)	26.4	34	9	140	4		10

Sheoaks AWS registered a northwest wind of approximately 30 km/h during the afternoon, tending westnorthwest and decreasing to approximately 10 km/h from about 1600 hours. The seabreeze change passed the station between 1830 and 1900 hours as a southwesterly wind of approximately 15 km/h. Staffordshire Reef AWS registered a westnorthwest wind of 12 km/h just prior to the change, with the wind shifting southerly at approximately 8 km/h between 1820 and 1830 hours. The wind remained light over the remainder of the night, veering to the west and later north to northwest at Sheoaks whilst at Staffordshire Reef it remained very light southeast to easterly. The change moved towards the northeast at around 30 km/h and would have crossed the fire area in about 10 minutes. During this period, the Fire Danger Index at Staffordshire Reef AWS decreased from Very High (36) at 1800 hours to High (18) at 1900 hours.

It is worth noting that the wind speed following the change in the 1,000 m above the surface may actually have been much stronger than registered at either the Staffordshire Reef or Sheoaks AWSs. Leggett (1998) provided observations from a fire tower on Cherry Tree Hill (elevation 480 m), 12 km northwest of Berringa. The southsouthwesterly wind change at the fire tower reached 30-40 km/h for a 20 minute period from around 1835 hours then eased back to 10-20 km/h by 2000 hours. The implications of the structure of the low-level wind profile above the fire are discussed more fully later in this paper.

Temperatures over much of the SW of Victoria reached 40°C during the afternoon. The highest temperature recorded at the CNR AWS at Staffordshire Reef was 37.5°C at 1740 hours whilst the maximum reported from Sheoaks was 37.3°C. High temperatures across the State corresponded with a ridge of warm air in the low-mid levels of the atmosphere and the lengthy trajectory of northwesterly wind over a hot land surface.

The lower atmosphere was particularly dry with dewpoint temperature values at Sheoaks registering as low as –6°C at times during the afternoon corresponding to a relative humidity of 6% to 7%. The Staffordshire Reef AWS recorded a relative humidity of 9% (dewpoint 2°C) just prior to the southerly change with a rapid increase in humidity to 23% (dewpoint 8°C) in the 10 minutes following the change. Relative humidity increased further to remain at around 40% throughout the rest of the night.

Radar and visual observations of the smoke plume and cloud complex
The weather-watch radar at Laverton allowed the history of the smoke plume and convection column above the fire to be documented in detail. The radar performed a "volumetric" scan of the atmosphere once every 10 minutes, completing 15 rotations at incremented elevations over a period of five minutes. The radar data can be displayed in several formats including horizontal plan view along beam centre (PPI format), simulated vertical cross-sections along a selected radial (RHI format) and simulated three dimensional solids. Radar reflectivity, measured in dBZ, indicates the intensity of energy re-radiated from a target. As a general guide, reflectivity's from meteorological targets in the order of 10-30 dBZ are associated with light rainfall, whilst those greater than 55 dBZ are associated with thunderstorms producing heavy rain and hail.

Although weather-watch radar is primarily used for mapping the location and development of precipitation, it has been used to observe other atmospheric phenomena including smoke from bushfires. For example, Reid and Vines (1972) used radar data in a study of a smoke plume near Melbourne in 1968. There are several possible contributors to radar returns from bushfires. The Mass Detection Observations Handbook (Bureau of Meteorology 1972) suggests that coarse particles and charred debris, for example leaves, bark and ashes, are the main contributors. In a series of large scale prescribed burns in Western Australia in 1970, Vines *et al.* (1971) found the majority of smoke particles were less than 1 μm in diameter with most particles approximately 0.1 μm. Reid and Vines (1972) used this finding to rule out the smoke particles themselves as contributing to the radar observations of bushfire smoke. The energy returned to the radar from a "target" is proportional to the sixth power of its diameter.

Another possible source of non-precipitation radar observations is Bragg scattering, sharp gradients in the refractive index of air brought about by turbulence. Turbulence would certainly be associated with convective development over the bushfires. Indeed based on the growth of radar echo top above the Berringa fire between 1632 and 1642 hours, vertical velocities were estimated to be at least 10.5 m/s. Vines *et al.* (1972) state that in a prescribed burning operation in Western Australia, a light aircraft on level flight was forced to rise vertically at up to 15 m/s when penetrating the smoke plume. In some instances, precipitation may also contribute to radar observations of bushfire smoke once appropriate microphysical processes have become established within the cloud capping the smoke plume.

Radar echoes from the smoke were first detected at 1252 hours at which time the echo top height was 3,300 m above ground level (AGL) and maximum echo reflectivity 17 dBZ. The northwest edge of the plume was approximately 27 km southsouthwest of Ballarat. By 1322 hours the echo had become elongated along a westnorthwest to eastsoutheast orientation and was about 30 km long by 12 km wide. It then appeared to dissipate but subsequently re-developed from around 1412 hours. Maximum reflectivity were now more intense and the echo top reached a height of 4,500 m AGL. The orientation of the smoke plume up to this time was consistent with mean wind direction between 1,500 m and 4,200 m measured at Laverton at 1500 hours. A sequence of hourly radar PPI images from 1500 until 2300 hours on 25 February is shown in Figure 4.

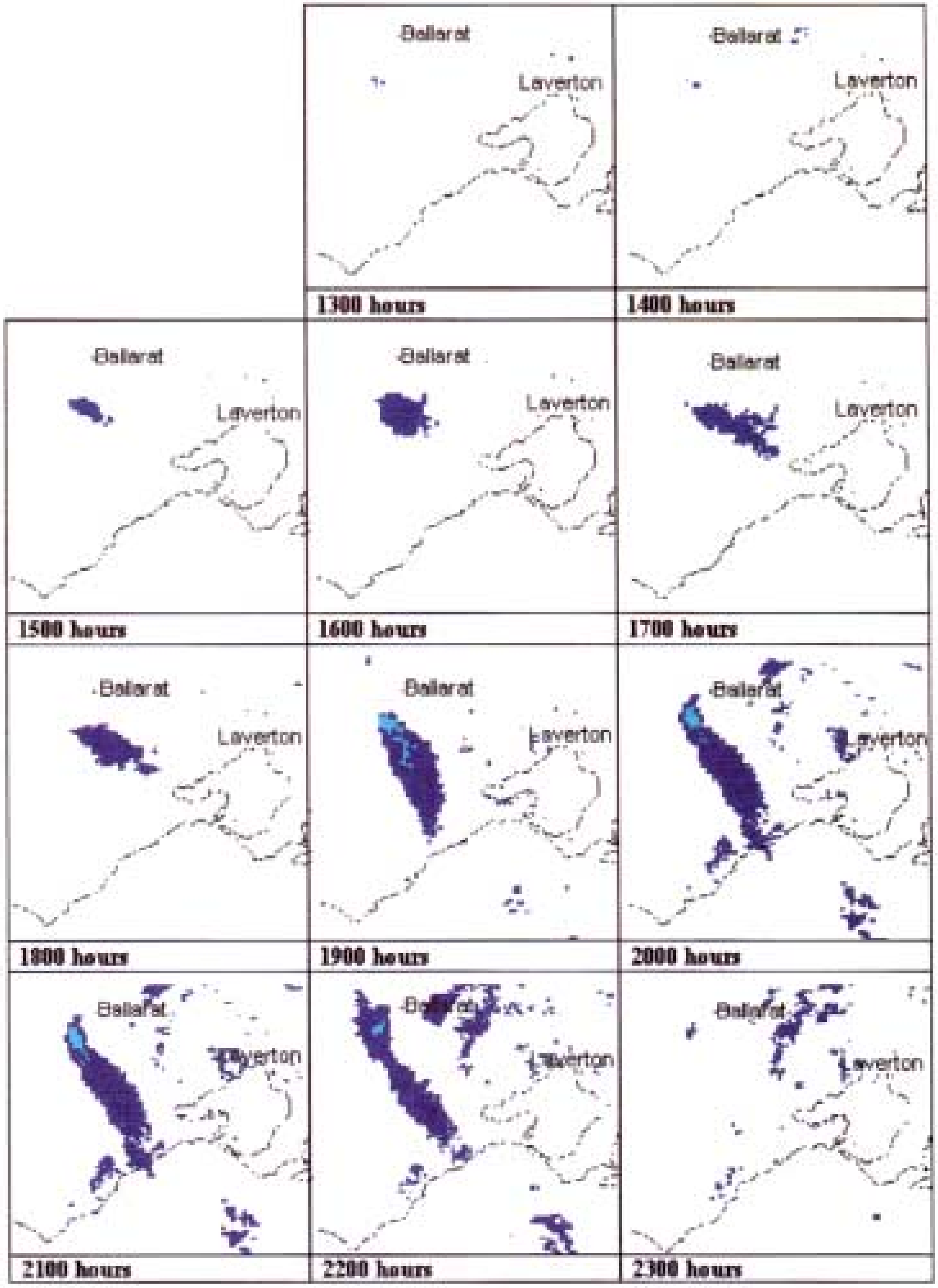

Figure 4. Hourly radar imagery from Laverton weather-watch radar from 1300 hours to 2300 hours on 25 February. The images present a plan view of the smoke plume below a height of around 4,000 m. Dark tones indicates radar reflectivity between 12 and 28 dBZ, light tones between 28 and 39 dBZ. Reflectivity less than 12 dBZ is not displayed.

This second intensification phase continued over the next hour with radar height reaching 7,800 m by 1522 hours. Maximum reflectivity at the northwest edge of the echo increased to around 30 dBZ. The echo by now had become much broader, being approximately 35 km long by 30 km wide, corresponding with a horizontal area of around 55,000 ha. The broadening occurred as smoke and cloud material pushed upward into a more northerly wind regime. The echo top height then fell over the next hour and the plume once more became elongated.

Kevin Tolhurst[2] provided three 35 mm colour transparencies of the smoke plume taken at 1556, 1819 and 1957 hours. Given the focal length of the camera lens and the approximate distance to the fire, the heights of smoke and cloud features could be calculated using photogrammetric equations (Holle 1988). Figure 5 shows a photograph of the smoke plume taken at 1556 hours from a distance of approximately 31 km. The dense smoke from the fire is generally confined below approximately 4,000 m by a relatively stable mid-level layer but convective development above the fire itself reaches to around 6,100 m (± 670 m). Some cloud not associated with the fire, possibly mid-level Altocumulus, can be seen in the right background of the photograph indicating a slight increase in mid-level moisture. Radar imagery at 1552 hours indicated an echo top height of approximately 7,200 m which is just over 1,000 m higher than that derived from the photographs.

Figure 5. The smoke plume at 1556 hours looking towards the southwest from a distance of approximately 31 km. Dense smoke is generally confined below a height of 4,000 with convective development above the fire itself reaching 6,100 m. (Photograph courtesy of Kevin Tolhurst.)

By 1800 hours the radar echo had become fragmented. The photograph in Figure 6 taken at about this time, shows that smoke rising from the fire was less dense than at 1600 hours. The top of the more convective portions of the plume was now approximately 5,700 m (±620 m). This compares to radar echo top height of approximately 6,700 m.

[2] At the time of the fire, Kevin Tolhurst was a Fire Research Scientist with CNR, however he is now a Lecturer with the University of Melbourne.

Figure 6. The smoke plume at 1819 hours just prior to the southerly wind change. Tops of the more convective portions of the cloud reach 5,700 m. (Photograph courtesy of Kevin Tolhurst.)

Spectacular growth then occurred between radar images at 1832 and 1842 hours (Figure 7) with echo top height increasing from 3,900 to 9,600 m near the point latitude 37°45'36"S, longitude 143°44'24". An hourly map of the fireline produced by Tolhurst and Chatto (1998) indicates this is near the northeastern flank of the fire. The rate of growth equates with an upward motion of 6,300 m in about 10 minutes, giving a vertical velocity of at least 37.8 km/h (10.5 m/s). The maximum radar top height attained during this intensification phase was approximately 11,500 m which was maintained until 1922 hours when echo tops dropped to approximately 9,000 m. The rapid development seen on the radar was coincident with the passage of a southerly wind change across the fire.

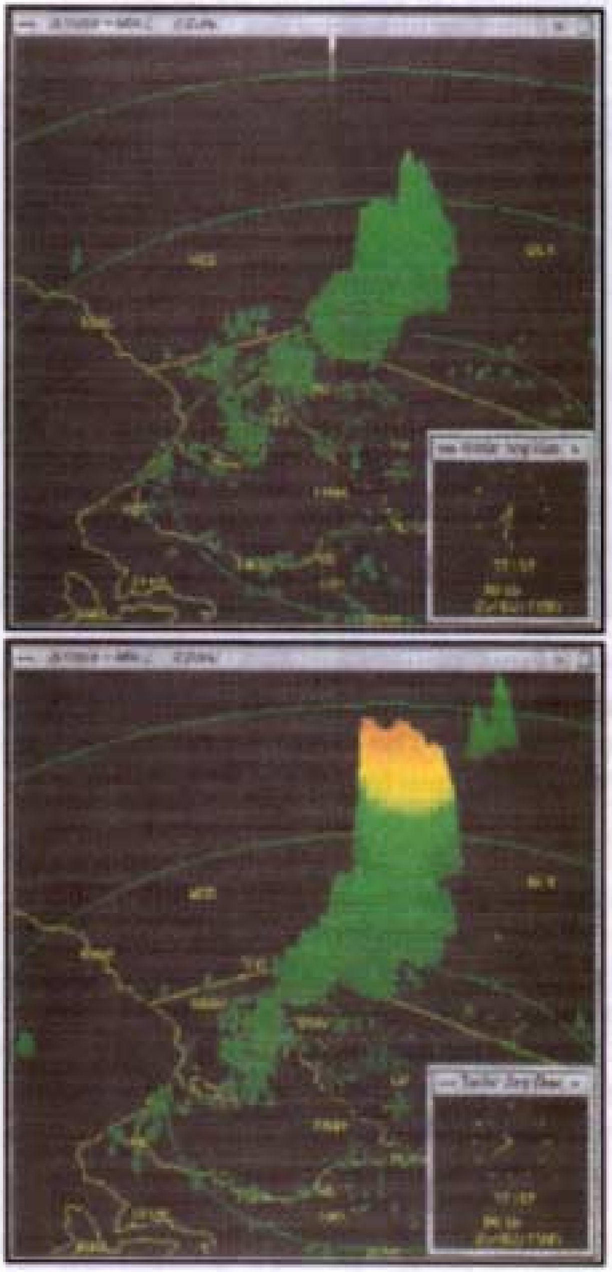

Figure 7. Three-dimensional weather radar imagery showing spectacular growth in radar echo between 1832 hours (0732Z) and 1852 hours (0752Z). Radar top height increased from 3,300 m to 11,500 m during this period. Colours represent echo height increasing from green to yellow and then brown. The view is looking towards the west-northwest.

The photograph at 1957 hours (Figure 8) was taken at Ballarat aerodrome looking towards the south and shows the large convective cloud capping the smoke plume which developed following the southerly wind change at 1830 hours. The height of the convective cloud at this time was calculated at 10,100 m (±800 m). The strength of the updraught has been sufficient to force mid-level cloud material back towards the northwest against the prevailing wind, which at 2100 hours above Laverton was westnorthwest 41 km/h. To the left of the tower, smoke can be seen streaming out towards the southeast.

Figure 8. The large convective tower capping the smoke plume at 1957 hours, seen looking south from Ballarat aerodrome. The height of the tower was calculated at 10,100 m. The measured radar top height at 1952 hours was 9,800 m. (Photograph courtesy of Kevin Tolhurst.)

Over the next two hours the area of the plume as measured by radar increased dramatically to extend from Ballarat in the north to Airey's Inlet on the coast, a distance exceeding 100 km. It is also possible, when viewing the radar sequence in a three-dimensional window, to detect a series of surges in echo activity. These occurred from 1942 to 2012 hours, at 2052 hours and from 2122 to 2132 hours. One further interesting observation during these periods of intensification was the region of maximum echo height become displaced downwind considerably from the low level region of highest reflectivity.

Upper level conditions

At 0900 hours on 25 February, an upper-level low was centred around 900 km to the northwest of Berringa within a broad upper trough. The low to middle levels of the atmosphere were particularly warm with a 1000-500 hPa thickness ridge lying across southwest Victoria. Skies were generally clear apart from cloud associated with the upper low and an advancing cold front located over ocean waters to the south of the mainland.

Wind in the low levels above Laverton were initially strong, with a peak wind of 59 km/h from the northwest 600 m altitude. The low-level wind direction turned anticlockwise (backed) to the westnorthwest with increasing height below 3000 m altitude, consistent with the advection of warm air from the north. The low-level flow eased markedly during the day to be only 26 km/h at 600 m altitude by 1500 hours. By 2100 hours however, winds up to 900 m altitude had shifted southsouthwest and strengthened to a maximum of 48 km/h behind the sea-breeze change. However, the wind at 1,500 m altitude remained light northwesterly indicating the shallow depth of the change.

Winds in the mid-levels of the atmosphere were initially light with a minimum of 7 km/h at 5,700 m. Wind direction turned clockwise (veered) through north with increasing height consistent with the advection of cooler middle-level air which would assist destabilisation of the atmosphere. During the day, wind speeds increased as the upper level trough approached from the west and wind direction tended north to northwest throughout. At higher levels (approximately 11,000 m) two jet streaks with speeds approximately 90 km/h approached from the west, providing a favourable area for up-motion over southwest Victoria during the afternoon and evening.

Following the event, the Bureau of Meteorology Research Centre (BMRC) provided forecast charts at 5 km resolution from their Local Analysis and Prediction System mesoscale atmospheric model (G. Mills 1997 pers. comm.). The charts showed mid-level up-motion developing over the coast of southwest Victoria during the afternoon which intensified and moved inland during the late afternoon and evening. The region of up-motion was slightly southwards of the seabreeze wind change which was also captured by the model. The up-motion would have resulted from lower-level convergence of the wind field in the vicinity of the seabreeze front and enhanced by high-level divergence of air in the vicinity of the jet streaks.

Several upper atmosphere wind speed profiles have been related to the behaviour of wildfires in the United States of America by Byram (1954). The most hazardous of these, which were associated with "blow-up" fires, displayed a low-level wind speed maximum of 29 km/h or more, wind speed decreasing with height for 1,000 m or so above the maxima, dry and plentiful fuels and unstable atmospheric conditions. The low-level wind maximum either occurred at the surface or in the form of a low-level jet point below 1,000 m AGL. Fires burning under these wind speed profiles were found to develop convective smoke plumes, display erratic fire behaviour and burn with more intensity than weather conditions would indicate. Steiner (1976) suggests the low-level wind maxima acts to enhance surface convergence of the wind in the vicinity of the fire, thereby aiding the development of convection above the fire, and also the spread of embers downwind ahead of the fire. These relationships are further discussed in the Bureau of Meteorology's Fire Weather Supplement (1963).

Wind speeds profiles constructed for the Berringa fire using upper wind data from Laverton, together with surface wind observations from Sheoaks AWS are shown in Figure 9. The Laverton upper wind data was considered as broadly representative of wind structure in the vicinity of the fire. The profile for 0900 hours shows a low-level jet with a peak wind speed of 59 km/h at 600 m. The jet points are low-level maxima in wind speed. In hilly terrain these may impinge at ground level resulting in a rise of surface wind speed. Wind speed then generally decreases to an altitude above 3,600 m before increasing once more at high-level. The profile up to an altitude of 3,600 m resembles Byram's Type 2b profile shown as Figure 10. The profile at 1500 hours differs markedly with wind speeds reasonably constant at about 30 km/h up to a height above 3,600 m. This type of profile is reminiscent of Byram's 4b or 4c (Figure 10) although wind speeds are approximately twice the strength. Byram considered this profile "safe" as long as fires were not burning upslope.

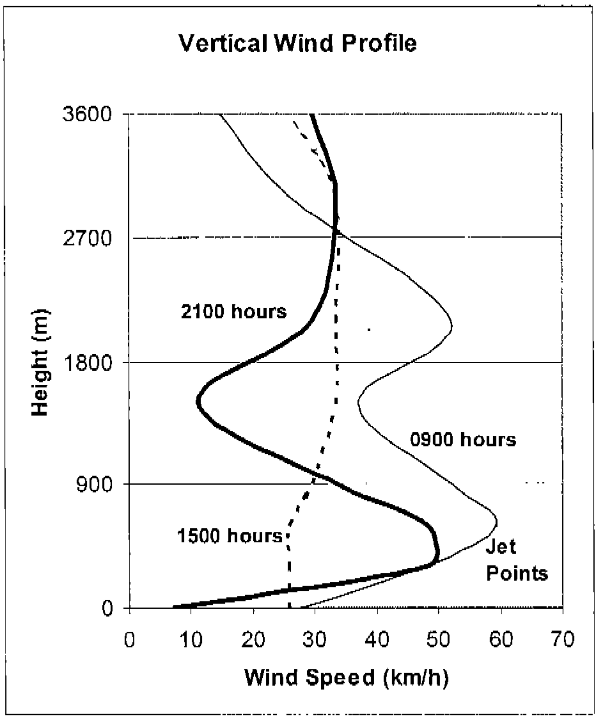

Figure 9. Vertical wind profiles near the fire site at 0900, 1500 and 2100 hours on 25 February. Profiles are constructed from upper wind data from Laverton Observing Office with surface observations from Sheoaks AWS. The thin line is the 0900 hours profile, the dashed line 1500 hours and the thick line 2100 hours.

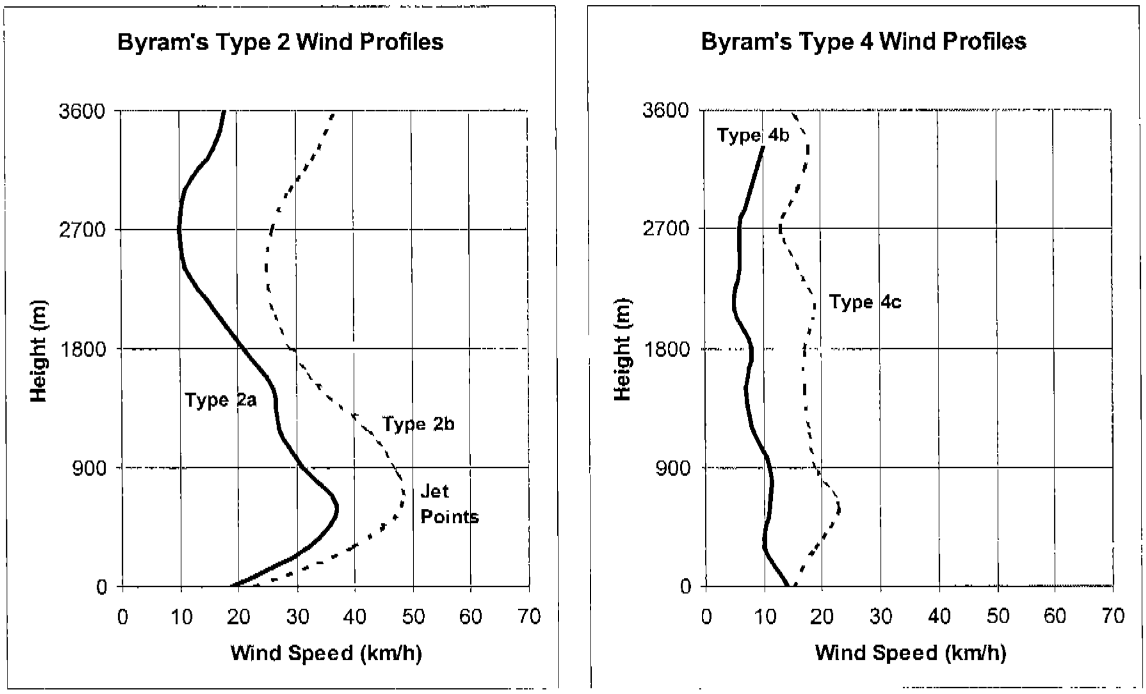

Figure 10. Byram's Type 2 and Type 4 wind speed profiles (adapted from Byram 1954).

The shallow southerly wind change at 1830 hours brought much stronger low-level wind speeds with a peak of 48 km/h at 300 and 600 m. Wind speed then decreased to a minimum of 11 km/h at 1,500 m before once more increasing in speed with height. This profile appears to be a combination of Byram's Type 2a and 2b profiles with the strength of the low-level jet similar to the Type 2b and the minima of 11 km/h similar to that on the Type 2a only about 1,000 m lower. Byram stated that fires burning under the Type 2a profile were amongst the most dangerous, particularly in hilly terrain where the jet-point may impact at ground level enhancing low-level convergence and increasing surface wind speeds.

Atmospheric Stability

Upper air soundings were available from Laverton at 0900 and 2100 hours. The sounding data is provided in Appendix 1. A comparison of the soundings (Figure 11) shows warming had occurred during the day below around 2,800 m whilst cooling had taken place above this to a height of around 5,500 m. Thus net destabilisation of the atmosphere had occurred, eroding a mid-level temperature inversion of around 1.5°C. Warming in the low levels was due to a combination of surface heating and mixing of the lower atmosphere coupled with the advection of warm air from the north. Evidence of thorough mixing during the afternoon is shown on the 2100 hours sounding by an almost constant mixing ratio and dry adiabatic temperature lapse rate between 1500 m and 3500 m. Conditions below 1500 m had been modified by diurnal cooling together with the effects of the shallow southerly seabreeze change. Cooling in the middle-levels resulted from the eastward progression of the thickness ridge in combination with the approach of the upper trough. Destabilisation was also assisted by middle-level vertical motion.

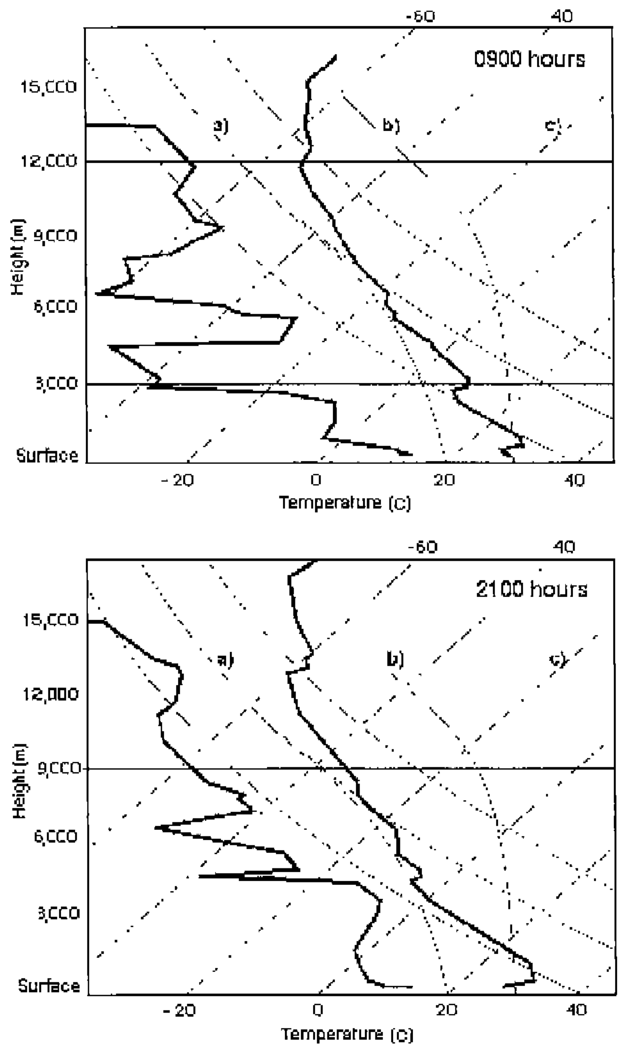

Figure 11. Upper air soundings from Laverton at 0900 hours and 2100 hours. Each sounding consists of two lines, the right-hand line representing air temperature and the left-hand line dewpoint temperature. Destabilization is evident in the erosion by evening of the mid-level inversion seen at approximately 3,000 m on the 0900 sounding. The moisture introduced by the sea-breeze front extends to a height of approximately 1,000m on the 2100 hours sounding. Dry adiabats are marked at a), saturated adiabats at b) and isotherms at c). The vertical scale shows height in the standard ICAO atmosphere.

In an attempt to relate the potential for large fire growth to atmospheric stability and moisture, Haines (1988) presented a Lower Atmospheric Severity Index (LASI), known also as the Haines Index. The stability component of the Haines Index is calculated from the temperature lapse rate in the low to mid-level atmosphere above the boundary layer. The index can be calculated at three levels; low-level from 950-850 hPa, (approximately 500 to 1,500 m), mid-level from 850-700 hPa (approximately 1,500 to 3,000 m) and high-level from 700-500 hPa (approximately 3,000 to 5,700 m). An unstable lapse rate allows convective growth of the smoke column to a greater height. Mass continuity then requires increased inflow at the surface to replace the buoyant air taken aloft and this in turn supplies energy and oxygen for combustion. The moisture component is calculated from the dewpoint depression immediately above boundary layer. Low moisture increases fuel availability as fine fuels dry out so the energy of the fire is available for combustion rather than evaporation. The index ranges from 2 to 6 with a high index denoting unstable and dry conditions suitable for large fire growth.

In a study of the Haines Index in Tasmania, Bally (1995) found that 84% of fire activity occurred with an index of 5 or 6. Bally concluded that the mid-level Haines Index when used in conjunction with the Fire Danger Index, was a more skilful indicator of fire activity in Tasmania than either index used alone. Bally has since developed a continuous mid-level algorithm (J. Bally 1998 pers. comm.) which allows finer resolution across categories. This is particularly useful at the high end of the scale where most fire activity occurs.

Haines Index was calculated from the Laverton soundings at 0900 and 2100 hours with Table 2 summarising the results. The low-level index at both times was in the maximum category. However, this would be expected for southeast Australian conditions where the low levels of the atmosphere are generally well mixed on hot summer days, displaying a dry adiabatic lapse rate and low humidity. It is therefore more meaningful to consider the mid-level or high-level Haines Index to discriminate days when dry and unstable conditions may contribute to the possibility of deep convection above fires. This was certainly the case with the mid-level Haines Index calculated at the maximum 6 for both 0900 and 2100 hours. However, using Bally's continuous mid-level algorithm, the mid-level index actually increased from 5.7 at 0900 hours to 6.9 at 2100 hours. Conditions were therefore much more conducive for convective plume growth by evening. The high-level index actually decreased markedly from 5 at 0900 hours to 2 at 2100 hours due to an increase in moisture at the 700 hPa (3,000 m) level.

Table 2. Haines Index at Laverton at 0900 and 2100 hours, 25th February.

Haines Index	*0900 hours*	*2100 hours*
Low (950 – 850 hPa)	6	6
Mid (850 – 700 hPa)*	6 (5.7)	6 (6.9)
High (700 – 500 hPa)	5	2

* Figures in brackets are calculated using Bally's continuous mid-level algorithm

RESULTS

Modeling the plume and convective development with PLUMP

A one-dimensional plume and cloud model "PLUMP" developed by Latham (1994) was used to analyse plume and cloud development. The model includes cloud physics and entrainment and generates output fields including plume height, cloud base and vertical velocity. Cloud top is assumed to be the plume top height when cloud is generated. Inputs to the fuel mass option of PLUMP are duration of burn, burn area, fuel loading, fuel moisture and model time.

Plume top heights derived from the unmodified 0900 and 2100 hours soundings were quite low and reflected the diurnal stability of the surface boundary layer. The low to mid-levels of the atmosphere were therefore modified to be representative of conditions at the fire site during the afternoon and evening. Five soundings were finally used as input. The fuel mass option of PLUMP was run on all five soundings using the inputs listed in Table 3. Most runs were made with default values of burn duration and area suggested by Latham (1994). Burned fuel loading at the fire site was estimated at 26 t/ha and fuel moisture content at 6% (Tolhurst and Chatto 1998). PLUMP did not appear to be sensitive to changes in fuel moisture content. When fuel moisture content was varied from 3% to 10% holding other parameters constant, plume top height did not change.

Table 3. Results of PLUMP model using the five modified soundings.

Sounding Number	*1*	*2*	*3*	*4*	*5*
Time (hours)	0900	2100	2100	2100	2100
Burn Duration (min)	30*	30*	30*	30*	60
Burn Area (ha)	400*	400*	400*	400*	2,500
Fuel Loading (kg/m^2)	2.6	2.6	2.6	2.6	2.6
Fuel Moisture (%)	6	6	6	6	6
Surface Temperature (°C)	38	38	38	38	38
Surface Dewpoint (°C)	-3	-3	2	8	8
Cloud Base (m)	Nil	4,700	4,300	3,900	3,900
Plume Top Height (m)	4,400	5,800	6,200	8,200	10,300

* Latham's default values

The 0900 hours sounding was modified for a surface temperature of 38°C and dewpoint of -3°C (Sounding No. 1). These values were considered as representative of the surface conditions in the vicinity of the fire during the afternoon and acted as a rudimentary forecast sounding. This modification resulted in a well mixed layer below around 3,000 m and appeared very representative of afternoon conditions, although in hindsight did not allow sufficiently for middle-level cooling. This resulted in a smoke plume height of 4,400 m, but no cloud was generated.

An input sounding using the same surface conditions and burn characteristics (Sounding No. 2) was then constructed based on the 2100 hours Laverton sounding. This generated a total plume height of 5,800 m with a cloud base at 4,700 m. The cloud base and plume height from this sounding are in good agreement with those measured photogrametrically and by radar during the afternoon.

To test the affect of low-level moisture on plume development, a similar sounding was constructed using a surface dewpoint of 2°C and run with the same input data (Sounding No. 3). This yielded a lower cloud base at 4,300 m and a increased plume height of 6,200 m. The increase in moisture causes saturation of the air rising within the smoke plume at a lower level, hence a lower cloud base. Energy released by the condensation of water vapour as the air rises above the convective condensation level also allows cloud to develop to a greater height.

To further test the effect of moisture on plume development, another sounding (Sounding No. 4) was constructed with a surface dewpoint of 8°C to take account of the rapid increase in moisture following the change. The surface temperature was left at 38°C as it was unclear how the heat of the fire area, which at this stage was around 2,500 ha in size, would affect the surface temperature. It is worth noting that the temperature fall at Staffordshire Reef AWS was initially only slight following the change and a steep low-level lapse rate would have persisted in the vicinity of the fire immediately above the surface for some time following the change. It is also unclear how the effects of convergence of the low-level wind field and physical lifting in the vicinity of the wind change would affect the sounding near the fire. This sounding saw a dramatic increase in the total height of the plume, up to 8,200 m with the cloud base lowering further to 3,900 m. When the burn area was then increased to 2,500 ha over a duration of 60 minutes (approximately the area burnt during this time) total plume height increases to 10,300 m (Sounding No. 5). This is in agreement with radar observations at 1952 hours which gave an echo top height of 10,100 m and the visual photogrammetric estimates at 1957 hours of 9,000 m.

Numerous mechanisms can be suggested for enhancing convective development above the fire coincident with the southerly wind change. The most obvious factor is enhanced vertical motion in the vicinity of the wind change, generated through convergence in the low-level wind field (ie. northwest wind ahead and southsouthwest following) and assisted in middle-high levels by a favourable jetstream pattern. Another factor, illustrated by the PLUMP runs, is the importance of the increase in low-level moisture following the shallow southerly change. The development of convective cloud can be described simply by considering the processes acting on a small "parcel" of air which does not exchange energy with its surrounding environment (i.e. the parcel is adiabatic). The unsaturated parcel of air rising through the atmosphere cools at the dry adiabatic lapse rate until reaching its dewpoint temperature, where moisture in the parcel condenses forming cloud. When the parcel of air now rises above the condensation level it cools at the lesser saturated adiabatic lapse rate. It will now rise on its own accord whilst the temperature of the saturated air in the parcel exceeds that of its surrounding environment.

Reid and Vines (1972) compared plume development from a fire in 1968 with the closest aerological sounding. They found "substantial agreement" between the observed base and top heights of convective cloud capping the plume and heights derived from the sounding using the simple "parcel" theory and the surface conditions at the time of the fire. They concluded from this that neither the heat of the fire, or the water vapour added as a by-product of combustion, contributed to the growth of the convective cloud above the fire.

An attempt was made for the Berringa fire to model the depth of the convective cloud above the fire using simple meteorological "parcel" theory. On all modified soundings prior to the southerly wind change, the boundary layer of the atmosphere was much too dry for surface driven convection despite the low to mid-levels of the atmosphere being extremely unstable. However, following the change, the low-level atmosphere did possess sufficient moisture to form a lifted cloud base at 3,700 with the cloud top extending to a level at 7,600 m. Therefore in this case, the aerological sounding does not explain the full depth of the convective cloud.

DISCUSSION

It would be desirable to better understand weather conditions likely to give rise to fires dominated by convective processes for a number of reasons. First, because of the potential for large fire growth under these conditions as described by Haines (1988). Second, because of the dangers posed to fire crews through erratic fire behaviour as discussed by Byram (1954) and third, the potential for strong downburst winds which can drive fires across control lines (K. Tolhurst 1995 pers. comm.).

The weather conditions when the convection column above the Berringa fire became most active, were similar in many respects to that associated with thunderstorm development. Thunderstorms typically require three main "ingredients" for development to occur. These include an unstable atmospheric lapse rate, sufficient low-level moisture and an initiating mechanism. As Doswell (1985) argues convincingly, thunderstorms do not occur randomly but require a mechanism to focus the release of buoyant energy within a suitable environment. Meteorological examples include cold fronts, pressure troughs, outflow boundaries from pre-existing or decaying storms and convergence of winds associated with topographical features.

Conditions on the evening of 25 February possessed most of these ingredients. The atmosphere was very unstable, a low-level initiation mechanism was present in the form of the southerly seabreeze front and there was substantial mid-level up-motion as a result. The reason that convective activity was not widespread along the length of the wind change was that moisture was a limiting factor. Even following the wind change, the increase in moisture was not sufficient on its own to produce substantial convection. However, the simulations using PLUMP show that the increase was sufficient to allow dramatic growth of convection above the fire itself. The view that "blow-up" fires may occur under weather conditions conducive to thunderstorm development is also supported by Taylor and Williams (1968). They argued that weather conditions conducive to the development of severe thunderstorms and tornadoes where analogous with those conducive to convection above fires. They found the passage of a surface trough was a contributing factor to enhancing convection above the "Hellgate" fire in 1965 in Virginia.

Another feature of importance related to convection is the possibility that they may generate strong downburst winds. The mechanism for downburst formation would most likely be similar to that which generates dry microbursts from high based thunderstorms or middle level cloud. These are documented by Fujita (1985). Days on which these occur are typically characterised by mid to high-level cloud base above a very dry low to mid-level atmosphere. These conditions are analogous to a convection column with a mid-level base developing over a fire site.

Downbursts are generated when precipitation, particularly ice particles, evaporates when falling towards the ground. Energy is required during these phase changes with the net result that the environmental air cools and becomes negatively buoyant. It then accelerates towards the ground as a downburst of air. The cloud which formed above the Berringa fire was certainly tall enough and cold enough (cloud top temperatures were in the order of -45°C to -50°C) to generate ice crystal processes. The base of the convective cloud was relatively high at around 4,000 m and the environmental air below the cloud base, apart from the lowest levels, was dry.

A method has been devised by McCann (1994) to calculate the theoretical downburst speed under these conditions. This was calculated as 85 km/h for conditions on the evening of the Berringa fire based on the Laverton 2100 hours sounding with a surface temperature of 38°C and dewpoint of 8°C. Although downburst winds were not documented with the Berringa fire, meteorological reasoning indicates that they may occur with fires dominated by convective processes at a speed that may impact on fire crew safety and fire suppression.

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Appendix 1. Laverton upper air soundings at a) 0900 and b) 2100 hours, 25 February.

a)

Pressure Level (hPa)	Temperature (°C)	Dewpoint Temperature (°C)	Wind Direction (° true)	Wind Speed (knots)
1016	28.6	13.6	360	14
1000	27.2	11.2		
984	26.4	10.4		
963	28.8	6.8		
929	27.2	-2.8		
904	25.2	-2.8		
850	20.2	-3.8	300	20
766	11.8	-7.2		
725	9.2	-17.8		
710	10.4	-37.6		
700	10.2	-37.8	290	14
676	9.2	-37.8		
600	1.6	-47.4	330	10
571	-1.7	-50.7		
554	-2.9	-25.9		
500	-10.7	-27.7	360	4
487	-12.7	-27.7		
477	-13.1	-36.1		
455	-16.1	-41.1		
428	-17.7	-61.7		
400	-21.9	-58.9	65	10
356	-28.9	-63.9		
347	-30.1	-58.1		
303	-36.9	-54.9		
300	-37.3	-54.3	20	26
287	-39.1	-60.1		
250	-46.5	-67.5	30	30
217	-53.1	-69.1		
200	-54.5	-74.5	35	44
197	-54.5	-75.5		
174	-59.5	-82.5		
150	-63.5		50	46
137	-66.9			
121	-66.5			
108	-69.5			
104	-69.5			
100	-68.3		85	28

Pressure Level (hPa)	Temperature (°C)	Dewpoint Temperature (°C)	Wind Direction (° true)	Wind Speed (knots)
1014	27.2	14.2	230	10
1000	28.6	9.6		
980	30.2	7.2		
898	26.8	2.8		
850	22.6	0.6	325	6
700	7.6	-2.4	320	18
660	3	-4		
606	-2.1	-10.1		
601	-2.5	-14.5		
600	-2.5	-15.5	295	22
588	-1.9	-32.9		
571	-3.1	-20.1		
527	-8.5	-24.5		
500	-10.3	-34.3	335	24
464	-13.1	-47.1		
425	-18.9	-35.9		
400	-22.7	-39.7	340	32
391	-23.9	-39.9		
369	-25.9	-46.9		
300	-37.7	-59.7	345	42
265	-44.3	-64.3		
250	-46.9	-63.9	350	50
216	-52.7	-67.7		
208	-51.5	-69.5		
200	-52.7	-73.7	360	48
194	-52.9	-75.9		
166	-60.1	-87.1		
150	-63.9		305	22
135	-67.9			
111	-66.1			
100	-67.7		355	20

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