Final Client Report

Nature of Severe Fire Events

Client Report for

Fire Management Unit
Department of Urban Services
ACT Government

By

Andrew Sullivan

July 2004

Forestry and
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Executive Summary

A severe fire event is defined as a bushfire or series of concurrent bushfires that burn, or threaten to burn, assets (lives, property or resources).

Seven case histories are presented that illustrate the nature of severe fire events in Australia's recent past.

These case histories are:

- Victoria/NSW/ACT, (Black Friday) January 1939
- Canberra, 1951/1952
- Mangoplah, NSW, January 1952
- Dwellingup, WA, January 1961
- Hobart, Tasmania, 7 February 1967
- Western Districts, Victoria, 12 February 1977
- SA/Victoria, Ash Wednesday, 16 February 1983
- Sydney, January 1994
- Victoria/NSW/ACT, January-March 2003

Common factors have been identified in the case histories and other significant fire events that characterise the a severe fire event:

- Antecedent rainfall deficit, although not necessarily in case of extensive grass fires;
- Synoptic weather pattern that directs strong, hot gusty wind from centre of continent over region in question. Unstable atmosphere that is conducive to mixing of strong upper winds to the surface and the development of strong fire convection;
- Low fuel moisture contents resulting from high diurnal air temperature and low relative humidity sustained for long periods throughout the day, associated strong gusty winds; and
- Fires burning prior to the arrival of extreme fire weather or ignitions, generally multiple ignitions, resulting from the passage of dry summer thunderstorms, arson or spotting from existing fires.

The result of the combination of the above factors is severe high-intensity, at times erratic fire behaviour (including sustained periods of rapid fire spread and massive spotting in certain fuel types), and extreme difficulty of suppression.

Fires burning under these conditions will burn out considerable areas of land, travel considerable distances, threaten homes, lives and other assets and be uncontrollable until the weather abates.

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1. Introduction

A severe fire event is defined as a bushfire or, more commonly, a series of bushfires occurring concurrently, which burn or threaten to burn significant assets (either area or other resources) under conditions of very high to extreme fire weather. A severe fire event is characterised by periods of extreme fire behaviour, which can include rapid fire spread in terms of area, perimeter and head fire propagation, high flames, ignition of extensive spot fires from the main front, and is generally uncontrollable, at least until conditions moderate. A severe fire event may also be characterised by the area burnt. However, given that enormous tracts of northern Australia are burnt each year by bushfires by fires that are not considered severe fire events, area alone is insufficient. The impact on asset values or on lives, property or environmental values is also important.

The behaviour of bushfire is largely the result of the combination of fuel, weather, and topography in which the fire is burning, and the fire itself (Cheney *et al.* 1993, Gould *et al.* 2003). Fuel is the dominant vegetation stratum through which the fire propagates. In forests this is generally the surface layer, but as fire intensity increases, the strata of fuel involved changes. Topography (and, in particular, slope) influences the spread rate of the fire through increasing the heat exchange between the flame front and unburnt fuel. For every 10º increase in slope, the rate of forward spread will increase twofold (McArthur 1962). Negative slopes will result in a corresponding decrease in rate of forward spread. Breaks in topography can reduce overall spread of the fire but increased spotting from ridge tops following upslope runs (Luke and McArthur 1978) can overcome these, resulting in fire spread rates comparable to that over level ground. Weather is the most important component determining fire behaviour. The Fire Danger Meters (both grass (McArthur 1966, Cheney and Sullivan 1997) and forest (McArthur 1967)) are essentially fire weather indices with fuel aspects. Unlike fuel and topography, weather can change rapidly and have an immediate effect on fire behaviour. Fuel is the only component determining fire behaviour that can be modified to any extent. Interaction between individual fires or spot fires and the main fire can also play a major part in the determination of fire behaviour (Cheney 1976).

This report summarises several Australian severe fire events, identifying several common characteristics, particularly for south-eastern Australia and the ACT region. The implications for fire management planning and operations are explored.

2. Case histories

The following case histories were selected to illustrate the range, scope, impact and conditions under which some of the most devastating severe fire events have occurred and have been documented in Australia. While there have been others in the long history of catastrophic bushfire events in Australia with respect to area burnt, lives lost, etc (e.g. Black Thursday 1851, Longwood 1964, western-central Victoria 1969, Blue Mountains 1977), these have been chosen because of the significant amount of meteorological and fire behaviour information available, and they represent a unique cross-section of antecedent conditions, fire extent, location, main fuel type involved and synoptic and diurnal conditions under which severe fire events have occurred.

2.1 Victoria/NSW/ACT/SA, January 1939[1]

The fires of the 1938/39 fire season were characterised by below average winter rainfall throughout 1938. The first fires of the fire season in Victoria occurred in August and resulted in crown fire spread. Grasslands were cured early by a dry spring. In the western highlands of Victoria, the worst fires in many years had occurred by October of 1938.

A high-pressure system (sometimes referred to as an anti-cyclone) developed over the Tasman Sea in early January and remained in place for almost a fortnight. This resulted in steadily increasing daily temperatures. The general flow of wind over south-eastern Australia was from the north-west.

Fronts frequently passed over south-eastern Australia at 2-3 day intervals following heat wave events during this period. During these heat wave events, hundreds of fires spread fiercely before conditions abated following the passage of a front. Adelaide experienced 10 consecutive days over 36°C and three days over 45°C. Melbourne set a record high temperature of 44.7°C on 10 January, only for it to be surpassed 3 days later on January 13, Black Friday. Three other Australian capital cities experienced their extreme maximum temperatures during the January 1939 period Canberra reached 42.8°C on 11 January; Adelaide reached 47.6°C on 12 January; and Sydney reached 45.3°C on 14 January.

January 13, Black Friday, brought further record-breaking temperatures to south-eastern Australia: Melbourne reached 45.6°C, Wangaratta reached 46.0°C. A low-pressure depression stretching from western and central Australia developed, resulting in strong, hot and gusty north-westerly winds directed over south-eastern Australia. In Melbourne, the winds started at about 0800 hrs. By 1000 hrs, the temperature had reached 43.3°C. Black Friday's extreme fire weather reached 45.6°C, 8% relative humidity and average wind speed 30 km/h-60 km/h in places, resulting in a forest fire danger index of about 100.

Bushfires killed 71 people in Victoria and 650 major buildings, including the township of Narbethong, were destroyed. From December 1938 to January 1939 between 1.5 and 2.0 million ha were burnt out in Victoria, including over 1.4 million ha of forested land (Figure 1). There were relatively few fires in grasslands due to a lack of fuel as a result of grazing pressure and poor pasture growth during the extended rainfall deficit.

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[1] Sources include: Luke and McArthur (1978), Furler *et al.* (1984), Elspin *et al.* (2003)

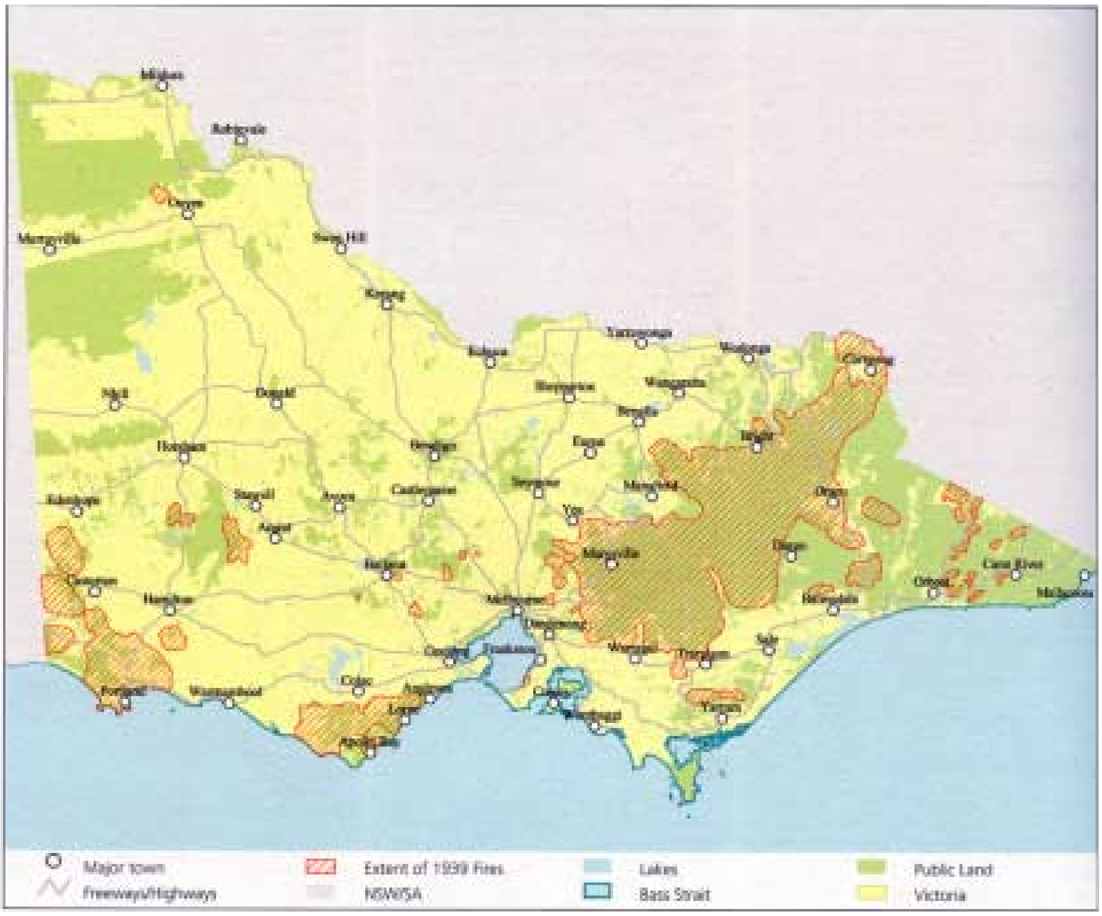

Figure 1. Areas burnt in Victoria during January 1939 bushfires. (Source: Esplin *et al.* 2003)

In the ACT, heat wave conditions lasted from 7 January to 14 January. On 13 January existing fires in NSW reached the ACT on three fronts: one near Mt Franklin; one at Two Sticks; and one near Horseshoe Bend along the northern ACT border. Overnight, temperature remained high and relative humidity low. The next morning, under the influence of winds up to 70 km/h, all fires spotted heavily from the Brindabella Range. The Mt Franklin fire burnt right across the ACT, the Two Sticks fire burnt into Uriarra and was halted along the line of the Murrumbidgee River. A cool change with rain moved through the area on 15 January, resulting in control and extinguishment of the fires. Again, few fires spread in grasslands due to a lack of fuel, mainly the result of grazing by rabbits.

McArthur used the conditions of Black Friday as his benchmark of 'worst possible' or 100 for his forest fire danger index (temperature 45°C, relative humidity 8%,wind speed 36 km/h).

2.2 ACT, 1951/52 season[2]

The 1951/52 fire season in the ACT, eastern NSW and Queensland was one of the worst ever experienced (Cheney 1976, Luke and McArthur 1978). The autumn, and most of the winter and spring months were particularly dry, with the result that the fire season began about six weeks earlier than usual (Luke and McArthur 1978). There were widespread lightning ignitions throughout the Brindabella Ranges as well

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[2] Sources included: Cheney 1976, Luke and McArthur 1978, individual ACT fire reports

as the plains regions and 51 fires were reported over the 3-month period from December 1951 to February 1952, of which 20 were greater than 2 ha (Barling[3]). In the ACT nearly 25,000 ha were burnt, with 3 fire events burning nearly 22,500 ha. The first of these occurred on 25 January. One fire, the Tanner fire on the eastern slopes of Oakey Hill re-ignited from a smouldering stump from a fire that burnt on 23 January (itself ignited by a magpie shorting out transmission lines). Three other fires were the result of electrical faults in power transmission lines. These fires merged 'into one huge conflagration' and was finally halted at London Bridge 16 miles downwind of the ignition point, burning out 50 sq. miles (13,000 ha) in the ACT and 50 sq. miles in NSW (Cole 1952a). Two people were killed.

Nine fires were ignited by lightning (or suspected lightning) at mid-morning on 5 February. One of these, a fire that started on Walker Hill at 1053 hrs, burnt nearly 3000 ha of grass country over 20 separate leases and entered the Stromlo pine plantation where it destroyed over 350 ha of mature and young pine as well as several observatory buildings (Cole 1952b). The wind was a strong westerly at about 70 km/h (Barling[3]).

It is suspected (Cole 1952c) that the lightning storms that ignited the fires of 5 February on the Canberra plains, also ignited several fires in the ranges to the west of Canberra. Over the period 7 February to 4 March, fires burnt in three main centres: Baldy Mountain (7 to 15 February for a total of about 1200 ha); California (7 to 18 February for a total of 600 ha); and Bug Range (7 to 24 February for a total of 4000 ha) (Shoobridge 1952). Numerous roads and firebreaks were established in efforts to control these fires. Considerable fire fighting was done at night when conditions had moderated.

2.3 Mangoplah, New South Wales, 22 January 1952[4]

Occurring in the same fire season as the Canberra fires, this fire burnt from Mangoplah, north of Holbrook, NSW, to Corryong in north-eastern Victoria, a distance of 98 km, during two consecutive days of extreme fire danger. The area burnt, mostly on 25 January, was more than 330,000 ha.

The fire commenced on the 22 January from fettlers burning-off on the Rock-Westby railway line near Mangoplah. The original fire was brought under control by local bushfire brigades after burning an area of 150 ha. However, on the 24 January, under extreme conditions (grass curing 100%, temperature 42.5°C, relative humidity 29%, wind speed 40 km/h, Grassland Fire Danger Index (GFDI) 60), the fire broke away from sparks from a stump reported to be 350 m inside the burnt country. It spread under a strong north-westerly wind, and by midnight had burnt out an estimated at 27,000 ha. The wind continued to blow throughout the night, although abating somewhat, and thwarted attempts to hold the fire on the Hume Highway near Garryowen.

On the 25 January the mean wind speed increased to around 48 km/h, still from the north-west. With a temperature of 41°C and a relative humidity of 15%, the maximum

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[3] P. Barling, Firebreak webpage accessed 31/5/2004: www.esb.act.gov.au/firebreak5152.html

[4] Sources include: Cheney 1976, Cheney and Sullivan (1997)

GFDI reached 115. The fire crossed the Murray River near Jingellic at 1030 hrs and burnt in a south-easterly direction for another 13 km before a cold front with a westerly wind change passed through the area at 1130 hrs. By midnight the fire had burnt out most of the total area eventually affected, and perimeters in grasslands had mostly been controlled. However, the fire continued to burn in timbered country until 10 February before it was totally brought under control.

The Mangoplah fire illustrates the enormous areas that can be affected when a fire burns over two consecutive days of extreme fire danger. The wind did not abate sufficiently at night to allow firefighters to bring the fire under control on the Hume Highway and, although the organisation of firefighters that night was described as chaotic, they were always going to have difficulties controlling the fire along a tree-lined road while the wind continued to blow. Fire fighting resources and equipment have improved since 1952, but a similar, or greater, area can still be burnt over two consecutive days of extreme fire weather.

McArthur used the conditions of the Mangoplah fire as his benchmark of 'worst possible' or 100 for his GFDI (grass curing 100%, temperature 38°C, relative humidity 20%, wind speed 48 km/h).

2.4 Dwellingup, WA, 24 January 1961[5]

The late summer and autumn of 1960 in most areas of Western Australia was marked by above average rainfall, resulting in abundant growth of grass fuels. The winter and spring months throughout the South-West Land Division, however, had below average rainfall, resulting in “a considerable build-up of fuel dryness over the spring period” (Rodgers 1961, p 10). By the middle of October, grasslands in the east had become fully cured enabling a fire to burn over 1.5 million ha through a region that normally had insufficient growth to support widespread fire.

The 1960/61 fire season was also marked by well above average maximum temperatures during the spring and summer months. Perth recorded its hottest October day on the 24th with 35.9°C. The presence of a tropical low-pressure system in the state's north-west with low pressure troughs extending down the west coast were the main cause of these above average temperatures. The occasional formation of intense tropical cyclones and the associated west coast low-pressure troughs controlled the patterns of weather throughout the 1960/61 fire season, maintaining high temperatures, occasional strong cyclonic winds and unusually severe thunderstorms. For the seven-month period from June to December 1960, the region of Dwellingup received 32% of its normal rainfall (Rodgers 1961).

The thunderstorms associated with the dominant weather patterns resulted in the order of 110 lightning-lit fires, burning a total of more than 210,000 ha or 42% of the total area burnt that season. The remainder of the area burnt was the result of escapes from settlers' burning-off operations. On 19 January, severe electrical storms produced a series of fires extending from Mundaring in the north to Manjimup in the south. The fires that ignited burnt under continued heatwave conditions for the next 5 days,

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[5] Sources include: Rodgers (1961), Cheney (1976), Luke and McArthur (1978)

culminating in a disastrous 'blow-up' on the evening of 24 January, when cyclonic wind squalls associated with the southern movement of a tropical cyclone hit miles of partially controlled and uncontrolled fires.

In the Dwellingup district on the 19 January, 10 fires started from lightning strikes in state forests within 10-12 miles of the township. An additional 9 fires were ignited by further lightning strikes on the 20 January. For the following 4 days, conditions of high temperature (hovering in the high 30s), low relative humidity (20%) and mild wind conditions (8-24 km/h) prevailed. On the 24 January, maximum air temperature reached 41.1°C, humidity dropped to 14%, and wind speed averaged 20-37 km/h. Massive southerly fire spread resulted. In the evening, the wind increased to gale force, estimated to be in the order of 100-110 km/h and lasting 1-1½ hours, resulting in rapid fire spread and dense spotting ahead of the main front. Wind speeds outside the fire area, however, were measured to be only 40-55 km/h and lasting only 15 minutes, leading to the suggestion that the extended strong winds experienced in the fire area were fire-induced.

The fire burnt an area of 146,000 ha (Figure 2). The towns of Dwellingup, Holyoake and Nanga Brook were severely damaged and more than 140 buildings (including the district hospital) were destroyed. No lives were lost.

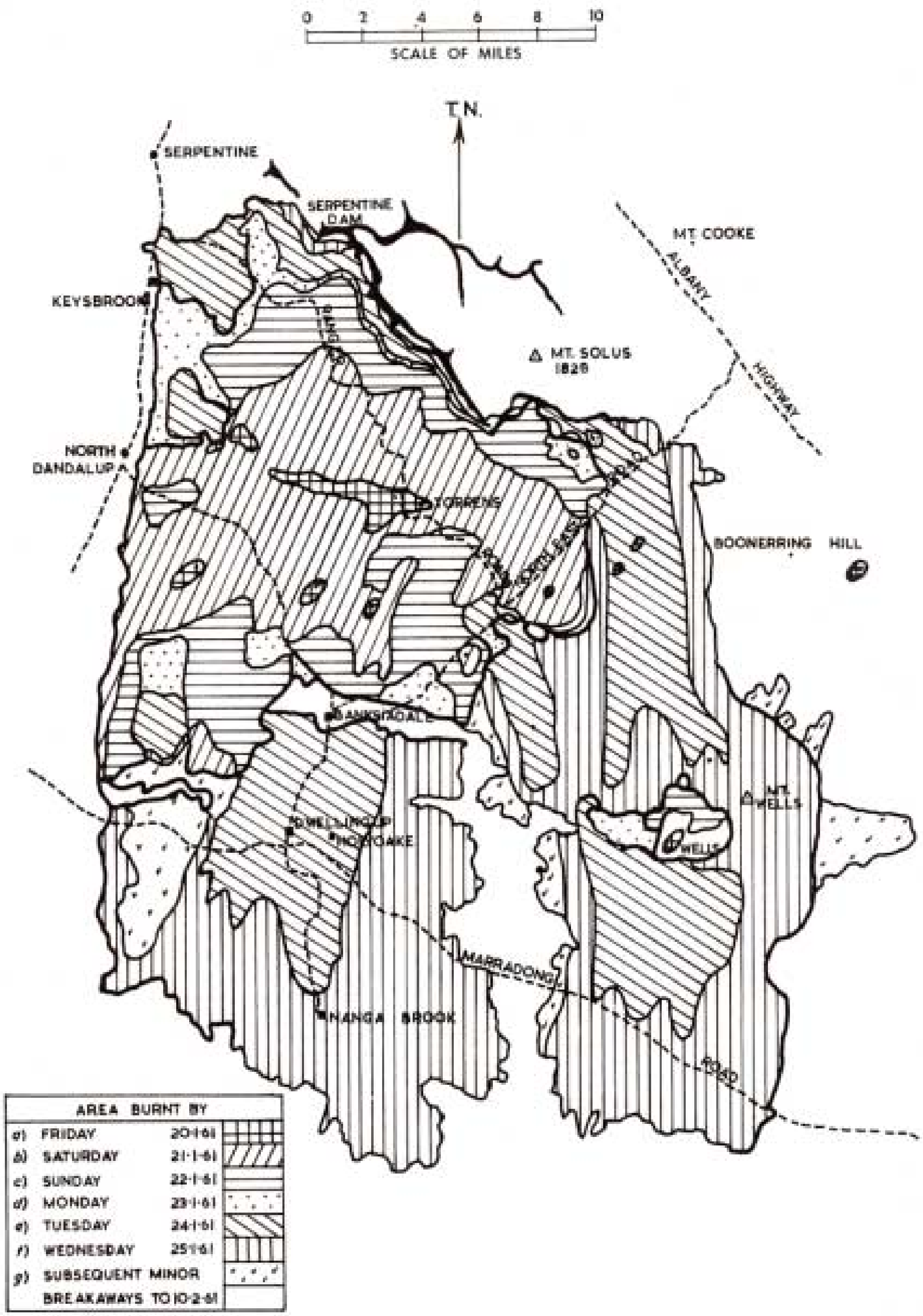

Figure 2. The area burnt by the Dwellingup fire, 19-25 January 1961 showing the daily movement of fire perimeters. Source: Rodgers (1961).

2.5 Hobart, Tasmania, 7 February 1967[6]

On the morning of 7 February 1967, in excess of 80 uncontrolled fires were burning in and around Hobart but, until that time, had only burnt a total of 1500 ha (or 0.6 of the total area that would eventually burn (Cheney 1976)). Some fires were pre-existing; some were lit on the day, some within the suburbs and some up to 100 km from the city. Dry conditions had prevailed from October 1966 throughout southern and eastern Tasmania. Grass was prolific due to above average rains in September-October. However, the winter had been relatively mild and not very wet. Grass growth was further enhanced by above average temperatures and the low incidence of frost during the spring growth period. By early February this grass had become fully cured.

On the morning of the 6 February, a high pressure system that had been located in the Tasman Sea since early on the 3 February, merged with a new high pressure system that had passed over Tasmania on the 5 February, resulting in steadily increasing maximum air temperatures during this period. On the 7 February, a low-pressure system that had moved into the area on the 6 February from the Southern Ocean and which contained a number of cold fronts pushed the isobars tighter over southern Victoria and Tasmania. This resulted in air temperatures rising from 29°C at 0900 hrs to 39°C at 1200 hrs. Temperatures remained above 35°C for a period of almost 5 hours. Relative humidity had dropped to 14% by 1200 hrs and remained almost constant for 3 hours. Mean wind speed increased from 11-13 km/h between 0900 and 1000 hrs to 37-41 km/h between 1000 and 1100 hrs. After this time, the wind became gusty and after 1200 hrs gusts frequently exceeded 93 km/h, the maximum recorded being 120 km/h at 1330 hrs. Mean wind speeds between 1200 hrs and 1500 hrs were between 41 and 67 km/h. The GFDI reached a maximum of 96 and remained at the extreme rating for 7 hours. The main cold front arrived at 1930 hrs and was preceded by a gradual diminishing of fire weather conditions.

In total 62 people were killed as a result of these fires, 20 as a result of a single fire that burnt through the western suburban fringe of Hobart burning an area of 6680 ha. A total of 226,500 ha were burnt in the 5½ hours between 1030 hrs and 1600 hrs, 85% of the final area burnt (Figure 3). In all, 1446 major buildings were destroyed and 795 square miles were burnt out. Damage costs were in excess of $40 million.

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[6] Sources include: Bond *et al.* (1967), Cheney (1976).

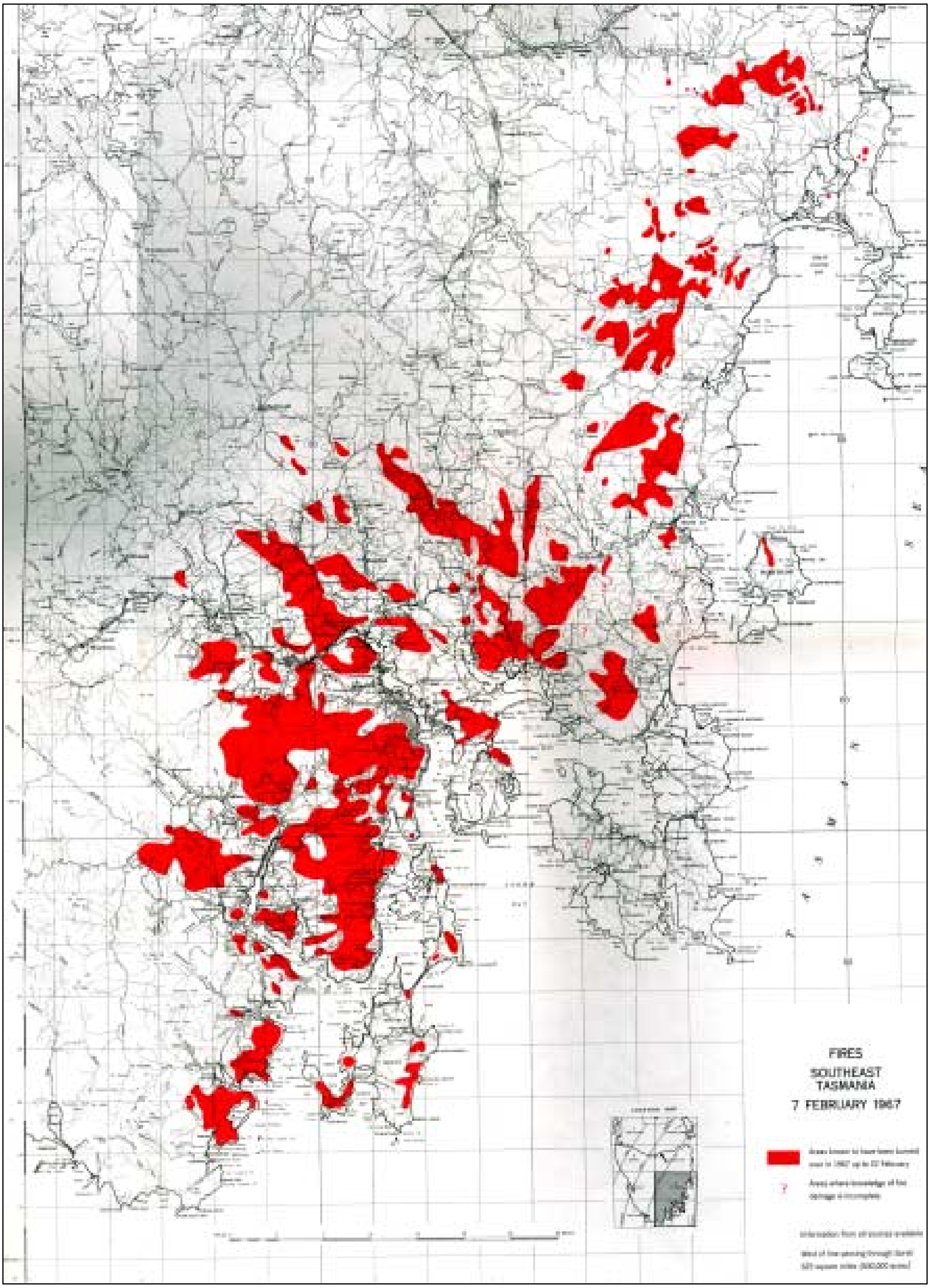

Figure 3. The total area burnt in Hobart February 1967. Source: Bond *et al*. (1967).

2.6 Western District of Victoria, 12 February 1977[7]

On 12 February 1977, some 69 fires started throughout Victoria. Although most were controlled to less than 1,000 ha, eleven major fires burnt 103,000 ha (Figure 4); only 3 of these burnt more than 10,000 ha each. Nine of the 11 major fires were started by sparks from power lines. The largest, the Wallinduc-Cressy fire (Figure 5), burnt 39,200 ha and resulted in the deaths of 3 people and the destruction of 39 houses and other buildings.

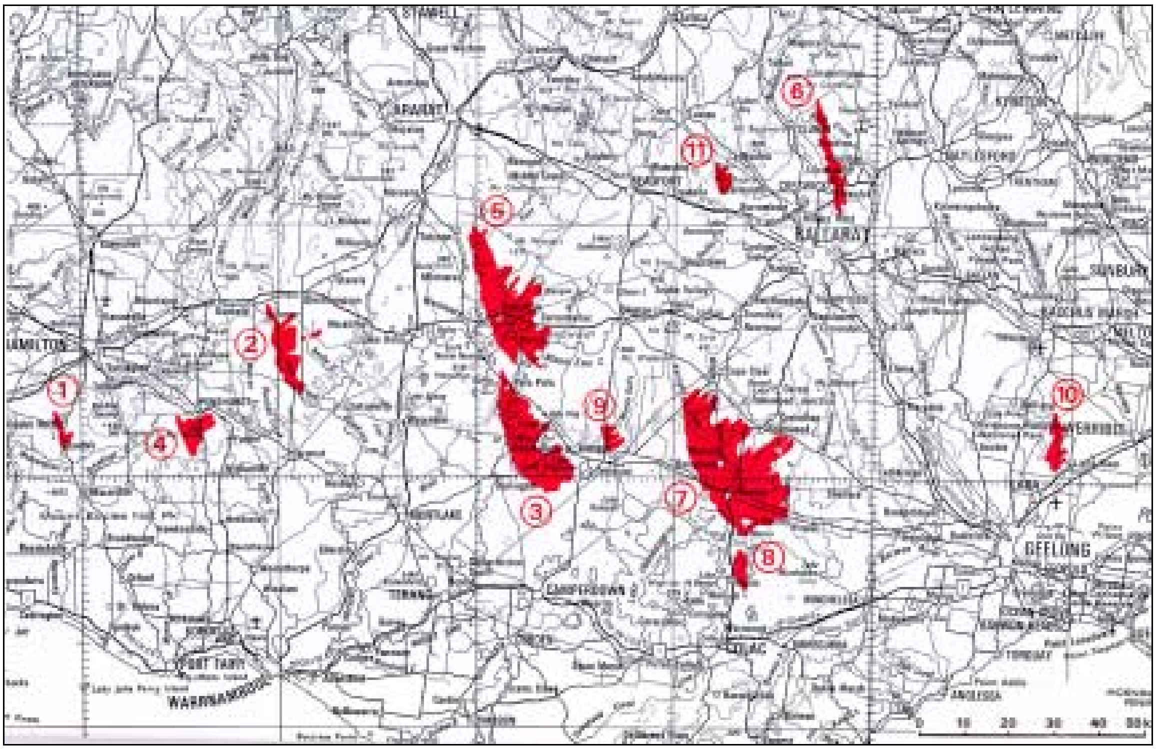

Figure 4. Location and area of eleven major grassfires (of a total of 69 throughout Victoria) that burnt on 12 February 1977. Source: McArthur *et al.* (1982).

Conditions during this fire were such that grasses were fully cured, and had been for some days. The fire started at 1332 hrs, and for much of the afternoon a north-north-westerly wind blew, up to a maximum speed of 50-55 km/h, producing a maximum GFDI of 98 (temperature 36°C; relative humidity 22%). Sustained rates of spread in the order of 16.6 km/h were recorded for extended periods (up to ½ hour), with a mean spread rate of 13.6 km/h over 2½ hours. Three hours after ignition the fire had travelled about 34 km and burnt some 16,700 ha. Then a south-westerly cold front passed through the area, with wind speeds of around 40 km/h. The entire eastern flank took off at 12.8 km/h initially, and over the next two and a half hours burnt 22,500 ha before the fire became controllable and was extinguished.

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[7] Sources include: McArthur *et al.* (1982), Cheney and Sullivan (1997).

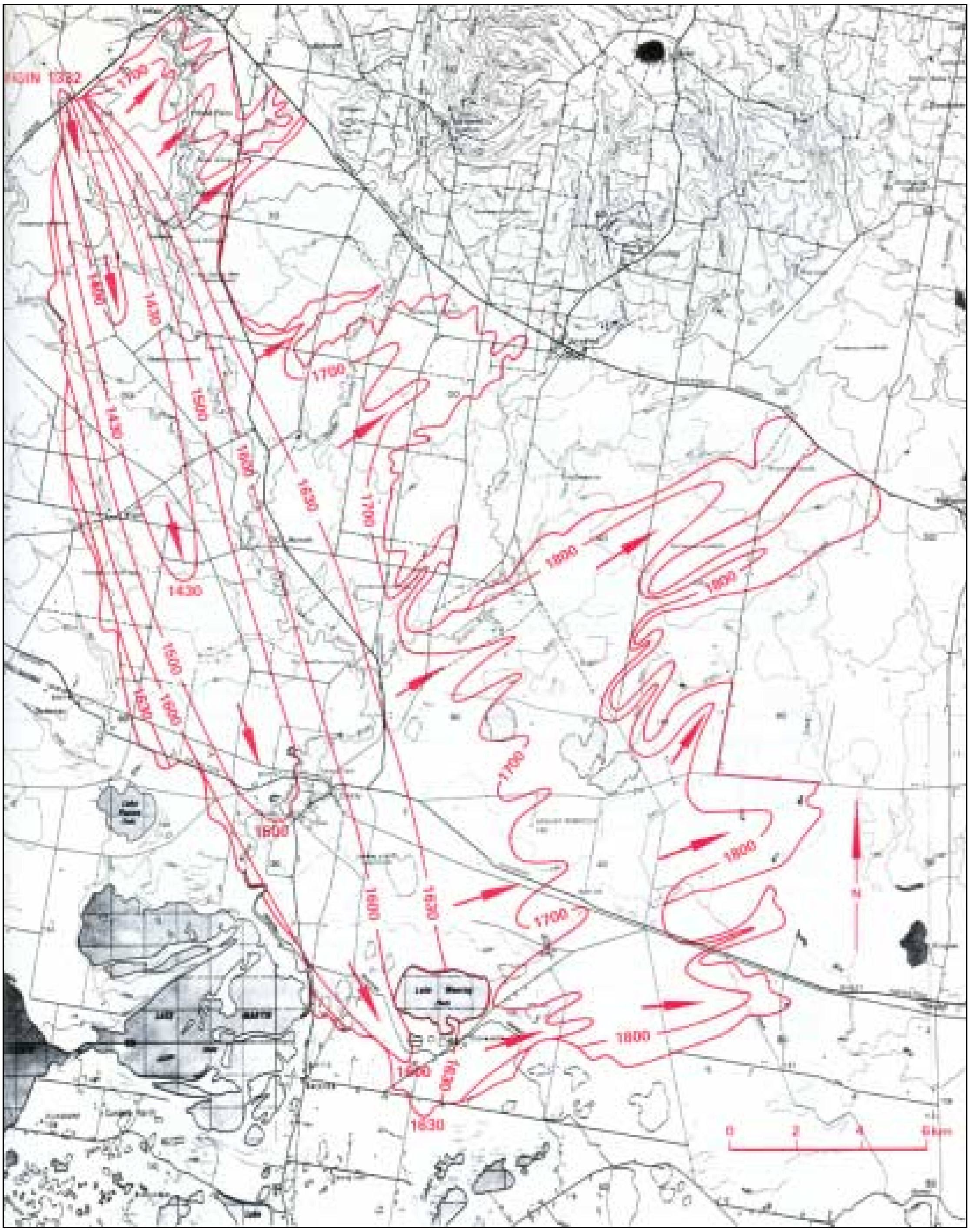

Figure 5. The spread pattern of the Wallinduc-Cressy fire, 12 February 1977. Source: McArthur *et al.* (1982).

Another of the day's fires, the Tatyoon-Streatham fire, started 14 minutes before the Wallinduc-Cressy fire and 70 km to the north-west. It sustained a maximum rate of spread of 18.6 km/h over ½ hour, but had a slightly lower mean rate of spread (11.8 km/h) than the Wallinduc-Cressy fire and burnt a total of 20,100 ha. One man was killed, 38 houses were destroyed, and the small township of Streatham was severely damaged when 22 structures were burnt to the ground.

These two fires show the importance of effective suppression on the eastern flank. Both fires had burnt about the same area (15-16,000 ha) prior to the wind change. On the Tatyoon-Streatham fire, firefighters were able to control 22.5 km along the eastern flank before the wind change and thus limit the area burnt after the change to only 5000 ha. By contrast, fire suppression on the eastern flank of the Wallinduc-Cressy fire was severely hindered by rough, stony country near the origin and the fact that local firefighters did not receive support from additional brigades from the north and west as these were already engaged on fires to the west which had started earlier. Firefighters were able to control only 1.5 km of the eastern flank, and as a result more than 22,500 ha burnt after the wind change.

2.7 South Australia and Victoria, Ash Wednesday, 16 February 1983[8]

Ash Wednesday, 16 February 1983, brought the worst fire disaster in Australia since Black Friday in 1939. A total of about 370,000 ha were burnt, 76 people were killed, and some 2500 structures were destroyed. Ash Wednesday is a prime example of particularly severe fire weather conditions in south-eastern Australia. Timing of the passage of the cold front was such that, as it swept across southern Australia during daylight hours, extreme fire weather extended from Port Lincoln in South Australia to east of Melbourne, Victoria, a distance of 800 km. At most locations, hot strong northerly winds started blowing early in the morning (0900 hrs EDST), and increased to average mean speeds of 45-50 km/h for several hours preceding the front. Unusually strong westerly winds were associated with the frontal change, which reached Ceduna at 1230 hrs, Adelaide at 1445 hrs and Melbourne at 2030 hrs. Mean wind speeds were in excess of 70 km/h, with gust speeds up to 110 km/h.

Much of south-eastern Australia was experiencing severe drought at the time (Figure 6), and most of the damage occurred in forested areas. However, a number of severe grassfires occurred in South Australia and Victoria in areas where the drought was not extreme.

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[8] Sources include: CFA (1983), Keeves and Douglas (1983), Rawson *et al.* (1983), Cheney and Sullivan (1997)

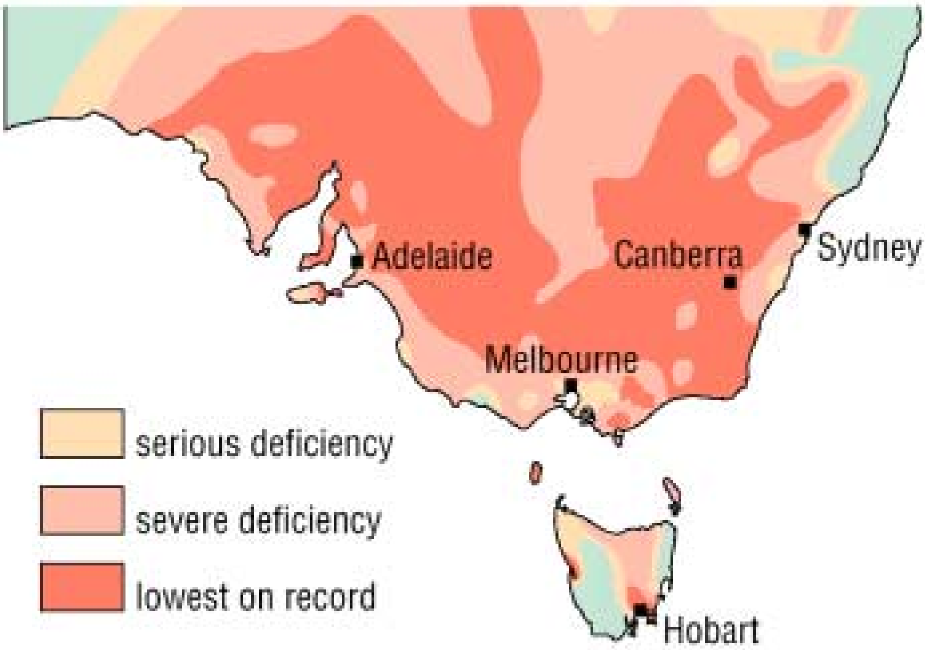

Figure 6. Rainfall deficiency map showing the extent and seriousness of drought throughout south-eastern Australia prior to Ash Wednesday, 16 February 1983. Source: Furler *et al.* (1984) in Cheney and Sullivan (1997).

The pastoral area of south-eastern South Australia was one area with abundant, fully cured, grassy fuels, and two major fires, the Narraweena and Clay Wells fires, started in these grasslands and burnt parallel to each other through grassland and pine plantation. The Narraweena fire was the larger of these (Figure 7), and burnt for four hours with average maximum rates of spread of 18 km/h. After the wind change, the two fires swept together very rapidly and the southern end of the Narraweena fire entered conifer plantations more than 65 km from its origin.

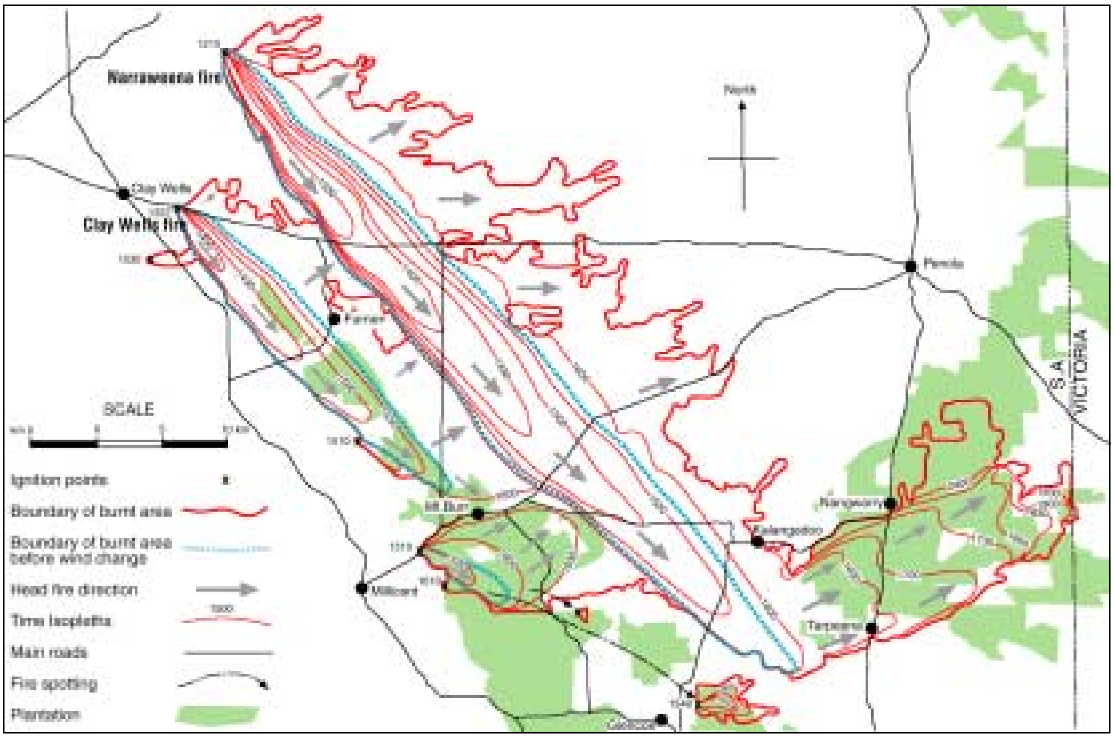

Figure 7. Spread pattern of the Narraweena fire, 16 February 1983. Source: Keeves and Douglas (1983) in Cheney and Sullivan (1997).

As winds abated and humidity rose 2 hours after the arrival of the front, the fires in the grasslands were brought under control. However, those in the forests continued to burn throughout the night and were not completely controlled for another 2 days.

The extremely strong winds associated with the frontal change extinguished, by blowing out, large sections of the western flanks of both the Narraweena and Clay Wells fires. The eastern flank of the Narraweena fire did not travel as far as might have been expected considering the strength of the winds immediately behind the change. Most of the evidence suggests that this reduced rate of spread was due to increasing fuel moisture contents caused by the rapidly increasing humidity and, in places, scattered light rain behind the front and not to the very high wind speeds.

Other major fires on Ash Wednesday were at Clare and in the Adelaide Hills, South Australia, the Western District of Victoria, the Otway Ranges, Trentham-Mt Macedon, and the Dandenong Ranges (Warburton, Cockatoo, Beaconsfield).

2.8 Sydney, January 1994[9]

January 1994 was preceded in 1991/92 by serious rainfall deficiencies throughout Queensland and northern NSW, the majority of these regions experiencing lowest decile rainfalls for the period March to November. In 1993, however, eastern Australia experienced average to above average rainfall. Large parts of NSW and Victoria recorded highest decile rainfall for the July-December period. Despite this, parts of the northern NSW coast experienced lowest decile rainfall. Over 800 fires occurred during the period 17 December-16 January, mostly in the coastal strip within

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[9] Sources include: Cheney and Gould (1994a), Cheney and Gould (1994b), DBFS (1994), Gill and Moore (1998), Cockerill (1994), Ramsay and McArthur (1995), Speer *et al.* (1996).

100 km of the coast between Bateman's Bay and the NSW/Queensland border. The total area burnt was in excess of 800,000 ha (Figure 8). 4 people were killed and over 300 houses destroyed.

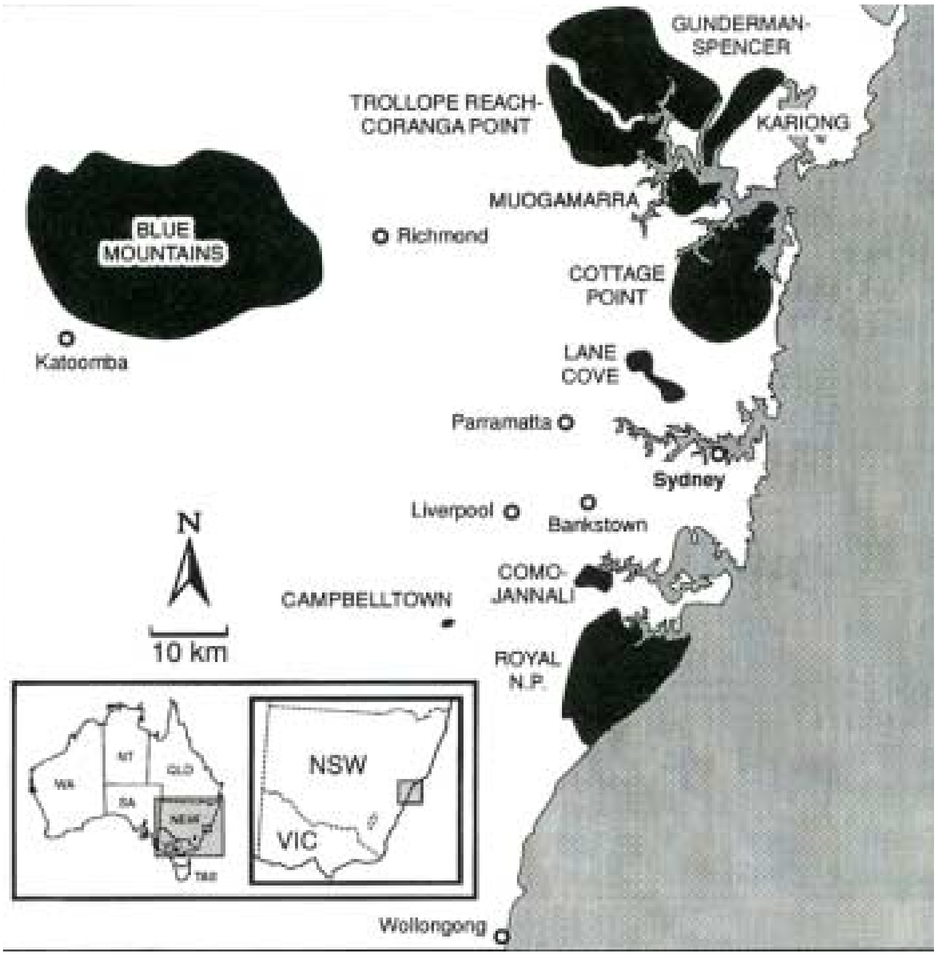

Figure 8. Areas burnt in the Greater Sydney region during December 1993-January 1994. Source: Gill and Moore (1998).

In late December, a series of intense low-pressure systems south of south-east Australia, a much more northerly latitude for that time of year, brought unseasonal strong hot westerly winds across NSW, conditions more typical of late winter or spring. In the first week of 1994, an intense low-pressure system developed south of Tasmania and remained there for a period of about a week (Figure 9). Weak seabreezes near the coast gave way to dry and gusty westerly or northwesterly winds in the afternoons. From 4-8 January, extreme fire danger was experienced every afternoon (Figure 10), causing existing fires to spread out of control and allowing many other new outbreaks to get away.

The fire that caused the most damage to houses and caused the only fire-related fatality was the Como-Jannali fire (8 - 9 January) (Figure 11). It was also one of the smallest. During this period, over 300 fires were being fought throughout NSW, including the Land Cove fire, Cottage Point fire. On the afternoon of 6 January a fire started in Menai, west of the Woronora River. This fire burnt for a day and a half under north-westerly winds before reaching, and being mostly contained by, the banks of the Woronora River by midnight of the 7th. To the north the fire had crossed Still

Creek and was heading into the suburb of Illawong. In addition, a spotfire had cross the Woronora River at 1830 hrs and burnt out a good portion of the Jannali Reserve before being contained before midnight.

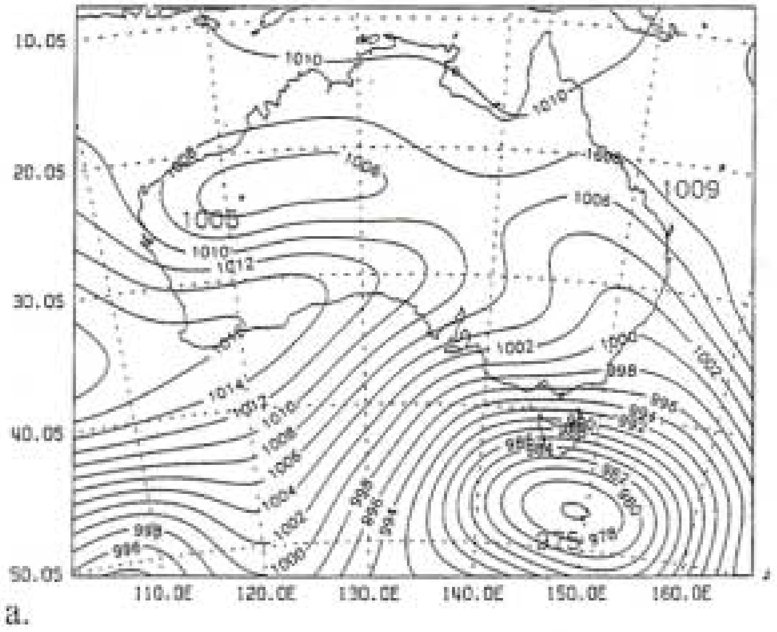

Figure 9. Synoptic situation as at 0900 January 8, 1994. Source: Speer *et al.* (1996).

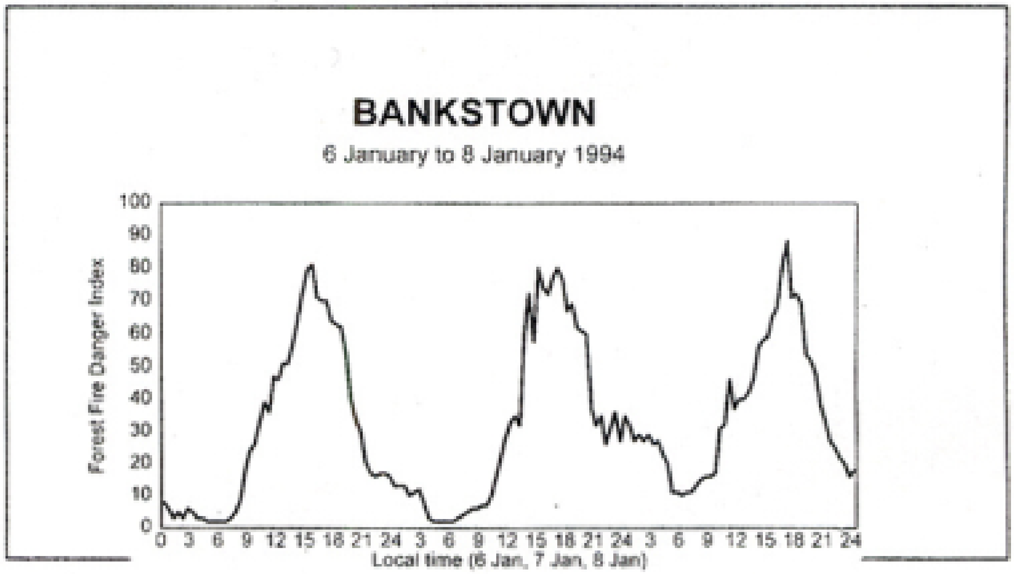

Figure 10. Forest Fire Danger Index derived from data taken at Bankstown Airport, 6-8 January 1994. Source: Speer *et al.* (1996).

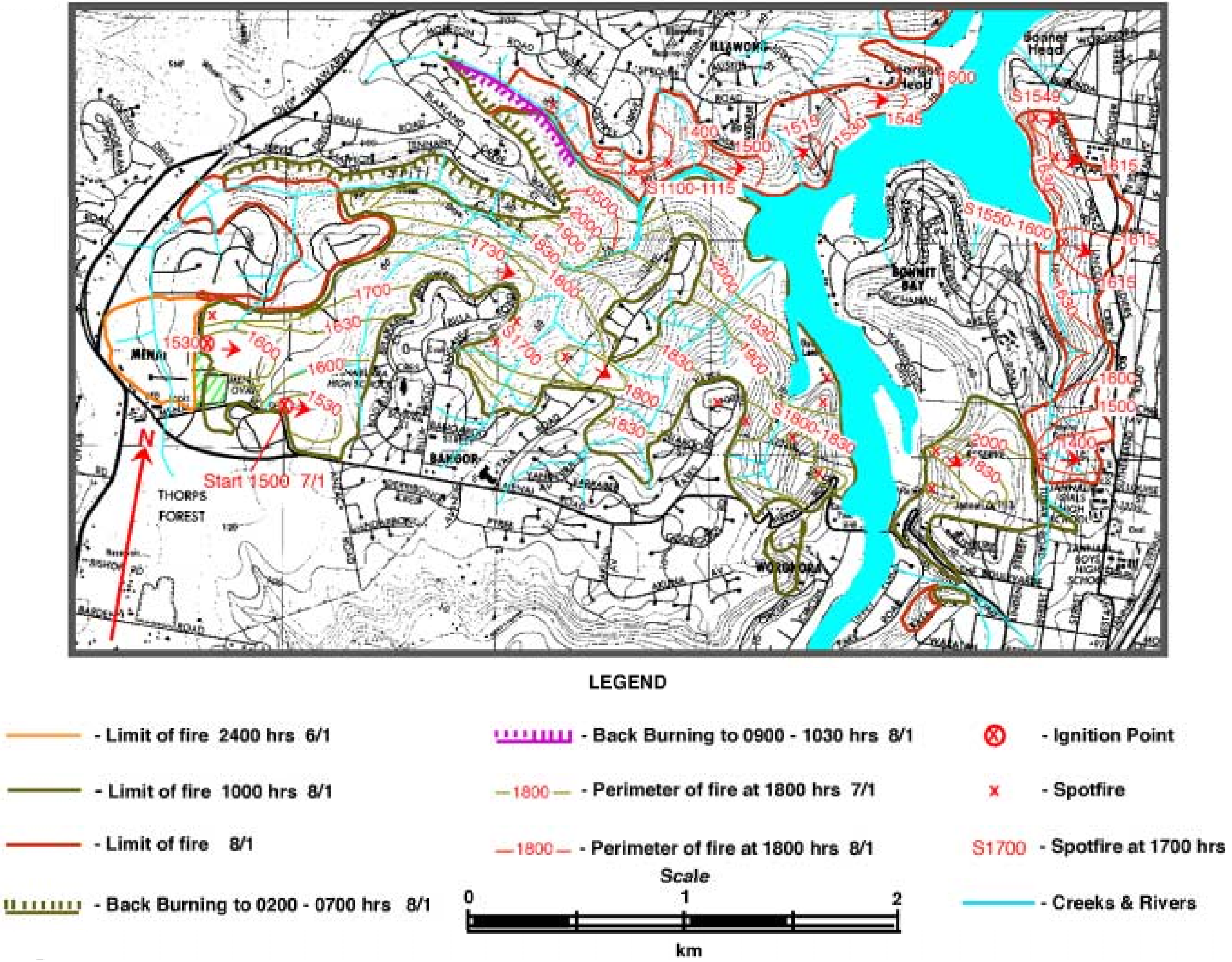

Figure 11. Origin and spread of the Menai-Como/Janalli complex of fires, 7-8 January 1994. Source: Cheney and Gould (1994a).

Backburning continued over night and early the next morning. By 1100 hrs, winds increased to over 30 km/h and spotfires, either from the northern flank or the backburns set to contain it, broke out to the east, north of Still Creek. This fire developed rapidly and by 1545 had reached the Woronora River at Georges Head, a distance of approximately 2 km. At about this time, spotfires were observed across the Woronora River in a hillside reserve (the Glen Reserve) below Woronora Crescent, a distance of over half a kilometre.

These spotfires developed rapidly upslope toward Woronora Crescent in Como and Lincoln Crescent in Jannali, reaching the top of the reserve--a distance of about 500 metres--within 5-10 minutes of ignition. Temperature at Bankstown Met Station at about this time was 36°C, relative humidity 10% and wind speed 46 km/h gusting up to 85 km/h (FFDI 87). Spotfires were thrown some distance into neighbouring streets. Over 100 houses in these and adjacent streets were destroyed or damaged and a woman in Woronora Crescent killed. At about the same time, the fire in the Jannali Reserve broke away and burnt into the southern extremities of the fire in the Glen Reserve. By 1615 this fire had stopped spreading. By 1630 the Glen Reserve was completely burnt out and by 1700 very little smoke was observed coming from it.

A total area burnt by the Menai/Como/Jannali fire was 1400 ha, however, the fire that burnt the Glen Reserve and caused the most damage in Como and Jannali was only approximately 30 ha and ignited, spread and burnt out in 45 minutes. It is highly probable that the same magnitude of damage could have occurred in this area under these conditions even in the absence of other fire.

2.9 Victoria/NSW/ACT, 2003[10]

For the period March to December 2002, over 95% of the country had experienced below average rainfall and 61% of the country had recorded rainfall in the lowest decile (i.e. very much below average or lowest on record). This was the second largest area to experience the lowest decile rainfall for any 10-month period on record. Between April and October, 68% of the country experienced the lowest decile rainfall, the largest area for any 7-month period on record.

Evaporation rates were higher than normal due to well-above average daytime temperatures. From March to November 2002, a maximum temperature anomaly of +1.65°C was observed, an all-Australia maximum for this 3 season period.

In Victoria, the highest season mean maximum temperatures for autumn, winter and spring were recorded. By the end of 2002, Victoria had experienced 6 years of below average rainfall, with only 20-40% of normal rainfall recorded in most areas from October to December 2002. The number of fire occurrences throughout the season was much greater than the 20-year average and was on a par with the 1982/83 season.

On 17 December, lightning ignited a major fire in the Big Desert. This fire burnt out 181,000 ha over 8 days and at the time was the largest Victorian fire for 20 years.

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[10] Sources include: Bannister and Gill (2003), McLeod (2003), Wareing and Flinn (2003), Jacobs (2004), Tolhurst (2004), Wouters (2004)

Prior to 8 January, there had been 20 days of Fire Weather Warnings in Victoria and 12 Total Fire Ban days, including some of the earliest on record.

On the evening of 7 January and on the 8 January, a cold front and associated pre-frontal trough passed over south-eastern Australia. Upper level thunderstorms formed as the front passed over the alpine regions. These thunderstorms resulted in the ignition of at least 89 fires in Victoria, 74 in NSW and 3 in the ACT. In Victoria, rapid initial attack in the first few days succeeded in controlling all but 9 of these fires due to difficult terrain. Over the next 60 days, over 1.2 million ha of land was burnt in Victoria, 600,000 ha in NSW and 160,000 in the ACT (Figure 12). During this period, most of the fire-affected regions did not receive any substantial rainfall for 50 days.

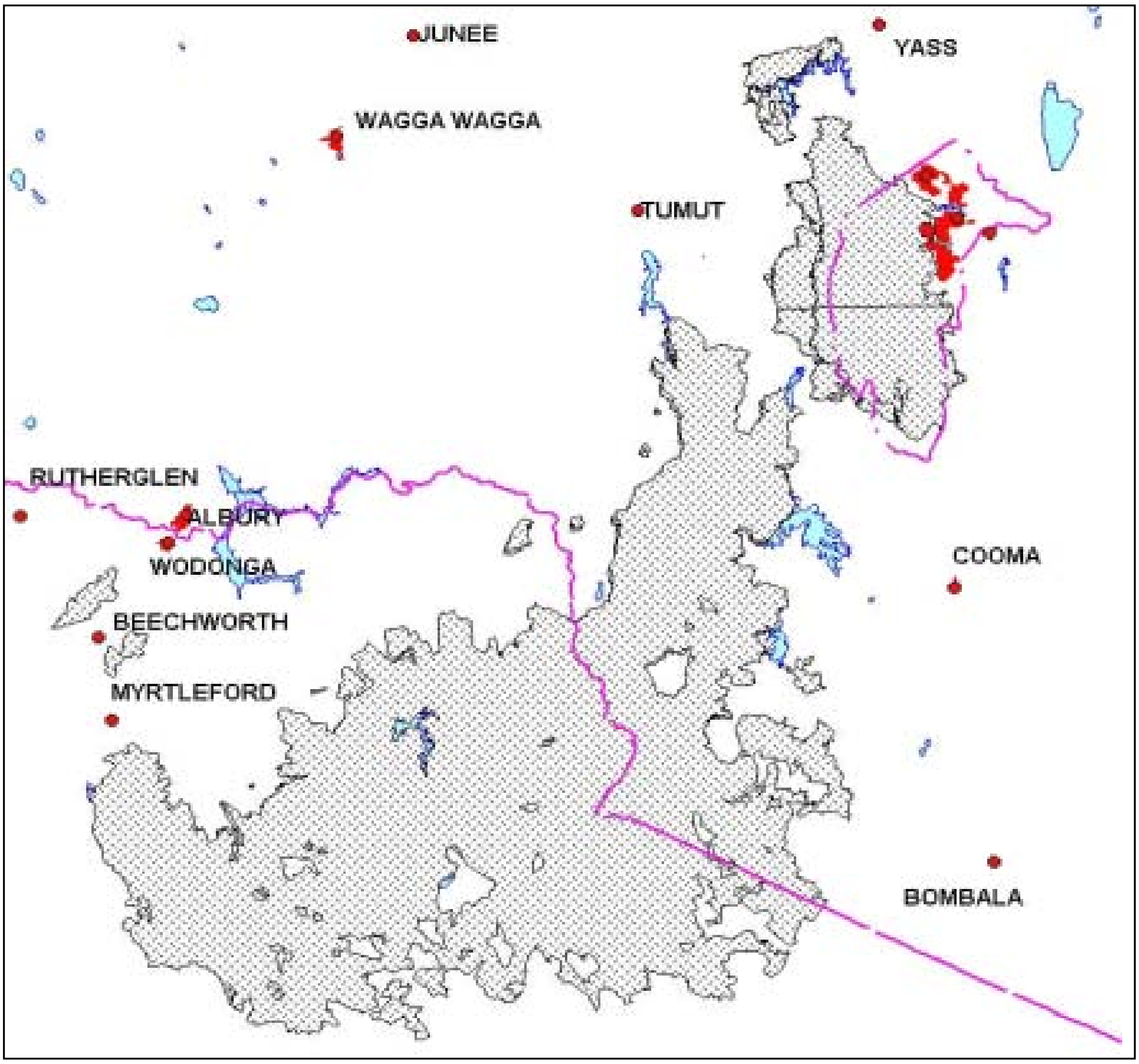

Figure 12. Area burnt in Victoria, NSW and ACT during January - March 2003. Source: ESB (2003)

More than half the area burnt in Victoria occurred during 26 hours over a 3 day period, including 57,000 ha in 4.5 hours, 251,000 in 11 hours, and 252,000 in 9.5 hours.

In the ACT, it was the third driest October - December period on record. Total monthly rainfall was 11.6 mm in October, 10.4 mm in November, 18.2 mm in December and 10.4 mm in January. The Keetch-Byram Drought Index (KBDI) (Keetch and Byram 1968) reached 100 in December and was 135 by early January (Davis 2004). Two fires (the Stockyard Spur fire and the Gingera fire) merged on 15 January, resulting in a single fire of 3100 ha (Cheney[11] pers. comm. 2004). The McIntyre's Hut fire, which started in NSW about 7 km from the ACT border, did not cross into the ACT until early on 18 January, at which stage it was just under 10,000 ha. By the end of 18 January it had extended its area by over 20,000 ha to be over 31,000 ha (Cheney[12] pers. comm. 2004) (Figure 13).

Over the night of 17 January, air temperature did not drop below 20°C and relative humidity did not rise above 45%. On 18 January, a blocking high-pressure system in the Tasman Sea and an approaching low-pressure system preceded by a trough produced a strong upper westerly air stream. This resulted in a deepening trough that led to increasing temperatures and greater mixing of strong upper winds to the surface. Average surface wind speeds were 30 km/h by mid-morning, peaking to very gusty 40-50 km/h mean wind speeds between 1500 and 1700 hrs. Peak gust of 78 km/h was recorded at Canberra Airport at 1530 hrs, about the time the McIntyre's Hut fire had entered Weston Creek. The FFDI reached 100 at 1300 hrs and remained well above 100 until 1700 hrs. Maximum air temperature was 35°C and relative humidity was 8% at about 1500 hrs. The relative humidity continued to decrease to a minimum of 4% at about 1700 hrs before a cooler south-easterly sea breeze occurred.

In total, 10 people were killed throughout Australia in connection with bushfires during the 2002/03 fire season (4 in the ACT) and 54 million ha were burnt, including 35 million ha in the NT. Over 400 houses were destroyed in the ACT, 41 in Victoria.

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[11] NP Cheney, Senior Principal Research Scientist, CSIRO Forestry and Forest Products.

[12] NP Cheney, *ibid.*

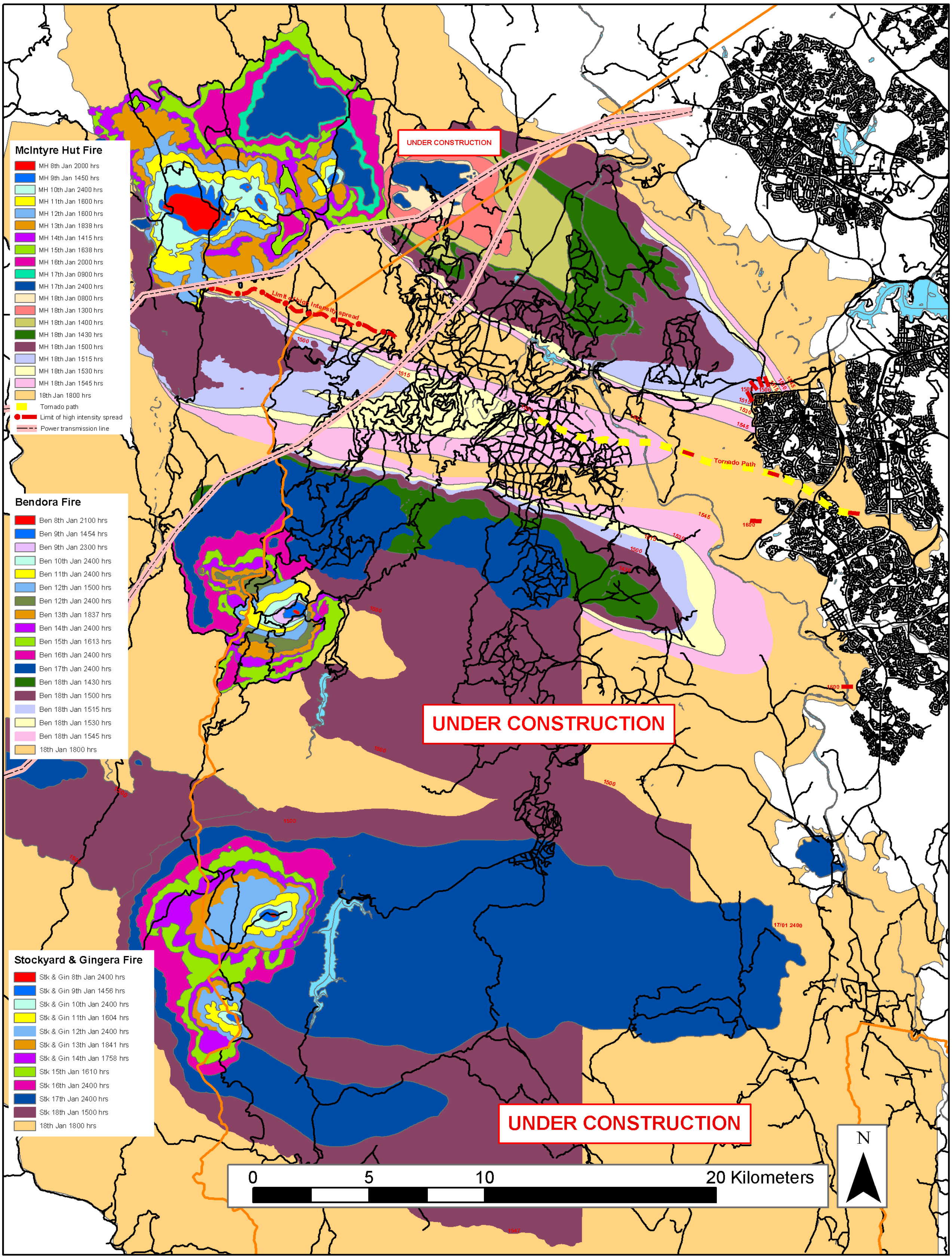

Figure 13. Intermediate spread patterns of the fires that burnt into the ACT, 8-18 January 2003. Source: Cheney (2003).

2.10 Summary of case studies

The preceding case studies provide a brief outline of some of the significant fire events in Australia's recent history. It is by no means complete or comprehensive. For each event outlined here, there are another dozen that could just as easily be included. The main feature of all the case studies presented is that they are all unique. While there are some common aspects shared among some of the case studies, other cases have significant different conditions. Table 1 summarises some of the characteristics and conditions of these case studies.

While nearly all of the events listed here were associated with multiple ignitions, the Mangoplah fire of 1952 was a single fire event. Most, but not all events, were associated with rainfall deficit and most, but not all, were associated with a blocking high pressure system in the Tasman. In all circumstances, severe fire events were associated with extreme (>50) fire danger indices, in most cases greater than 70.

Not all fire events consisted of large fires. While the ACT/Alpine fires of January 2003 involved nearly 2 million ha, the Como/Jannali fire was part of a complex only of 1400 ha, the fire itself only 30-odd ha. The Upper Beaconsfield fire of Ash Wednesday was approximately 8500 ha, destroyed 230 houses and killed 21 people. The next section will go into the common conditions that may lead to a severe fire event in more detail.

While there is some scope to identify thresholds of key parameters for the onset of severe fire events, the range of possible behaviour of severe fires precludes this. The McArthur Fire Danger Meters (for grasslands and forests) provides the only real method of combining forecast weather information into a scale of expected fire danger represented by the weather conditions. Setting of threshold values for levels of preparedness, resource planning, suppression, etc., is possible only after consideration of local fire and fire weather history and suppression capability. The McArthur rating system is McArthur's expert assessment of suppression difficulty (encompassing preparedness and suppression capability) for an average rural fire brigade in the 1960s. It has been found to be adequate for current use (Cheney *et al.* 1990) and has been used unchanged since its introduction.

Event	Antecedent conditions		Weather conditions							Fire behaviour				
	rainfall deficit?	KBDI	Blocking High?	Max. Temp (°C)	Min. RH (%)	Max. Mean Wind speed (km/h)	Fuel type	Max FDI	Main Topog.	Multiple ignitions	Max ROS (km/h) Grass	Max ROS (km/h) Forest	Spotting?	Impact/ Other notables
Black Friday 1939[&]	✓	?	✓	45.6	8	35	forest	100	mix	✓	?	?	✓	In Vic: 2 million ha 71 lives 650 buildings
Canberra 1952	?	?	?	?	?	?	mix	?	mix	✓	?	?	?	25000 ha 2 lives
Mangoplah 1952	?	?	?	41	15	48	grass	115	flat	×		?	?	330000 ha
Dwellingup 1961	✓	?	×	41.1	14	110	forest	?	flat	✓	-	?	✓	146000 ha 3 towns 140 buildings $2M+
Hobart 1967[&]	✓		×	39	14	120	mix	70+	hilly	✓	?	?	?	62 lives 1446 buildings $40M
Western Districts 1977[&]	×	64[^]	✓	36	22	50-55	grass	78	flat	✓	18.6	-	×	69 fires 3 lives 455+ buildings 103000 ha $16.3M
Ash Wednesday 1983[&]	✓	120+	✓	43	15	70+	mix*	100+	mix	✓	18	10	✓	190+ fires, 380000 ha 2100 buildings 72 lives, $220M
Sydney 1994	✓		×	37.8	8	40	heath/ forest	87	hilly	✓	?	?	✓	800 fires 300+ houses 4 lives 800000 ha
January-March 2003	✓	135[#]	✓	35[#]	4[#]	50[#]	forest/mix	100[#]	mountain	✓	?	?	✓	10 lives 450 buildings 1.9 million ha

^ At Ballarat (McArthur *et al.* 1982)
# In ACT 18 January (Davis 2004)
& Predominantly single day events
* in areas of extreme rainfall deficit, fire only occurred in forested regions.

3. Conditions that may lead to severe fire events

3.1 Rainfall deficit (and El Nino events)

In Australia's history, severe fire events are generally associated with extended periods of rainfall deficit (mostly over the preceding 3 - 10 months). During these extended periods, creek lines, wet soaks and swamps that would normally remain moist during summer dry out, increasing the potential for fires to become wide spread, particularly through forested regions. Large woody material, such as logs and stumps, will become fully dried and once alight will be very difficult to extinguish, providing complications for mop-up operations and increasing the potential for additional ignitions if fire weather conditions worsen.

At the same time, grasslands and pastures are generally eaten-out, particularly during extended drought when feed is scarce, and while they will still carry fire, will provide less difficulty in suppression activities when conditions have abated.

However, average or better rainfall during the winter and spring months in south-eastern Australia does not reduce the risk of widespread fire events. Good winter and spring rainfall will result in rigorous pasture growth across much of the country during the main growing season. Continuous swards of lush grass, particularly on roadside verges and other areas where grazing pressure are low, will dominate the countryside. The onset of early summer conditions, especially a few days of hot windy weather, will accelerate the curing process. Once the grasslands have become fully cured they will, in conjunction with the occurrence of suitable fire weather, provide the potential for large widespread conflagration fire across the landscape.

It has been determined that much of the variation in Australian rainfall is correlated to the El Nino-Southern Oscillation (ENSO) phenomenon, particularly for eastern Australia (Pittock 1975). In addition, there is statistical evidence to show that fire danger and the area burnt by wildfires in Victoria, NSW and Tasmania increases during an ENSO event (Skidmore 1987, Stern and Williams 1990).

The Southern Oscillation Index (SOI) is the mean sea level pressure difference at Papeete minus Darwin, normalised for each calendar month to a standard deviation equal to 10 (Walker and Bliss 1932 cited in Troup 1965) and with east equatorial Pacific sea-surface temperature (SST) can indicate likelihood of increased or decreased rainfall for eastern and northern Australia, depending on the positive or negative value of the SOI.

Negative SOI values are usually accompanied by sustained warming of the central and eastern tropical Pacific Ocean, a decrease in the strength of the Pacific Trade Winds, and a reduction in rainfall over eastern and northern Australia (Troup 1965). Positive values of the SOI are associated with stronger Pacific trade winds and warmer sea temperatures to the north of Australia. Waters in the central and eastern tropical Pacific Ocean become cooler during this time. Together these give an increased probability that rainfall in eastern and northern Australia will be greater than normal (called a La Niña event). An El Nino year is defined as those years when the twelve-month average (April to March) SOI is below -5 (Chiew *et al*. 1998). In the case of consecutive below -5 SOI years, only the first year is noted as an El Nino year.

Since Federation, there have been 18 El Nino years (Figure 14) (note that the 1991 event can be seen to last 4 years to 1994). Pittock (1975) found that there is a correlation between SOI and annual mean rainfall (r = 0.35 at 95% confidence) for eastern and northern Australia but that the correlation quickly drops away for central, southern and western Australia. Pittock (1984), however, found that the correlations do not remain constant with time (aperiodic intervals and irregular ENSO patterns (Williams 1998)), suggesting that there are other factors involved. The links between rainfall and ENSO, while statistically significant for most of the country, is not sufficiently strong to predict rainfall (Nicholls 1985, Chiew *et al.* 1998, Cai *et al* 2001). Of the 14 El Nino events since 1925, only 11 coincide with significant drought events. Many years of low SOI (not considered El Nino) result in drought and other years of El Nino result in average to above average rainfall[13].

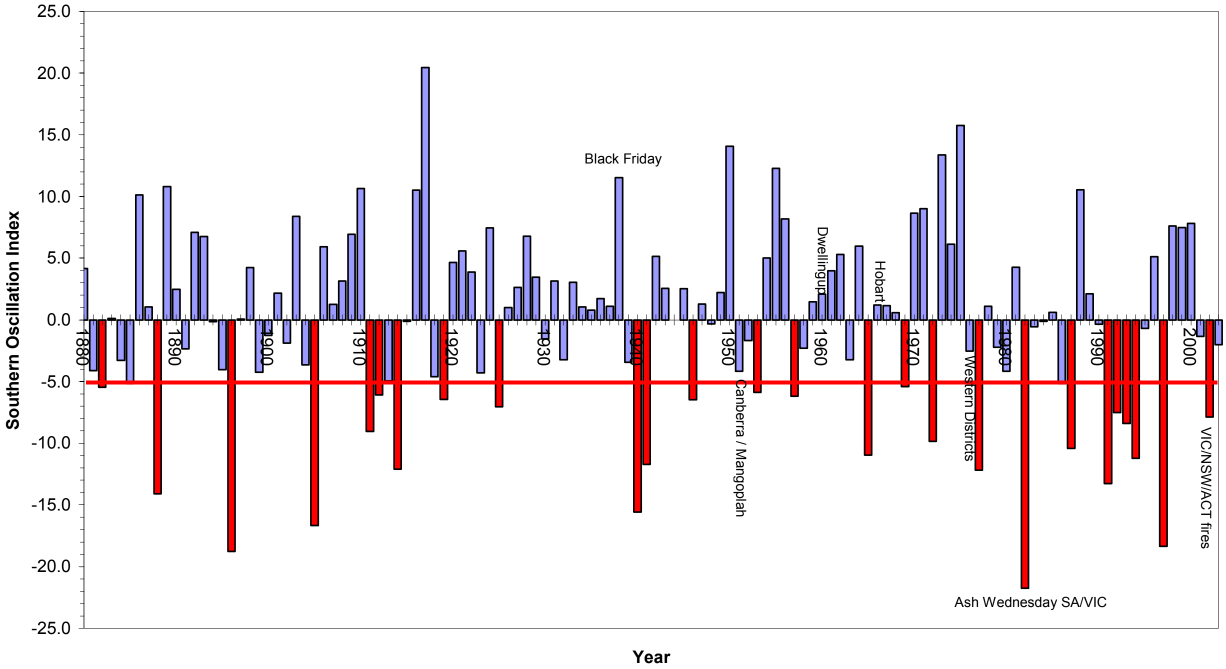

Figure 14. The yearly average (March-April) Southern Oscillation Index for years 1880-2003. Case history fires are superimposed over year preceding fire event. Data sourced from Bureau of Meteorology.

Of the case histories given in this report only the Victorian 2003 and Ash Wednesday 1983 fires coincide with an El Nino event of the preceding year. Many events not listed also occurred in El Nino years, e.g. Blue Mountains December 1977, NSW 1957/58, Sydney 1994, Dandenongs 1997. Fire events such as Mangoplah 1952, Canberra 1952, Western Districts 1977 and Ash Wednesday I (in SA) 1980 occurred following years of negative SOI. However, other major events, such as Black Friday 1938, Dwellingup 1961 and Hobart 1967 occurred following years of positive SOI. This is not surprising for Dwellingup, as the ENSO effect has been identified as being limited only to eastern Australia.

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[13] Bureau of Meteorology webpage accessed 3/6/2004: www.bom.gov.au/climate/enso/Australia_detail.shtml

The extensive fires of central Australia in 1974 that burnt 15.2% of this continent (Luke and McArthur 1978) occurred following two years of consecutive positive SOI. Years such as 1941, 1965, 1987 and 1991 in which the SOI was significantly negative and considered El Nino did not result in significant fire events.

While significant and extended rainfall deficit during the antecedent conditions contributes to the occurrence of severe fire events and these rainfall deficit events can be linked to the occurrence of an ENSO event, it is the synoptic situation that plays the major part in determining whether or not any given day will result in a major or severe fire event (Cheney 1976).

3.2 Synoptic situations

Severe fire events in Australia are associated with high temperatures, low relative humidity and strong winds. These conditions occur under synoptic situations where pressure systems are so located that hot dry strong wind from the centre of the continent is directed toward the coastal regions (Cheney 1976). The wind directions most common during the fire season are south-easterly in the Northern Territory, westerly in coastal Queensland and northern NSW, north to north-westerly in southern NSW, Victoria, Tasmania, South Australia and south-west Western Australia.

Extreme fire weather conditions arise when a synoptic pattern arises that remains stationary for some time, maintaining the hot dry conditions for a sustained period. In western Australia, this situation occurs with a high pressure system is located in the Great Australian Bight and, more often than not, a low pressure system or cyclone located off the north-west coast, with associated troughs located between the two systems.

In south-eastern Australia, severe fire weather occurs when a high pressure system has moved off the east coast into the Tasman Sea and a low-pressure trough is approaching from the west (Cheney 1976) (Figure 15). Hot northerly or north-westerly winds, which can be gale force depending on the intensity of the low, will dominate. As the trough and associated cool change passes, the wind will revert to a westerly or southerly direction. The frequency of such patterns occurs with the normal weather cycle, which is approximately 6 or 7 days. Days on which such weather coincides with the existence of active fires have been termed, from the US, 'blow-up' days (Byram 1959).

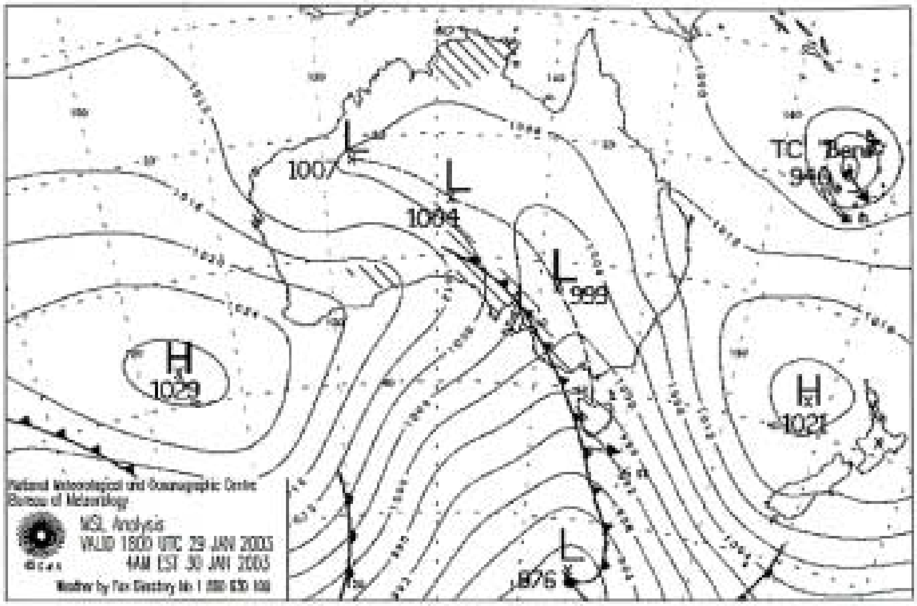

Figure 15. Synoptic pattern for morning of 30 January 2003 showing the classic blocking high-pressure system located in the Tasman and a cold front approaching from the south-west. Source: Bannister and Gill. (2003).

Occasionally the high-pressure system in the Tasman can become stationary, producing a ridge along the east coast that results in extended periods of extreme fire weather. During January 1939, such a high-pressure system remained stationary for nearly 2 weeks (Figure 16).

The passage of a trough and resulting cold front from the south-west will result in generally cooler, moister air reducing fire danger, but squalls and increased wind speed associated with the change can cause significant suppression issues for firefighters, as was the case on Ash Wednesday 1983.

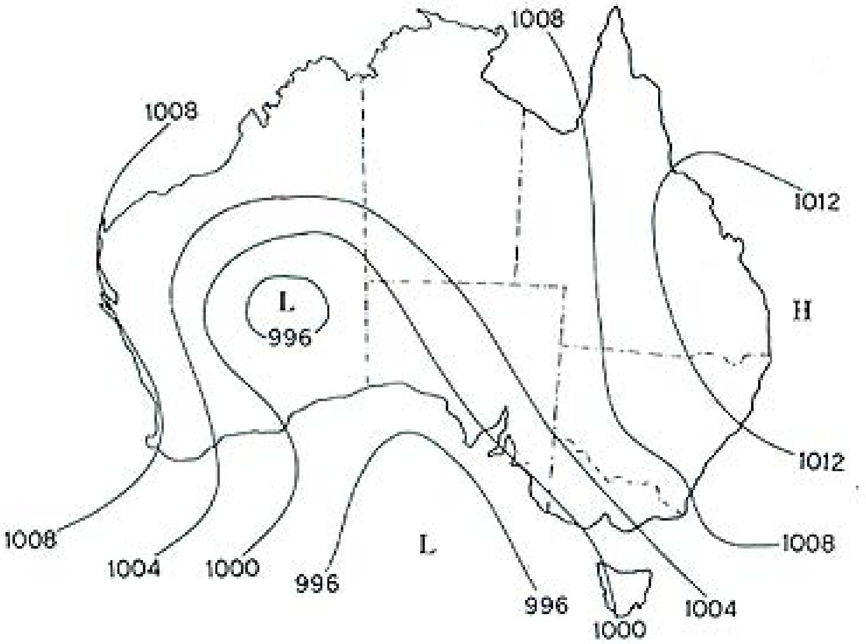

Figure 16. Synoptic situation at 0900 hrs EST on 13 January 1939 resulting in record temperatures and strong winds throughout south-eastern Australia. Source: Foley (1947) in Furler (1984).

3.3 Diurnal variation

The normal diurnal variation of weather conditions throughout the day, given suitable pre-existing antecedent and synoptic conditions, is the most important aspect of the weather determining the severity of a fire event. Generally, days of extreme fire weather in south-eastern Australia are characterised by the presence of blocking high pressure system in the Tasman Sea that dominates the weather patterns for some days. The result is a diurnal weather pattern that begins with a relatively high overnight temperature and low overnight relative humidity. Following sunrise there is a rapid rise in air temperature, such that by 1000 hrs, the temperature has reached 85-90% of the day's maximum temperature. Similarly, relative humidity drops rapidly and remains low for the remainder of the day.

The air temperature at Canberra airport only reached a low of 21°C over the night of 17 January 2003 and relative humidity maximum of 45% (Figure 17). By 1000 hrs on 18 January, air temperature had reached 86% of the day's maximum of 37.1°C. Relative humidity reached 8% at the time of maximum temperature and remained there for nearly an hour and then dropped to 4% later that evening. Air temperature and relative humidity play an important role in the moisture content of a fuel, which, in turn, affects the combustibility and heat yield of that fuel (see section 3.4).

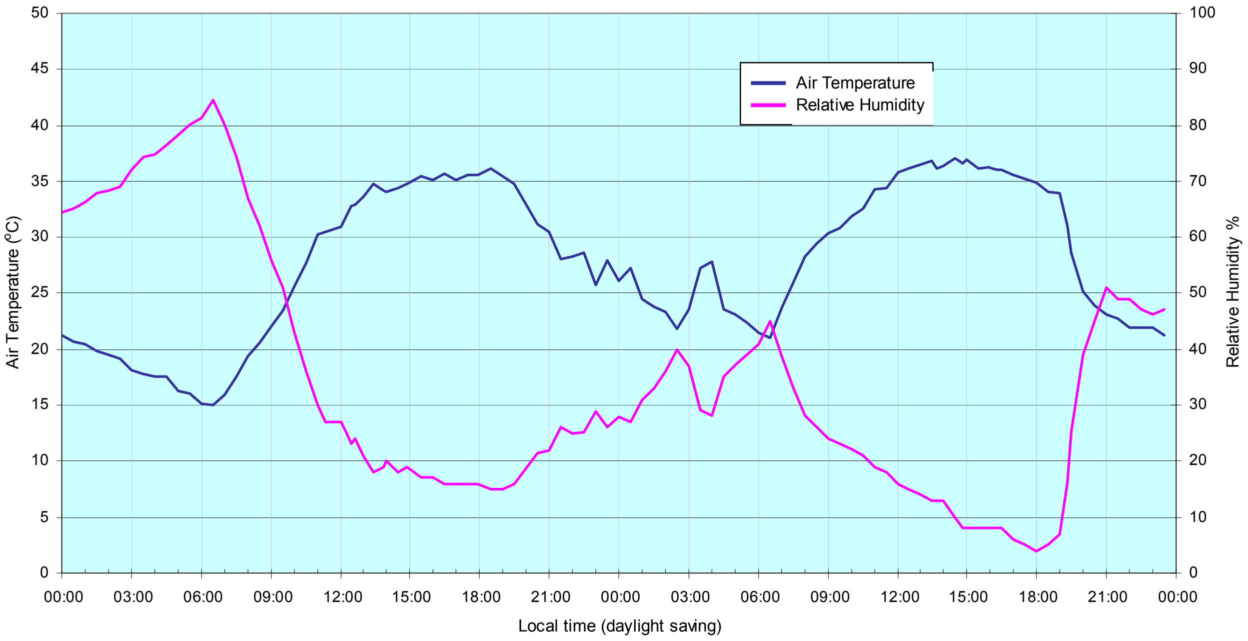

Figure 17. Air temperature and relative humidity for 48-hour period on 17 and 18 January 2003 at Canberra Airport, showing the failure to follow normal diurnal pattern of relative humidity rise and temperature drop overnight. Data sourced from Bureau of Meteorology.

3.4 Atmospheric stability

The synoptic and diurnal conditions described above are generally associated with conditions related to an unstable atmosphere. Atmospheric stability is essentially a term used to describe the potential for vertical motion in the atmosphere--stability can be defined as the resistance of the atmosphere to vertical motion.

A rising parcel of air will normally expand and cool as it rises. If the parcel falls to a level where the surrounding air is the same temperature as the parcel, the atmosphere is said to be stable. If the parcel of air remains the new level, the atmosphere is neutral. If the parcel, once cooled, continues to rise, the atmosphere is unstable.

3.4.1 Effect of fire behaviour

Atmospheric stability or instability can have a significant influence on fire behaviour. Most major fires burn under unstable atmospheric conditions, which allow the formation of a strong active convection column over the fire. This can lead to increased wind speed near the ground due to in-draughts, long-distance spotting and the formation of fire whirlwinds.

A stable atmosphere with a strong inversion layer above the fire can prevent the formation of a strong convection column, and all the smoke will be trapped beneath the inversion layer. This is the condition generally sought for prescribed burning operations. Signs of a stable atmosphere are a hazy sky and relatively constant wind direction; the top of the inversion layer is quite obvious from an aircraft.

Indicators of an unstable atmosphere are obvious well before a fire breaks out. The sky is very clear and visibility is very good, particularly after a cool change, and whirls of dust start to rise early in the day. Whirlwinds or dust-devils are common; they are initiated by irregular heating of the ground. Cumulus clouds may be present if there is sufficient moisture in the atmosphere.

Fire whirls are narrow twisting plumes of flame. With small fires, they persist for only a few seconds before dying out and reforming. However, large, fast-spreading fires can produce whirls that may build up to 20 m or more in height and travel down the flank of the fire for several minutes. Fire whirls can pick up loose burning debris and deposit them outside the fire perimeter, causing considerable trouble for suppression forces. More persistent fire whirlwinds commonly occur on the lee slopes of hills; the mechanical turbulence of the wind flow over a hill will frequently initiate them just beyond the crest. Although a fire may slow on the lee slope of a hill, spotting caused by whirlwinds can hamper fire suppression in the area.

3.4.2 Wind speed: gusts, lulls and turbulence

An unstable atmosphere can also result in gusty, turbulent wind flow at the surface. Convective action arising through the heating of the ground by the sun under conditions of an unstable atmosphere, where the heated air can continue to rise, can bring very strong upper winds down to the surface in the form of large-scale eddies (Figure 18). These strong eddies result in extremely gusty wind at the surface and can cause havoc for fire suppression activities.

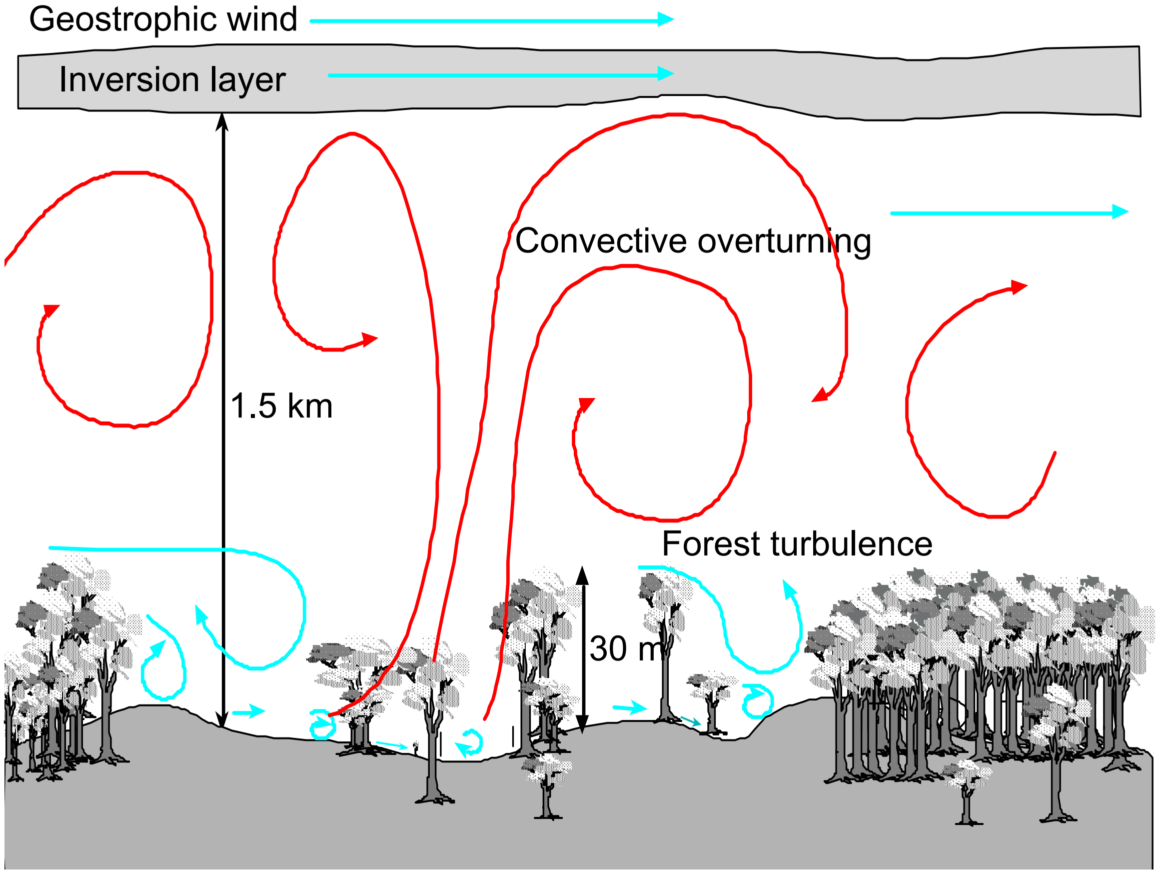

Figure 18. Schematic showing the formation of eddies within the planetary boundary layer sandwiched between the geostrophic wind and the inversion layer and the planet surface. Eddies are initiated by the convective overturning of the boundary layer through convective heating of the surface and facilitated by an unstable atmosphere.

The speed of the wind, therefore, will generally also follow a diurnal trend, starting from low values early in the morning, increasing in magnitude during day and decreasing at night as the solar heating of the surface increases and decreases with sub angle. Under severe fire weather conditions in south-eastern Australia, particularly those involving a blocking high synoptic situation, the speed of the wind may increase very early in the morning around sunrise and maintain strong speeds throughout the day and evening (Figure 19).

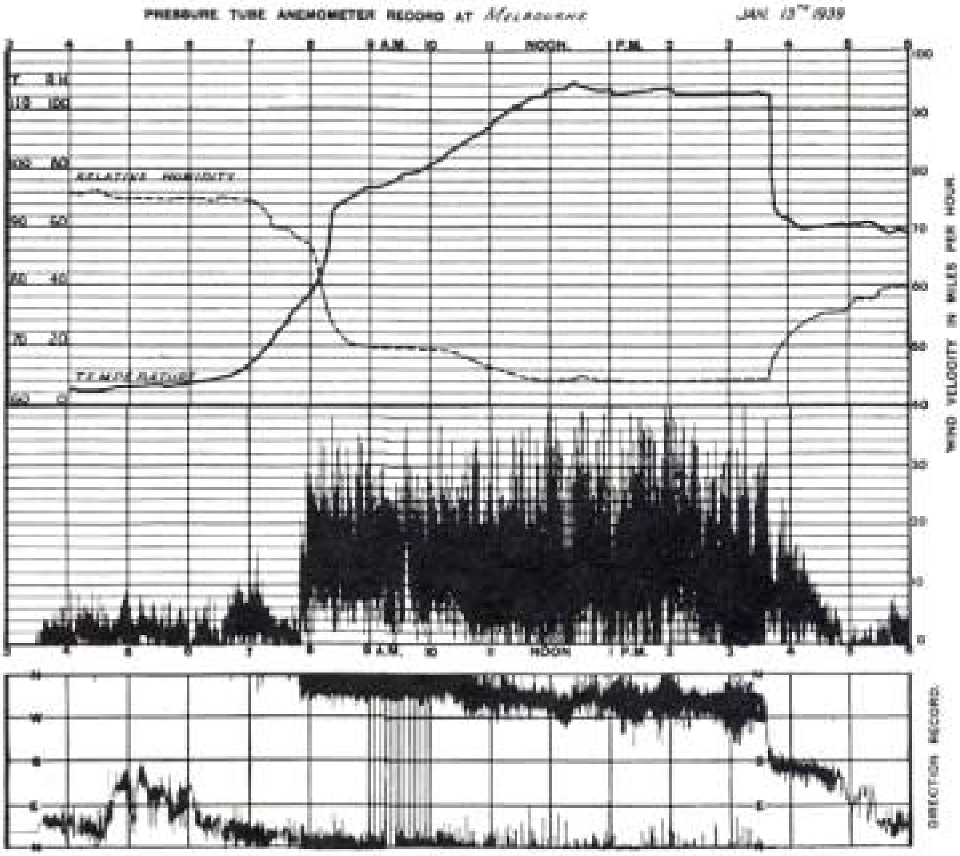

Figure 19. Diurnal pattern of wind speed and direction, temperature and relative humidity at Melbourne on 13 January 1939 showing the early increase in wind speed and temperature that is maintained throughout the day. Source: Foley (1947)

3.5 Fuel conditions and moisture content – forest and grass

Fuel moisture content (FMC) is a measure of the amount of moisture (water) that is present in a fuel and is critical to determining fire behaviour. The amount of water is normally expressed as a fraction of the oven-dry weight of the fuel. Dead fine fuel FMC ranges from about 3% under the hottest, driest weather conditions, to about 30-35% beyond which free water appears on the surface of the fuel and in the spaces between the cells. Above the fibre saturation point (approx 35%), the moisture content of the fuel bed is determined by the antecedent rainfall and weather. Below the fibre saturation point, the fuel loses moisture, depending on the amount of moisture in its surrounds (i.e. the atmosphere and soil).

The effect moisture in the fuel has on fire behaviour is essentially to restrict the efficiency with which particles of fuel ignite and then burn. During the ignition phase of the combustion process, energy is expended to heat a particle to ignition temperature. Once the fuel particle reaches this temperature, the fuel begins to burn, releasing energy in the form of heat and light. This energy then heats up adjacent fuel particles and the process continues. If a fuel particle is bone dry, it will achieve ignition temperature with a minimum expenditure of energy. However, if moisture is present in the fuel element, energy must be used to heat this water to boiling point and then boil the water away before the element itself will begin heating towards ignition temperature. The more water, the longer and more energy it will take to achieve ignition and begin burning; and when it does burn, it will be less efficient.

Because it takes longer and more energy to ignite adjacent particles of fuel, a fire will take longer to spread from particle to particle and therefore longer to spread across the fuel bed. As FMC decreases, the rate of spread of a bushfire will increase accordingly. Table 2 shows a list of fire behaviour at various FMC values. Under very dry and hot weather conditions, the behaviour of a bushfire is extreme and erratic. Sources of ignition that don't normally cause bushfires, such as sparks from metal striking rock, cigarette butts, etc, suddenly do (Cheney 1976, Cheney and Sullivan 1997). Under these conditions, phenomena such as spotting and crown fires are much more likely.

Table 2. Changes in dead fine fuel combustion characteristics with fuel moisture content.

FMC value	Fine dead fuel combustion characteristics
100%+	Live green leaves-must be dried to burn
~80%	Approximate wilting point-green leaves die and dry rapidly
30-35%	Fibre saturation level
28 - 30%	Eucalypt litter fuel will not burn
22-28%	Eucalypt litter fuel very difficult to ignite, burning difficult to sustain
20 - 24%	Grass fuel will not burn
16 - 22%	Eucalypt fuels difficult to ignite. Pine fuels burn readily. Prescribed burning window for pine.
13 - 16%	Eucalypt litter fuel moderately easy to ignite, burning sustained. Prescribed burning window for eucalypts. Pine fuels easy to ignite
10 - 13%	Burning readily sustained, fire behaviour predictable. Lower limit for low intensity prescribed burning
5 - 10%	Severe fire behaviour, crowning likely, progressively smaller fire brands start spot fires
3 - 5%	Extreme, erratic fire behaviour, crowning and spotting-common

Forest fuel can be stratified into 6 layers (Figure 20). Low intensity fire generally only involves the lower two fuel strata. Continuity of the surface fuel is critical to the continued spread of the fire. As the intensity of the fire increases, additional layers of the fuel are involved (Gould 2003), resulting in increased energy release and increased fire behaviour. Additional fire spread mechanisms such as spotting, also result.

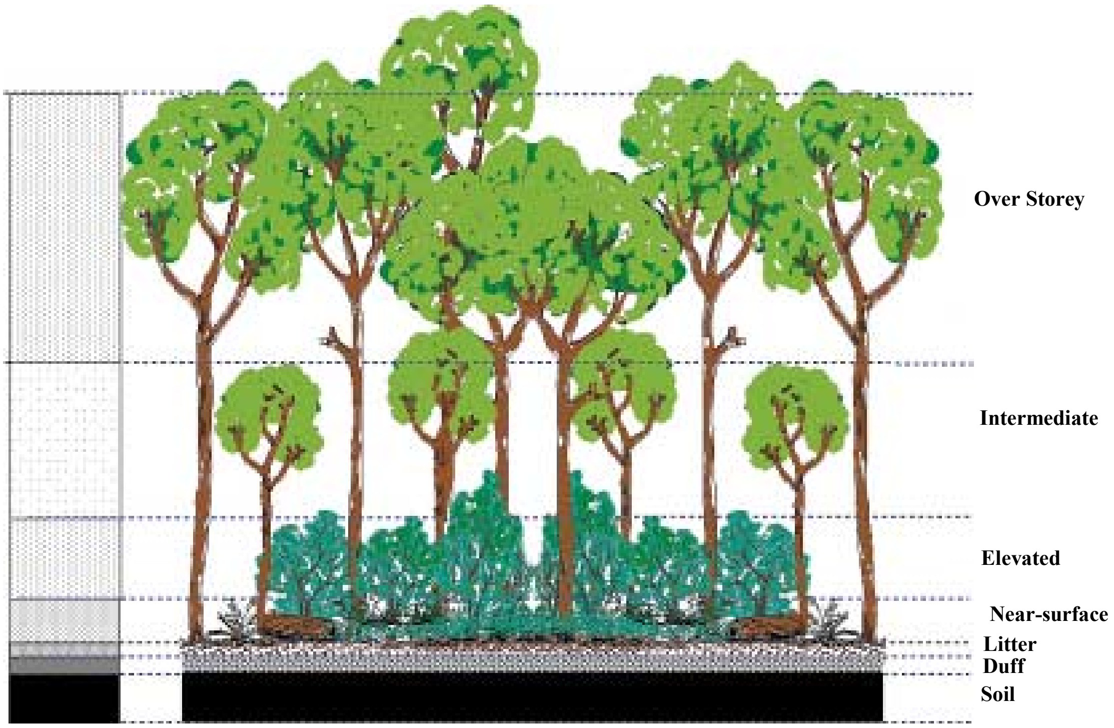

Figure 20. Schematic of the six strata according to their position in the forest profile.

Low FMC, particularly of large downed woody material, result in increased difficulty of suppression, control and mopping-up after the fire perimeter has been extinguished. Lofted embers lodged in the branches of stags provide ample sources of continued ember and spark generation.

Rainfall deficit, as reflected by low moisture contents of downed woody material, and reflected by high values of McArthur's Drought Factor, increases the amount of surface fuel available for complete consumption by the fire front. At a Drought Factor of 10, a result of very high soil moisture deficit as determined by indices such as the Keetch-Byram Drought Index (KBDI) (Keetch and Byram 1968) or the Mount (1971) Soil Dryness Index (SDI), and extended periods of little to no recent rainfall, all surface fuel is available for combustion in the passage of the fire front. Also at this Drought Factor during periods of extended rainfall deficit, areas that would normally be considered too moist to burn, such as creek lines, wet soaks, swamps, bogs, and other low lying wet areas, will have dried up and will no longer impede the spread of a fire. Therefore there is increased chance of widespread conflagration fires. Forest fires will be very difficult to control and may burn for several weeks before a change in the weather enables them to be controlled (Cheney and Sullivan 2000).

Curing is the term used to describe the drying of a grass following its annual or seasonal growth cycle with senescence following its flowering and seed setting. The state of curing of a grassland is expressed as a percentage of the dead material in the sward and varies from 0% when all the grass in the sward is alive and green, to 50% when half the sward is dead and yellow, to 100% when the whole sward is dead, yellow and fully cured. Fire will spread through a paddock when the curing state for the paddock is greater than 50%, although its rate of spread will be much less than its potential rate of spread.

Generally, the rate of curing increase will change only relatively slowly with time and will become fully cured over a period of 6-10 weeks. Once started, the curing process in annual pastures is not affected to any great extent by subsequent rainfall, although if the rainfall is sufficient to germinate seed green shoots may appear beneath the old sward. Such shoots are often not apparent at first, except where the old pasture has been burnt, and have no measurable effect on the rate of spread of fires in the fully cured older grasses that form a continuous sward. Once green shoots form more than 15% of the sward, however, they must be taken into account in the curing estimation and will affect ignition and the spread of fire. If rainfall is insufficient to maintain their growth, the green shoots will die before the life cycle is completed and have little effect on the overall curing. The period of curing can be rapidly accelerated, perhaps by as much as a week, by a single day of strong, hot, dry winds.

Perennial pastures cure more slowly than annual grasses, and curing is further delayed by rains early in the dry season. As perennials do not need to produce seed to continue their life cycle, rainfall after curing has started will delay the curing process in older leaves and produce new green shoots from the base of the clump that will continue to grow.

Grass paddocks will not cure uniformly, however. Grasses on ridges will cure early in the dry season. Grasses in creek lines and wet areas will remain green well into the dry season and will be an effective barrier to the spread of fires until they cure. When the pastures over the whole landscape are more than 90% cured, the potential exists for widespread devastating grassfires. Fire can spread unchecked and achieve its maximum potential rate of spread for the prevailing conditions.

3.6 Ignition potential and sources

Severe fire events are often associated with the development of uncontrolled fires from numerous ignition points following weather conditions conducive to extreme fire behaviour (Cheney 1976). In all the case studies presented in this report, multiple ignitions are the key factor in all but one. Events such as Black Friday 1939, Hobart 1967 and the ACT/Alpine fires of 2003, illustrate the catastrophic result of multiple existing fires burning prior to the arrival of severe to extreme fire weather conditions. Once the conditions arrived, control of those fires was impossible. Even when there are not multiple ignitions, such as the Mangoplah fire, fire behaviour under extreme fire weather is extreme and fire spread unstoppable until weather conditions abate.

Even when there are no existing fires, extreme fire weather conditions and associated low FMC through high air temperature and low relative humidity means that fuels are in a highly combustible state and sources that would not normally start fires under milder weather conditions can result in fire ignition. At moisture contents above 15%, only a sustained flame can cause ignition. Ignition becomes progressively easier as the moisture content of dead fuel decreases; below a moisture content of 6% very small embers or hot particles are capable of igniting grassy fuels (Cheney and Sullivan 1997). Under these conditions, possible sources include glowing carbon particles from defective exhausts, hot metal sparks from clashing power line conductors, grinding operations, and metal striking rock during the operation of slashers or bulldozers. (See section 4.1 on *Spotfires* for additional ignition sources.)

The Canberra 1952, Dwellingup 1961 and the 2003 fires illustrate the impact that the passage of dry summer thunderstorms can have on the occurrence of severe fire events. Lightning strikes in rugged terrain can remain undetected for some time (if inadequate detection systems are used) and when detected, the remoteness and difficult access to the ignition sites means that the fires can burn for some time, particularly under favourable fire weather conditions, ensuring that first attack will generally fail. An additional problem is that lightning strikes can be multiple across large tracts of land (Figure 21), making priority setting and rapid attack vital, as seen in the 2003 fires.

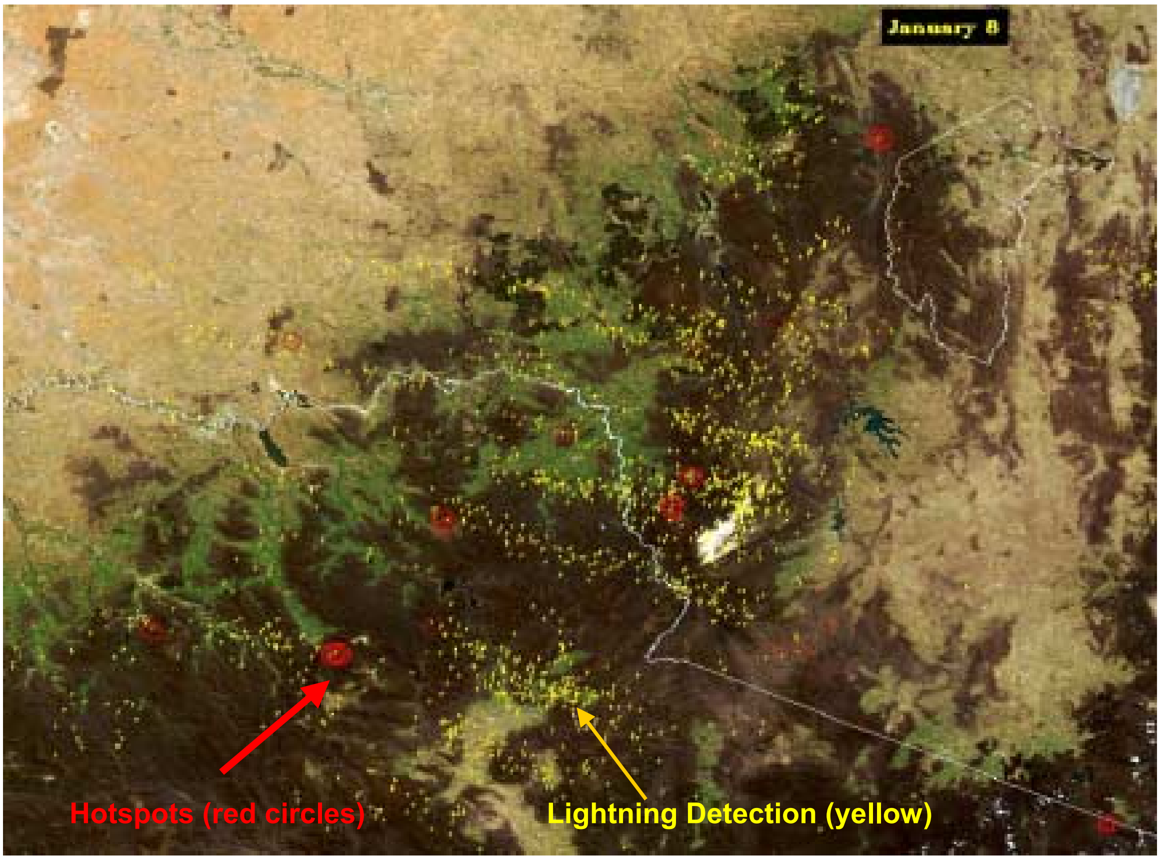

Figure 21. Superimposed image of lightning strike data and Hotspot data recorded on 7 and 8 January. Source: Cheney (2003).

4. Fire behaviour

The behaviour of fires associated with severe fire events can range from the quiescent to the extreme and erratic. The antecedent weather leading to a severe fire event is not necessarily extraordinary but the coincidence of multiple ignitions, extreme fire weather and dry fuel can lead to extraordinary – but not unprecedented – fire behaviour. Rates of forward spread over short periods can be extremely fast, particularly in regions of steep slopes aligned with the prevailing wind. High-intensity phenomena such as large fire whirls may increase the rate of spread of sections of fire perimeter (McArthur *et al.* 1982). Massive spotting, particularly in heavy or long-unburnt forest, may also occur.

The behaviour of fires under the influence of large convective interactions is less well understood than single fires or fires with less convection/atmosphere interactions. For example, while the behaviour of the main McIntyre's Hut and Bendora fires in the ACT, January 2003, pretty much follow current understanding of fire behaviour through those types of vegetation (given the uncertainty in environmental conditions driving those fires), the behaviour of the Goodradigby breakaway from the southern flank of the McIntyre's Hut fire on the afternoon of 18 January (figure suggests there are mechanisms at work beyond the current understanding. This section of fire averaged a rate of spread of approximately 20 km/h for a period of an hour through pastures of various conditions, pine plantation of various age (from recent plantings to mature forest) and eucalypt forest, without any conclusive evidence of change in rate of spread throughout that period (Cheney[14] pers. comm.). It is possible that this section of fire was influenced by the action of the convection columns of the adjacent McIntyre's Hut fire and Bendora fire but there is little research about this type of behaviour.

One common characteristic of all high-intensity severe fire events is that the majority of the area burnt and most damage (including loss of life) occurs over a relatively short period of time with respect to the total duration of the fire (Cheney 1976). As discussed in the case studies, over 50% of the area of the 2003 fires burnt during a total of 29 hours over three specific days of the 50 days of fire spread. Similarly, in the ACT, nearly 70% of the final area of the McIntyre's Hut fire was burnt in one day of the 11 days of fire spread.

The occurrence of a shift in the direction of the wind during the main run of a fire can also play a major role in the behaviour of a fire. The 1977 Western District fires and the 1983 Ash Wednesday fires illustrate the effect a major change in wind direction can have following a period of extended fire spread under a steady north-westerly synoptic wind. The arrival of the south-westerly change resulted in a 90° wind direction change, turning extended lengths of eastern flank into headfires, resulting in greatly increased areas burnt and length of active perimeter. These sorts of wind changes also pose great problems for suppression crews who may be working on the eastern flank in the knowledge that a forecast wind change may arrive and attempt to reduce its impact on that flank.

During a severe fire event, particularly on fires in or near the bushland-urban interface, it is common for fire suppression resources to be stretched beyond their capacity to suppress or control the fire, even when on single house protection duty, as was the case during the 1994 Sydney and 2003 ACT fires. Utility services such as water, electricity and gas can be adversely affected, leaving residents and firefighters alike without sufficient resources to effectively fight the fire and, in many cases, with additional complications to deal with.

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4.1 Spotfires

An additional source of fire ignitions are spotfires caused by lofted firebrands ahead of the main fire front, particularly in forest fuels (Luke and McArthur 1978, Cheney 1976, Ellis 2000). The low FMC of surface fuel means that ignition of spotfires by burning or smouldering embers can easily start new fires (Plucinski 2003) and these fires will quickly establish themselves, given favourable conditions as would be found in extreme fire weather. These additional fires add to the already considerable burden faced by suppression crews and can distract them from the major task of attempting to control the main fire.

Spotfires are the main cause of loss of control of fires during suppression operations (McCarthy and Tolhurst 1998). McCarthy and Tolhurst (1998) found that once the distance of spotfire occurrence exceeded 50 m, first attack suppression on a fire failed. While most spotfires are generally overrun by the spread of the main fire front, spotting under severe fire weather conditions enables the fire to breach landscape features that would normally be expected to halt the fire under milder conditions, such as breaks in topography, firelines and water bodies.

4.2 Broadscale fire behaviour

It is the effect of massive spotting, particularly under conditions of extreme fire weather when fuel moisture content is low and spotfires very quickly take hold, that can contribute to perceived extraordinary fire behaviour. Spotting is the main mechanism by which the fire will spread in broken topography, resulting in apparent rates of spread at the broad scale much faster than would be estimated for the conditions. This is particularly apparent when the spots thrown from a ridge land on the next windward slope, and so the fire as a whole appears to spread only in upslope runs, leaving the leeward slope to burnt out well behind the 'front' of the fire.

However, the spread of fires as seen at the small scale (i.e. the tactical scale) will still follow the current understanding of bushfire behaviour. This is evident when spotfires land, not on the next windward slope, but on the lee slope. These spotfires will then generally burn down the slope at a much-reduced rate of spread than witnessed on the windward slope.

Similarly, the changes in fuel moisture with change in aspect, reduction in wind speed with lee-topography, etc., will appear to have less effect at the broader scale (i.e. for large fires) than is found on small fires, but the fine scale fire behaviour will still reflect these affects.

The importance of the influence of a well-developed convection column on the spread and behaviour of a fire is appreciated qualitatively. It is commonly accepted that once a fire has achieved a certain size and development, it can appear to 'integrate' fine-scale variations in fuel and wind. However, the mechanisms by which it might do this are not at all well understood or defined and represent a major challenge for fire researchers.

5. Conclusions

The climate and vegetation of Australia are such that at any time of the year, the potential for disastrous bushfires exists somewhere in the country. In south-eastern Australia, the normal period for this potential is from October to February. During years of severe rainfall deficit, this period can extend from September to April, with the possibility of less severe fires prior to, and after, this period.

The occurrence of weather associated with severe fire events has been found not to be out of the ordinary, as mentioned by a number of authors (e.g. Rodgers (1961) about Dwellingup, Bannister and Gill (2003) on the Victorian Alpine fires). It is the combination of antecedent weather (long term drying of fuels), synoptic weather (short term fuel drying and wind), atmospheric conditions and fire ignitions that results in severe fire behaviour. It is then the occurrence of such a fire in a region of high value assets or over an extended period that results in what may be called a severe fire event.

As the trend towards living in the peri-urban bushland setting increases, particularly in the forested mountainous regions surrounding our capital cities, the potential for many smaller fire events to be considered a severe fire event through the value of assets destroyed and people killed increases without any necessary increase in the occurrence of severe fire weather or fuel accumulation.

The correlations between ENSO events and rainfall deficit, and rainfall deficit and severe fire events, do exist but are not strong. While many of the case studies presented here are a result of ENSO-rainfall deficit events (resulting in widespread conflagration fires such as the 2003 fires), the occurrence of a severe fire event does not depend on such antecedent conditions. Indeed, events such as the fires associated with Black Friday January 1939 occurred despite the lack of antecedent ENSO conditions.

In many normal to above average rainfall years, severe fire events such as the 1977 Western District fires or the 1969 Lara fire are the result of just one day of severe fire weather in an otherwise mild fire season. These large, fast-moving grassfires can be much more serious than the slower moving forest fires that burn for extended periods due to the devastating effect on people, townships, livestock and fencing over very large areas of land in short amounts of time. The Narraweena fire of Ash Wednesday covered 60 km before entering a plantation and causing massive damage to the forest asset. Even when growth yield is reduced or grasslands are eaten-out due to stocking pressures, fire can be carried by very strong winds, via discontinuous patches of fuel or firebrands (such as seed heads, dung, etc.)

In the ACT, as with much of the rest of south-eastern Australia, the predominant severe fire weather is associated with a high-pressure system located in the Tasman Sea directing strong hot winds from the centre of the continent over the region. The presence of the Brindabella Ranges to the west and the Southern Alps to the south of the Territory means that the passage of dry summer thunderstorms may result in lightning strikes in difficult terrain. During summer, the normal passage of high-pressure systems at post-solstice latitudes will ensure that at regular intervals (i.e. nearly weekly), fire weather conducive to high (or greater) fire danger and resultant severe fire behaviour will occur. In the common case of a blocking high pattern forming over the Tasman Sea, the fire weather may become extreme, with strong and gusty north to north-west winds occurring that will drive any fires located in the mountains to the west of Canberra toward the city, as was the case during the 1951/52 fire season and January 2003 fires. Under such extreme fire weather conditions, fire control is virtually impossible until the weather abates.

The importance of the size of the fire in determining its behaviour and rate of spread has been identified and applied to the development of new systems for predicting fire behaviour (Cheney *et al.* 1993, 1998, Gould *et al* 2003). There is anecdotal evidence of critical thresholds in fire conditions, particularly when the conditions are less than extreme, at which seemingly innocuous changes (i.e. minor changes in wind speed, wind direction, fuel, etc.) result in dramatic and sometimes devastating changes in fire behaviour. The implications of the change in the rate of spread of a fire resulting from a change in wind direction, in terms of firefighter safety, has been identified (Cheney *et al.* 2001). Interactions of multiple fires (called coalescence) has also been identified as a very important aspect of fire behaviour that can have considerable effect on the behaviour of bushfires, regardless of the scales involved. Convection columns of large fires and resultant behaviour modifiers such as fire whirls, spotting and convection-related atmospheric phenomena such as thunderstorms and tornados, have also been anecdotally identified. However, the understanding and quantification of the processes involved in these behaviours and critical thresholds does not exist and represents a significant area of knowledge vacuum and research potential. Improved understanding of the change in behaviour of bushfires at critical thresholds will better enable fire authorities and firefighters to plan suppression and egress strategies and provide a basis for safer communities living with fire.

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