EXTREME FIRE

A HANDBOOK

HighFire Risk Project.

This document aims to provide awareness for staff potentially involved in managing catastrophic wildfires. It relates to the current state-of-knowledge of extreme fires.

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Cover: Extreme fire on the Tinderry Ranges, 17 December 2009. [Photo: Steve Forbes, ACTESA]

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INTRODUCTION

In recent years we have experienced a number of fires which have exhibited unexpectedly severe behaviour.

We typically predict and explain fire severity using a continuous function of weather severity, such as the Fire Danger index. Smooth changes in the weather parameters such as wind speed or temperature give predictable smooth changes in FDI. As the weather becomes increasingly severe, so does the fire. It is then implicit that such a fire would produce features seen in the field, such as the monstrous smoke plumes.

While catastrophic weather may make the FDI become ridiculously high as a mathematical result, there is little insight to be had from this and little prediction of how the fire, and the threats that it produces, may evolve.

Unfortunately a number of enquiries have relied on the logic that we knew the weather, the fire's behaviour was predictable from that, and therefore when death or damage occurred key officers were negligent.

It is possible, after the fact, to "tweak" the parameters of any fire spread model to produce a final spread envelope that resembles what is seen. This is what is usually done to support those enquiries but also gives little insight.

One of the most obvious and well observed features of these events is the intense convection that is produced. Recently the development and use of remote sensing tools, and specifically weather radar, has permitted a greater investigation of intense convection. These observations can be combined with direct observations of the fire to give an enhanced insight into the exact processes at work.

The major scientific effort that has gone into understanding these events shows us that fire escalation stops being on the FDI continuum, and is instead driven by discrete processes. This leads to a coupled fire – atmosphere event – ***an extreme fire***. This may be thought of as a new type of fire, requiring a new set of tools. These tools allow forecasting, behaviour prediction, threat mitigation and prevention.

In parallel to the observations and studies of fire researchers, other researchers were taking note.

Volcano Watch

After a number of commercial airliners had come close to disaster after encountering volcanic ash plumes, researchers began looking at the sources of particulates in the Upper Troposphere and Lower Stratosphere (UTLS), around the general flight height of commercial intercontinental airliners. Some of the skills used here were developed to also look for covert nuclear detonations, and so were already in an advanced stage of development.

In 1999 a UTLS particulate cloud detected in the northern hemisphere was back-traced to Canada. After all other sources were ruled out, intense fires in the Yukon and Northwest Territories were suggested as the source (IAVW, 2004).

Following this a quantity of circumstantial evidence was collected. A reference case emerged in 2001, when a well observed fire near Chisholm, in Alberta, produced a very large particulate injection into the UTLS. (Fromm *et al.*, 2004; IAVW, March 2004).

Ground and space-based remote sensing, combined with atmospheric modelling, permitted the identification of the exact event that was the source. The fire behaviour was extraordinary, and it produced at least two large cumulonimbus clouds, with the final one in particular having many of the features of a thunderstorm. The height of this anvil's overshooting top was 14 km, well into the Stratosphere. (Rosenfeld *et al.* 2007, Damoah *et al.* 2006).

Studies of the data on this fire created interest in many areas. A confirmation was needed. The fire events near Canberra on 18 January 2003 produced another well-observed intense convection event. This was only slightly less intense than the Chisholm fire ($43*10^9$MJ as opposed to $71*10^9$MJ), but its UTLS impact was more clearly seen in its less polluted southern hemispheric setting.

Fromm *et al.* (2006) studied this event and concluded "Lastly, it appears that the brief (~3 hrs) and microscale (~10 km diameter) pyroCb has now been shown to have the explosive capacity to pollute the austral stratosphere with absorbing aerosols that intercept solar radiation–with significant implications for weather and climate…"

The Canberra Fires significantly raised the southern hemisphere's stratospheric particulate load for three months, peaking at 2.5 times the pre-fire level. The well formed pyro-cumulonimbus had many classic thunderstorm features, including a confirmed F2 tornado that narrowly missed heavily populated areas.

Transition model

In research following the Canberra fires, there was a focus on a risk model that encapsulated the process of formation of such a fire. This has been discussed in McRae & Sharples (2011).

Out of the research came the Transition Model. This is summarised in Figure 2. It relies on the following facts:

- All fires start small.
- Any fire can be placed into one of five specific scale classes, which reflect the placement of the fire on the landscape.
- Fires may, during any specified time interval, escalate to a larger scale class, stay in their current scale-class, or decay into a smaller scale class (or go out).

- The interactions of a fire and its environment reflect the fire's scale class.

Fire size classes are:

- Small fires are only on their site of ignition.
- Medium fires have spread around within the landform at the locality of ignition.
- Large fires have moved onto a small number of adjacent landform elements, giving a diversity of fire behaviour.
- Very large fires are burning on a number of landforms.
- Plume-driven fires – or extreme fires - are coupled fire-atmosphere events, and are largely landform independent.

From the point of view of an IMT active during a particular shift, this means that their task can be specified as:

"Given the fire at the start of this shift, what are the likelihoods of the fire's possible transitions given the current incident objectives?"

Tools are available to estimate these possibilities.

TRANSITN.EXE is a program that provides broad estimates of the transition probabilities.

The final scale class is given as "Plume-Driven Fires". There has been considerable debate over this term. An alternative term, which will be used here, is "Extreme Fire".

It is necessary to clarify the term "extreme" used here. Historically in Australia "extreme" has been used for a fire danger rating, corresponding to a fire danger index over 50 until 2009, and redefined after Black Saturday as being between 75 and 100. There is no correlation between extreme fire danger rating and an extreme fire as used here, where the term refers to the fire's dynamics. An additional point to note, which will be explained below, is that the behaviour of an extreme fire is poorly related to fire danger index.

Figure 1. Pyro-Cb, with overshooting top, over Omeo, seen from Kiandra. [Photo: Stephen Wilkes, NSWRFS.]

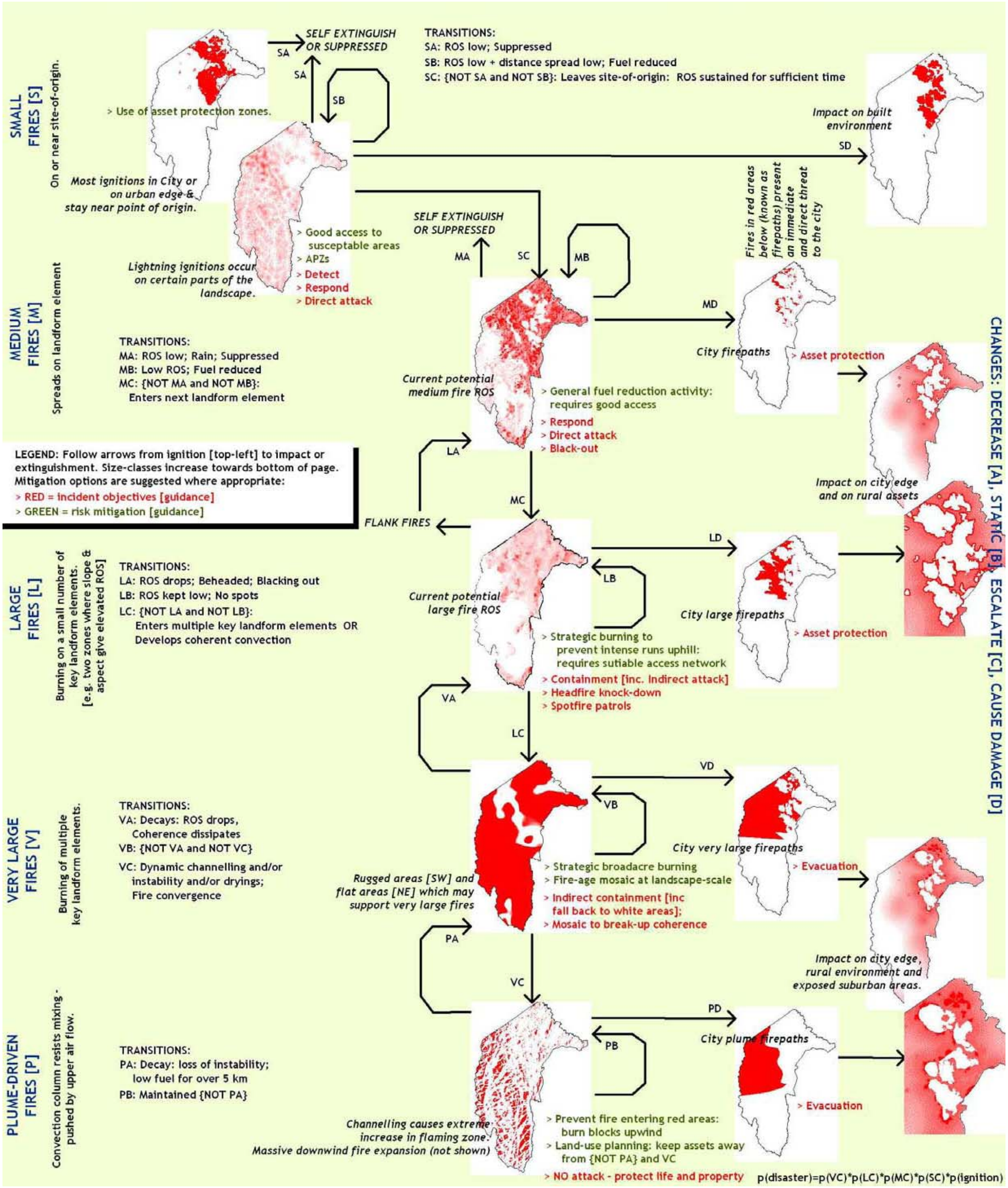


Figure 2. The Transition Model.

DEFINITIONS

It is important to define the terms used in this handbook. Many of the concepts have been used previously in a colloquial manner without being well defined in training material. Variation in usage has made some terms confusing or misleading. Additionally there are terms that are newly introduced from research into extreme fires this decade.

Term	Definition
Convergence	Similar air flows approaching each other at shallow angles, such as sea breeze from different parts of the coastline. (See Mills & Morgan, 2006)
DP	Dew Point Temperature, ˚C.
Ember attack	Embers lifted in the convection column, which fall out and threaten to ignite structures.
Ember storm	Embers created by partial combustion in strong wind fields, within *violent pyro-convection*, which blow in a horizontal layer.
Extreme fire	A fire whose behaviour is determined largely by energy transfer processes in the atmosphere, well above the surface.
FDI	Fire Danger Index – McArthur Mk 4 Grassland FDI, Purton's modified McArthur Mk 4 Grassland FDI, McArthur Mk5 Grassland FDI, McArthur Mk 5 Forest FDI, FMI.
FDR	Fire Danger Rating, a classification of *FDI*.
Fire Channelling	Atypical fire spread, involving lateral spread within an eddy and downwind spread by means of dense spotting (See Sharples *et al*., 2012).
Fire Tornado	A vortex anchored to the base on a *pyro-Cb*.
Fire Whirl	A vortex anchored to the ground.
FMC	Fuel Moisture Content, %.
Foehn wind	Air descending down the lee side of a barrier range, with the properties of either middle-level air from the windward side or low-level air from the windward side that was dried and warmed after losing water during its ascent. (See Sharples, 2009)
LCL	The Lifting Condensation Level, the height at which a rising air parcel cools to its *DP* and becomes saturated.

	The cloud base.
Low-level jet	An abrupt increase in wind speed above nocturnal inversions, due to removal of ground friction, which may experienced on high terrain features which protrude through the inversion. (See Sharples, 2009)
Overshooting top	The core of a *pyro-Cb* that has sufficient buoyancy to penetrate the *UTLS* and enter the stratosphere.
Plume-driven fire	*Extreme fire.*
Pyro-Cb	*Pyro-Cumulonimbus.*
Pyro-convection	The vertical movement of air parcels heated by a fire.
Pyro-Cumulonimbus	A thunderstorm that forms as part of *violent pyro-convection.*
RH	Relative Humidity, %.
Rugged terrain	Terrain where there is over 300m local relief within 1500m of any point.
T	Dry bulb temperature, ˚C, measured in a Stephenson Screen.
UTLS	Upper Troposphere – Lower Stratosphere, the major inversion that separates the two main layers of the lower atmosphere.
Violent pyro-convection	*Pyro-convection* associated with an *extreme fire.* (See Fromm et al 2006)
Wind channelling	Diversion of wind flow, with a marked change in direction, into valleys or lee slopes in response to friction or pressure gradients. (See Sharples, 2009)

An additional distinction needs to be made. A violent pyro-convective event that forms a pyro-Cb and breaks through into the Stratosphere is called a Tier 1 event. If a pyro-Cb forms but it stays below the UTLS it is called a Tier 2 event. They may be distinguished by use of satellite data, photography from a distance or examination of an Aerological Diagram. Three-dimension reconstruction of radar data may assist. Tier 1 events are more energetic and are more likely to cause damage. Research is underway to determine if climate change has increased the likelihood of Tier 1 events.

PRECURSORS

An extreme fire will develop only if certain precursors are in place. These are:

- A fire on the landscape.
- Sufficient fire behaviour for that fire's initial stages of escalation to occur before detection and suppression can succeed.

Some extreme fires have passed through each scale class through a lengthy process - a campaign fire. At some stage in the "life cycle" of a campaign fire there may be the triggers for escalation to an extreme fire. The likelihood of that escalation increases with the duration of the campaign. Thus in the alpine fires on 2003 and of 2006 fires that had been spreading for many days would catastrophically flare up for an afternoon, and then subside.

Others fires transition rapidly to an extreme fire in a matter of hours. This may be from a new ignition or from a break-out from a previously contained edge. Some of the fires on Black Saturday almost went straight to the largest size class. Break-outs on the Bendora and McIntyres Hut fires on 18th January 2003 quickly became some of the most intense fires ever studied in Australia.

Elevated FDR

Elevated fire danger rating (FDR) is a common ingredient for all extreme fires. It can arise from two processes: (a) the diurnal weather cycle and (b) discrete weather events.

Sharples *et al.* (2009a & 2009b) have shown that FDI is fundamentally wind speed divided by fuel moisture content (FMC). In turn, FMC reflects the drought factor (DF) and the difference between temperature (T) and relative humidity (RH). It is clear from their work that we can have elevated fire danger if one or more of these occur:

- DF approaches 10
- Wind speed becomes very high (say, over 50km/hr)
- T minus RH approaches 40

While it is significant that we need (T-RH) not just T, the former approaches 40 only when T is over 38°C and RH nears 0%.

Most instances of this can be well forecast as a part of the diurnal cycle as a cold front approaches, with various forms of frontogenesis and pre-frontal troughs bringing together the required weather elements.

Less easily forecast are discrete weather events, which usually have some element of interaction with the fire to achieve the elevated FDR. An example is an abrupt surface drying event (Mills 2005, 2008a & 2008b). Here a middle-level band of dry air is mixed down to the surface on a hot day, dropping the RH to very low values. The enhanced mixing from the fire may contribute to this. The Wangary Fire is a good example of this.

Discontinuous weather processes include:

- Wind changes
- Thunderstorms, especially downdraughts
- Dew point depression events
- Forced channelling events
- Abrupt surface drying events
- Low-level jets
- Foehn winds

Figure 3. Black Mountain Tower, Canberra, underneath a pyro-Cb. [Photo: unknown]

PLUME-DEVELOPMENT

The most extreme form of smoke plume above a fire is called violent pyro-convection.

Deep Flaming

As a rule-of-thumb we can take a representative diameter of the flaming zone of a fire and use this as a measure of the height to which the convection column will resist mixing with the air through which it is passing as it rises.

When a smoke plume rises, it cools at the dry adiabatic lapse rate of 10°C per kilometre. If it cools to the Dew Point Temperature (DP), then its moisture content will condense from vapour to liquid. This releases the latent heat of condensation. If the DP is negative, the latent heat of crystallisation is released as well, as ice particles form.

Studies of the Chisholm and Canberra fires have shown that for a significant fire this heat release can be up to triple that of the fire. The best way to think of this is that an extractor fan has been turned on above the fire, greatly enhancing its dynamics.

On a typical day of elevated FDR in southern Australia, we can consult the Aerological Diagrams (see Appendix) and read off the lifting condensation level. Low clouds are unlikely, and we should expect a value around 5km above sea level.

Therefore we can expect violent pyro-convection to occur when the flaming zone approaches 5km in depth. When can this occur?

Studies of significant fires have given us the following list:

- Wind changes, which cause a flank to become a headfire. Changes can happen from the arrival of a cold front or a trough line (both well established knowledge in bushfire circles) or from convergences (Mills & Morgan, 2006). Convergences happen when similar air masses with only slightly differing wind directions converge, either downwind of major terrain features, or inland from different parts of the coast.

- Extreme rates of spread, which can arise from some combination of near-zero FMC, strong winds and prolonged uphills runs. We need to also consider the potential for eruptive fire spread to achieve this (Viegas 2006). Eruptive fire spread happens when steep terrain elements allow the flame to lean over and attach to the surface. Nearly exponential accelerations may result.

- Fire channelling, which can entrain a fire and make it spread in two directions at once (Sharples *et al.* 2012). This results from a particular type of wind–terrain interaction, which creates lee-slope eddies either in entrenched valleys or on major lee-slopes. If fires enter such an eddy, the eddy becomes filled with embers and expands thermally into the prevailing winds blowing overhead. This peels off ember-laden air which ignites the landscape for some kilometres downwind. At the same time the eddy expands laterally, taking that process with it. There are numerous well documented cases of this, most notably the Canberra fires on 18th January 2003 (McRae 2010).

It must be noted that the environmental lapse rate in general terms constrains the buoyancy of a plume – the lumps and bumps seen on its trace on an Aerological Diagram will usually constrain a plume to low levels. The extreme heat from deep flaming will permit the plume to rise until it reaches a major inversion or the top of the troposphere (the lower layer of the atmosphere).

The stratosphere, above this, is normally free of cloud and smoke. The boundary between the two layers, the tropopause, is often difficult to pin down precisely. For this reason fire analysts often refer to the UTLS – the upper troposphere – lower stratosphere. In summer at mid-latitudes, the UTLS will typically be at 12 km ASL.

Satellite data easily picks up the signature of a major fire event, as it pollutes the stratosphere.

INSTABILITY

For maximum plume development it is clear the fire needs to be able to make a large quantity of air more buoyant than the air around it at the surface. Being buoyant, it will rise. As it rises, the properties of the air through which it is trying to pass will change. In some configurations the plume will reach an inversion and lose its instability and stop rising, in other configurations it will remain buoyant until reaching the UTLS.

Thus instability is a prerequisite for an extreme fire. There are a number of ways to assess whether the appropriate instability is present, but we will cover: the Aerological Diagram, the Lifted Index, the Haines Index, pressure charts and satellite imagery.

The Aerological Diagram

The Bureau of Meteorology routinely deploys balloon-borne atmospheric profilers. The data provide invaluable detailed knowledge of the properties of the atmosphere, including instability. The data are plotted on a “skew-T log-P” Aerological Diagram (see Appendix). These are quite complex and use of them requires specialised training.

They show the way the temperature and dew point change with decreasing pressure or increasing height. The relationship between pressure and height is based on the ICAO Standard Atmosphere, developed to assist the civil aviation industry (see Figure 4). It allows any measured pressure value to be matched to a stylised height above sea level.

The diagram also permits an assessment of the changes to a parcel of air that is lifted (by buoyancy) by adiabatic processes (ie no exchange of heat with the air through it passes). They are prepared showing the trace for a lifted parcel of surface air. Trained users can add to this the effects of a fire, for both temperature and dew point. The trace that results is the best practical prediction of the evolution of a plume.

Knowledge of the fire's intensity, size and rate of escalation is important for doing this prediction correctly. Clearly the ideal situation is to have balloon flights run specifically for the fire, but this is not done in Australia.

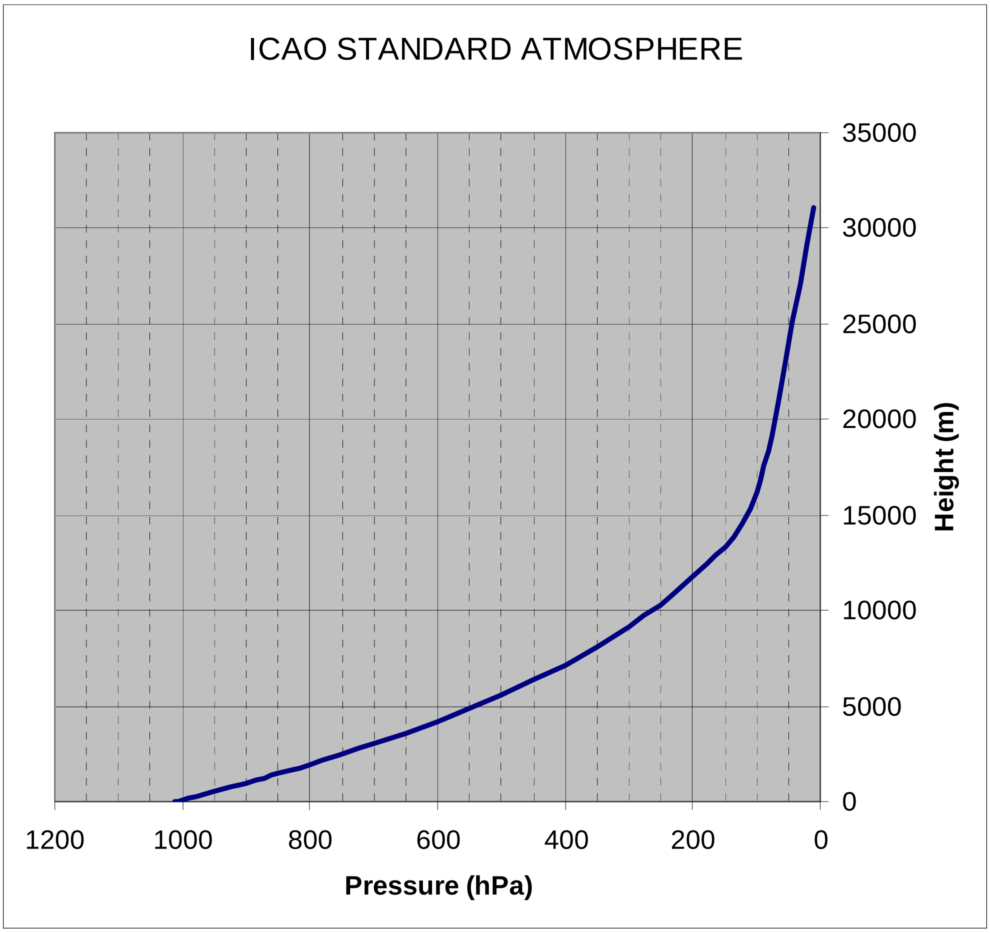


Figure 4.

Aerological Diagrams also show winds speed and direction at all measurement heights. This provides much valuable insight into fire escalation. Byram (1954) reviewed the wind profiles associated with what he called blowup fires, a subset of which are extreme fires.

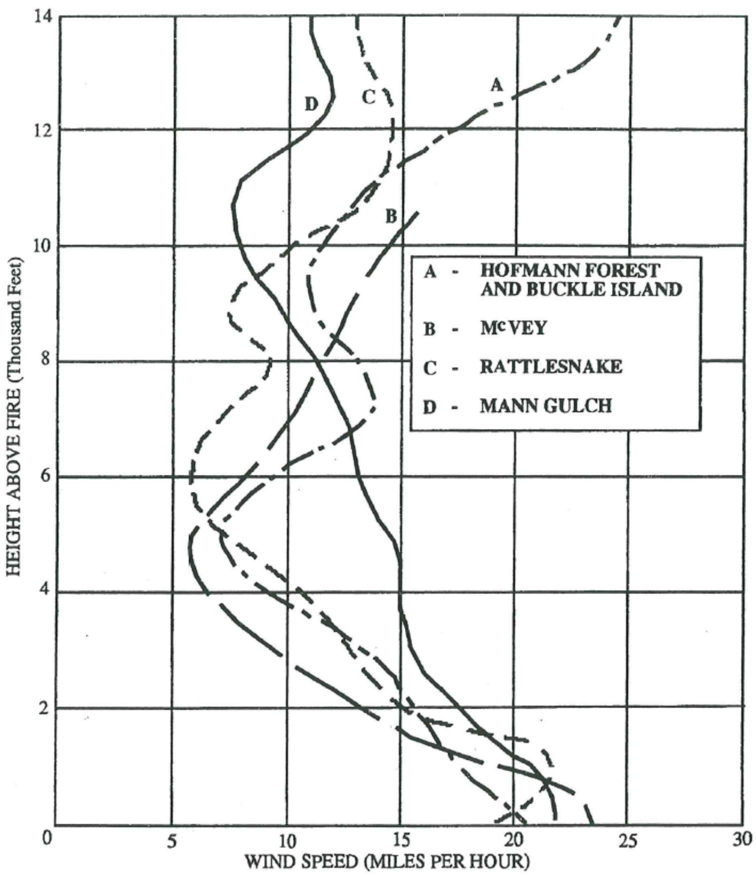


Figure 5. Wind profiles of notable fires (from Byram, 1954).

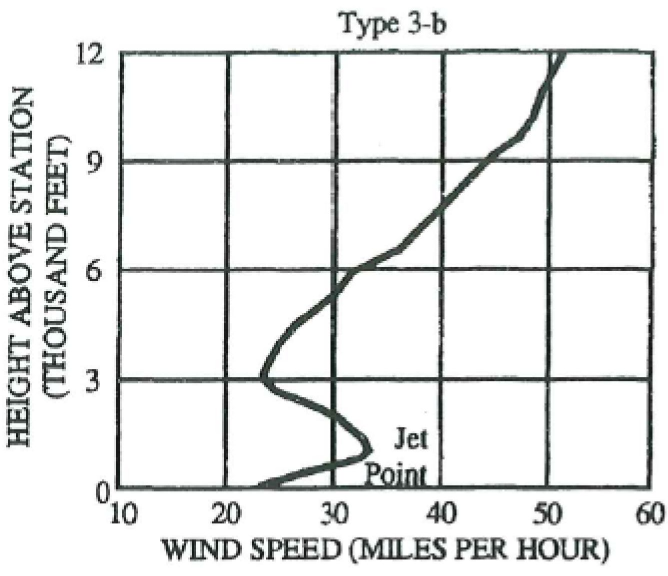


Figure 6. Byram's type 3-b wind profile.

In Figure 5 Byram shows profiles from a set of dangerous US fires. The decline in wind speed with height above the fire is significant. The "critical wind speed zone" close to the fire allows the power of the wind to exceed the power of the fire and change the fire's behaviour. Figure 6 shows a stylised profile involving a low level jet. Where rugged terrain carries a fire up into the jet, the profiles in Figure 5 result instead.

Unfortunately this sort of data in Australia will often be around 12 hours old when the fire escalates, and may be from a station hundreds of kilometres away from the fire.

The Lifted Index

The Lifted Index is a commonly used measure of the likelihood of thunderstorm formation. It is the difference between the temperature at 500hPa (5580m) and the expected temperature of a parcel of air adiabatically lifted up from the ground. If the latter is the higher temperature the LI will be negative. The more negative, the greater the assessed instability.

The LI is developed for thunderstorm formation. For fires there needs to be an assumption that there is sufficient low-level instability for the plume to reach the 500hPa level. If the plume cannot punch through low-level inversion then the LI will be irrelevant.

The Haines Index

The Haines Index (HI) is a measure of both instability and the dryness of the middle-level air. Unlike the LI, HI does not consider lifted surface air, it looks at the environmental profile of the atmosphere. There were three forms of HI developed for the continental US, reflecting the complexity of the Rocky Mountains. The middle-level HI was adopted in Australia.

HI looks at

(a) a measure of the dryness of air somewhat above the terrain, from the difference between the temperature and the dew point at 850hPa (1450m). Dry air at this level can be readily mixed down by thermal turbulence and cause problems for fires.

(b) a measure of the steepness of the environmental lapse rate for middle level air, from the temperature difference between 850hPa and 700hPa (3010m). A rapidly cooling ELR ensures the instability necessary for fire escalation.

Both are given as score of 1, 2 or 3, and the two scores added to give the HI.

A DP depression over 12° scores 3, between 6° and 12° scores 2 and under 6° scores 1. A temperature gradient over 10° scores 3, between 6° and 10° scores 2 and under 6° scores 1.

The resulting HI is interpreted as:

6 = High fire growth potential
5 = Medium fire growth potential
4 = Low fire growth potential
3 or less = Very low fire growth potential

Unfortunately in Australian mid-summer conditions HI is often at 6 and, while it picks up most days of elevated FDI, it does not discriminate the worst days.

To address this Mills and McCaw (2010) developed the Continuous Haines Index (CH).

CH looks at the same two features of the atmospheric profile, but treats them as continuous functions rather than assigning them to classes.

The DP depression is divided by three, reduced by one, prevented from exceeding nine and rescaled if it falls below five. The temperature gradient is halved and reduced by two. The two are added together to give the CH value, which can go over 13 in extreme cases.

Interpretation of CH relies on knowing the climatology of the local area. Dangerous conditions are high percentile values, with the nature of those dangerous conditions reflecting the known fire history of the area. If the local percentiles are unknown the higher the CH the higher the relative risk of dangerous fire conditions.

Pressure Charts

In standard mean sea level (MSL) pressure charts it is possible to detect the approach of trough lines and cold fronts. In general terms, tight changes in direction of isobars indicate situations in which air may find it easier to rise than to turn. Pre-frontal troughs are the most dangerous, as they do not necessarily have a moist air mass immediately following.

Satellite Imagery

In satellite imagery it is possible to follow the approach of systems that indicate instability. It must be remembered that satellite imagery processing and delivery typically takes a minimum of one hour.

Other notes

Some extreme fires have rapidly escalated away from a minor starting point. For example, the Bendora Fire in the ACT suffered a breakaway from a two-day old containment line early in the afternoon of 18 January 2003. Within three hours this had become one of the most intense fire events ever recorded in detail. A similar escalation happened at about the same time to the north on the western edge of the Mcintyres Hut Fire in NSW. A common element in both cases was the presence of a large tract of recently burnt ground immediately adjacent. On a sunny day burnt, blackened ground can easily be ten degrees warmer than unburnt ground. This added heat may be sufficient to overcome the near-surface inversion early in the day and permit convection to occur. Thus burnt ground may facilitate formation of vigorous convection and aid in the escalation process.

NOCTURNAL DEVELOPMENT

One of the most important aspects of extreme fire development is that it often occurs at night. While overnight FDIs may be quite elevated, it appears that a weather discontniuity may suffice. Examples are illustrative:

- Tharwa, ACT: On the night of the 17th January 2003 an extreme fire developed between Tharwa and Corin Dam. 26,000 ha burnt between 10pm and midnight. Potential causes include a subsidence inversion, a foehn-like wind event and a low-level jet.

- Pilliga Scrub fire, NSW, of 29th November 2006: Two mainly wind-driven fires burning in relatively flat terrain were hit by an overnight wind change, from SW to SE. When their left flanks became the headfires approximately 100,000 ha burnt.

- The Beechworth Complex, Black Saturday. As the wind change and its precedent weather moved across Victoria a number of fires escalated into extreme fires. The relative timing of this reflected the progress of the weather change. While fires such as Kilmore Gap and Murrindindi escalated at the diurnal peak, the Beechworth complex became extreme from midnight until 2am on Sunday 8th February 2009 (see Figure 7).

International research is underway into these processes. The important message is that the worst fire behaviour may not necessarily coincide with maxima in temperature or wind speed or with the minimum in relative humidity.

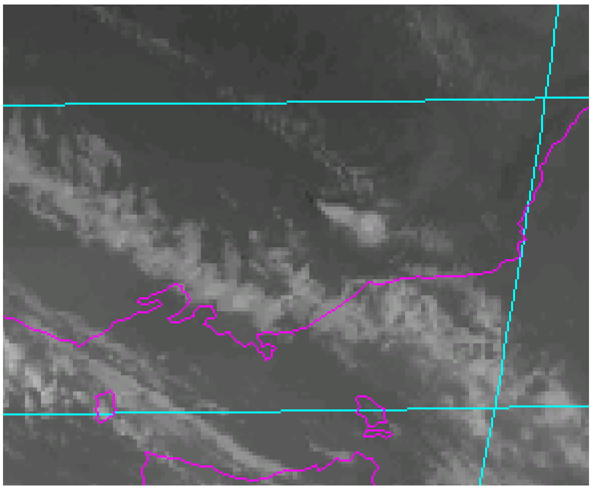


Figure 7. An infrared satellite image of the Beechworth Complex escalating, 1:30am AEDST, 8th Feburary, 2009. [Image: BoM]

During a nocturnal event intelligence gathering is seriously impeded:

- Most fire aircraft are on visual flight rules.
- There may be safety issues for observers operating on the ground. Safe egress options are harder to establish in the dark.
- Operations officers are limited in their ability to report on the smoke plume's behaviour.
- Visual satellite imagery is not available.

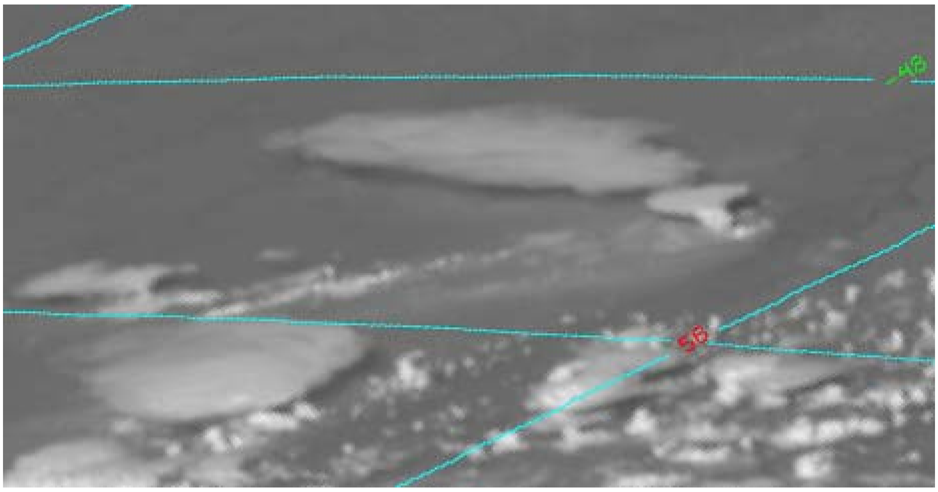


Figure 8. An oblique visual-band satellite view of the formation of a pyro-Cb, east of Moscow, 12:30UTC 26 July, 2010. This plume is 12km in diameter at its base and 15km tall. Its anvil is 45km wide. The previous plume, seen moving downwind to the upper left, is 70km wide and 170km long. This is about 80% of the way through its development.

PLUME BEHAVIOUR

Plume Spread

Studies of violent pyro-convection takes three forms: remote sensing, photogrammetry and numerical modelling.

An example of the first is the Canberra Fires.

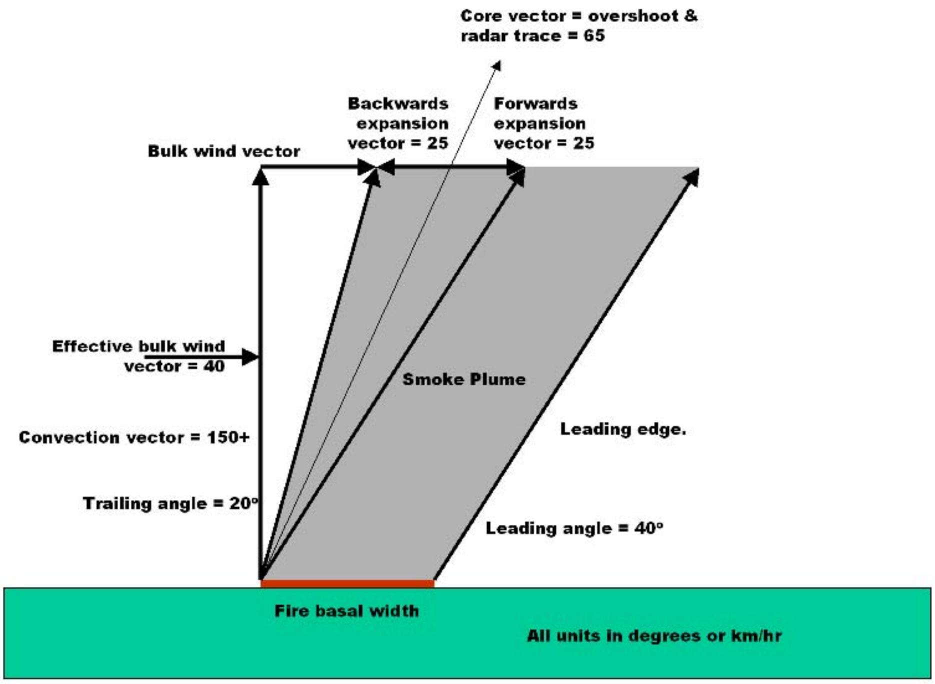


Figure 9. Extreme plume geometry.

In Figure 9 we see a summary of the air flow vectors deduced from photography. To the left of the plume we can see an upward vector of 150km/hr due to the convection, and a lateral wind flow vector of 40 km/hr. These combine to give a trailing angle of about 20˚. This is the face of the back of the plume against which the rest of the expanding plume is pushing as it rises. Weather radar data clearly shows that the core of this is travelling downwind at 65 km/hr, meaning that the expansion around the convective core is 25 km/hr. These deductions are in general accord with the numerical modelling of Cunningham and Reeder, 2009.

Fire Behaviour

Figure 10. Fire near Holder - still from video [Image: Graham Plumb, ACTESB].

An easy analog of this is to imagine that the plume is a concrete block, being pushed along by the winds aloft. The direction and speed of the fire across the landscape is set by the winds aloft. The only other control on the process is that there needs to be enough heat injected by the fire underneath to keep the plume resisting mixing up to the cloud base.

Figure 11. Reconstruction from a series of video stills.

The footprint of this activity is properly called the fire envelope. Within that there will be a wide range of actual fire behaviour occurring. Much of the landscape will be ignited by spotfires caused by the embers circulating within the plume.

Figure 10 shows a still from a video taken from an operational vehicle in the Canberra suburb of Holder on the 18th January 2003. Over 30 houses were lost in this area. Figure 11 shows a reconstruction from a series of stills of that locality from the video.

Photogrammetry indicates, based on the known height of the pine trees, that the spotfires were reaching a flame height of over 60m with effectively vertical flames.

Figure 12 gives some insight into how the landscape ignited. The dark grey areas are those that ultimately burnt. Within the clear polygons, the black areas are seen to be spotfires from the video. The implication of this is that the traditional notion of a headfire was not involved in these events.

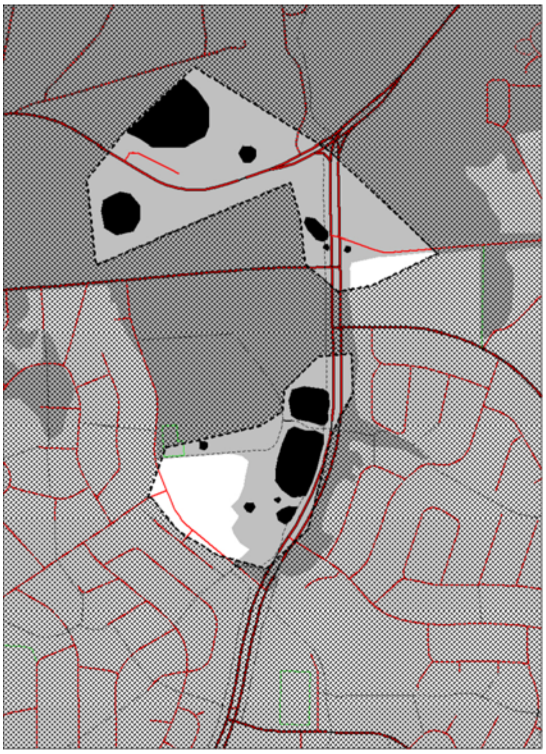


Figure 12. Map of the north end of Streeton Drive, Holder.

Within the envelope some spotfires will become large and exhibit headfire behaviour. While this will be locally important it may have little bearing on the overall picture.

Cb

Figure 13 shows a sketch of the thunderstorm that typically forms inside an event like this above the cloud base. The enormous energy released and the significant quantities of water created from burning biomass permit a thunderstorm, called a cumulonimbus or shortened to Cb, to form. These pyro-Cbs are very distinctive and occupy thousands of cubic kilometres of the atmosphere. They last for up to two hours. It is important to note that they can bring into the mix on the fireground all of the elements of a "normal" Cb – downbursts, hail, tornadoes, lightning and even lightning ignitions.

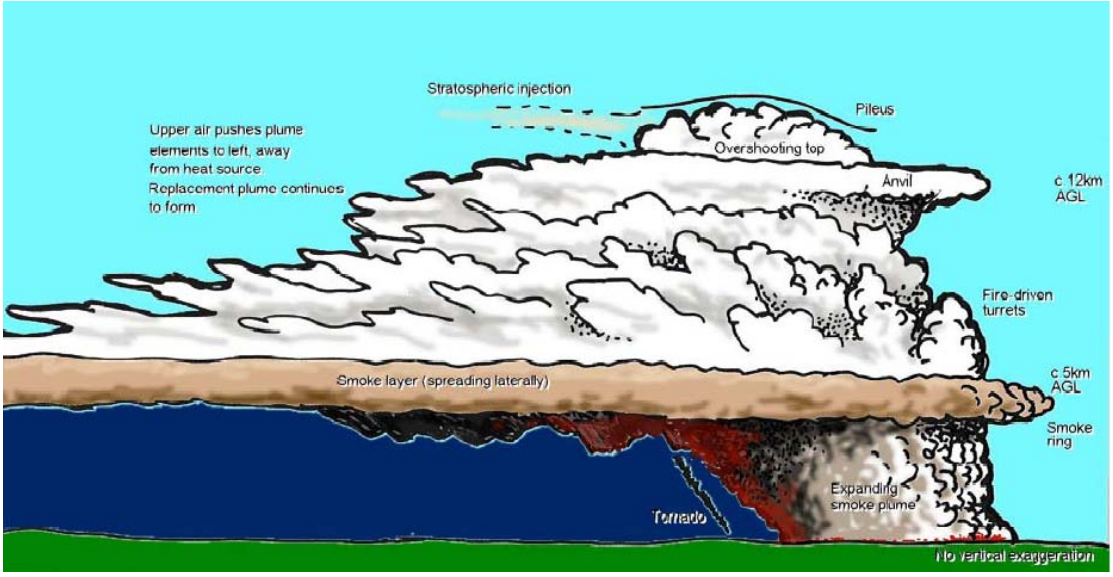


Figure 13. Schematic cross-section of the pyro-convection.

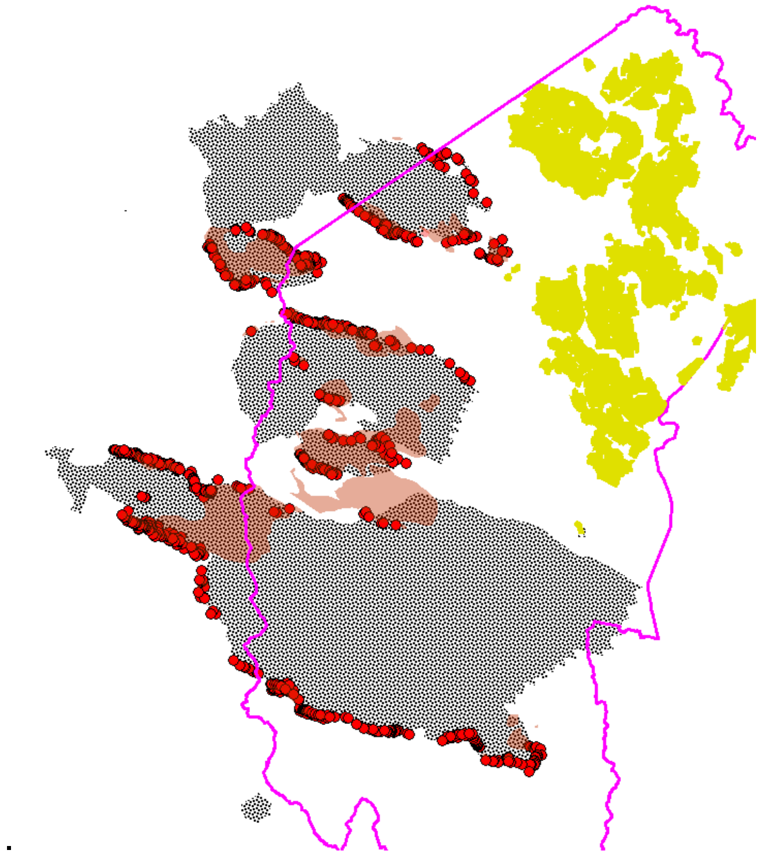


Figure 14. Ember storms.

Ember Storm

Figure 14 shows interpretation of a series of multispectral linescans from the afternoon of the 18th January 2003 in ACT and NSW. The ACT – NSW border is shown in magenta, and built-up areas of Canberra and Queanbeyan are shown in green. Areas burnt at the time of overflight are black stippled. The red dots are identifiable discrete spotfires, while the orange polygons are inferred ember storms.

Much of the ember storm and spotfire activity is linked with areas where forced channelling has dominated fire behaviour.

Figure 15. Horizontal sheet of embers being pushed by obvious strong winds out of the pines into Duffy. [Images: WinTV]

Figure 16. A suburban nature strip generating new embers, which are heading into the suburb.

Figure 15 shows a still from WinTV news footage taken in the ACT Fire Brigade Commander's vehicle on 18 January 2003. At the time there was catastrophic fire danger in place and very strong winds, blowing from the image's left to right. A layer to about one metre off the ground is filled with embers. Figure 16 shows new embers being added to this flow from a nature strip. The embers are following airflow streamlines, hitting things and bouncing off them or being caught and setting them alight. Some types of fluid flow like this generate static electricity in the entrained particles. If this is the case then the electric field on the pyro-Cb overhead would have a huge effect of the flow.

The attack of such an ember flow on structures is outside the scope of current building standards. Research is planned into this phenomenon.

Air Flow

Figure 17 shows a simplfied interpretation of the air flow in and around the 2003 pyroCb. There are a number of processes going on, reflecting the energy inputs from the fire and the plume and the conservation of mass.

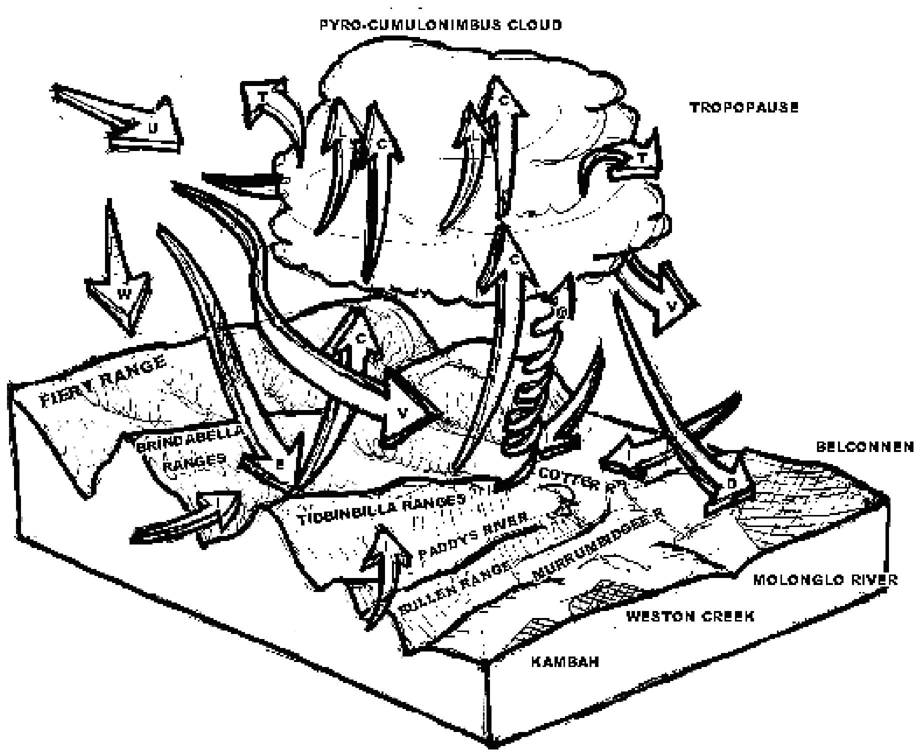


Figure 17. Air Flow around a pyro-Cb.

In Figure 17 the following codes are used:

W = bulk wind flow; U = upper winds; I = Lateral inflow; C = Convection from the fire; E = Entrained upper air; V = Diverted upper air (around convection coulmn); L = Latent heat of condensation; T = Tropopause inversion; D = Downburst.

At any point relative to the convective core the local winds will be the additive result of a number of these processes. A key point to remember is that the convective core is being pushed downwind. Thus, as experienced by most witnesses to these events, there will be major fluctuations on the local winds with time. Compare Figure 10 with Figure 15, taken at similar locations and times.

THREATS

The traditional approach to assessing the threats from fires use predictions of fire behaviour applied to the concept of a modified elliptical fire footprint.

When an extreme fire occurs this approach should not be used, because:

- The intelligence on the fire's location will be insufficient
- The weather driving the fire at any point will be poorly known
- The fire has become a coupled fire-atmosphere event, driven by factors not included in any fire spread model suitable for operational use.

It is possible to model an extreme fire. This has been done for the Chisholm Fire and the Canberra Fire. This is done using a three-dimensional computational fluid dynamics model – the same system used to design aircraft and F1 racing cars.

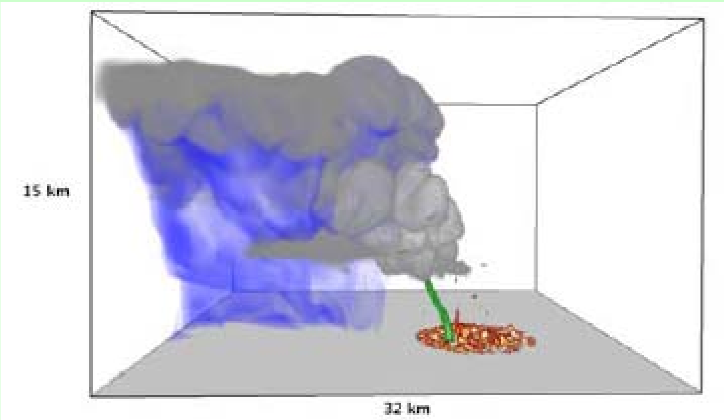


Figure 18. Reconstruction of the Canberra plume.

Figure 18 shows the output from a model of the Canberra Plume, from Cunningham and Reeder, 2009. Note that the simplistic fire used as the primary heat source leads to most of the features seen in the actual plume.

Analysis of satellite imagery taken after extreme fires shows a fairly consistent footprint of maximum impact. The representative dimensions of this footprint are 20km downwind and 15km cross-wind.

The recommended technique for threat assessment from an extreme fire is:

1. Identify each point from which extreme fire is developing.
2. Assess the middle-level winds.
3. From each point place a rectangle based on the representative footprint, aligned with the middle level wind and with the point midway across the upwind edge.

Given that an event such as this will normally last little more than two hours, there will not be enough time to generate a more refined threat analysis.

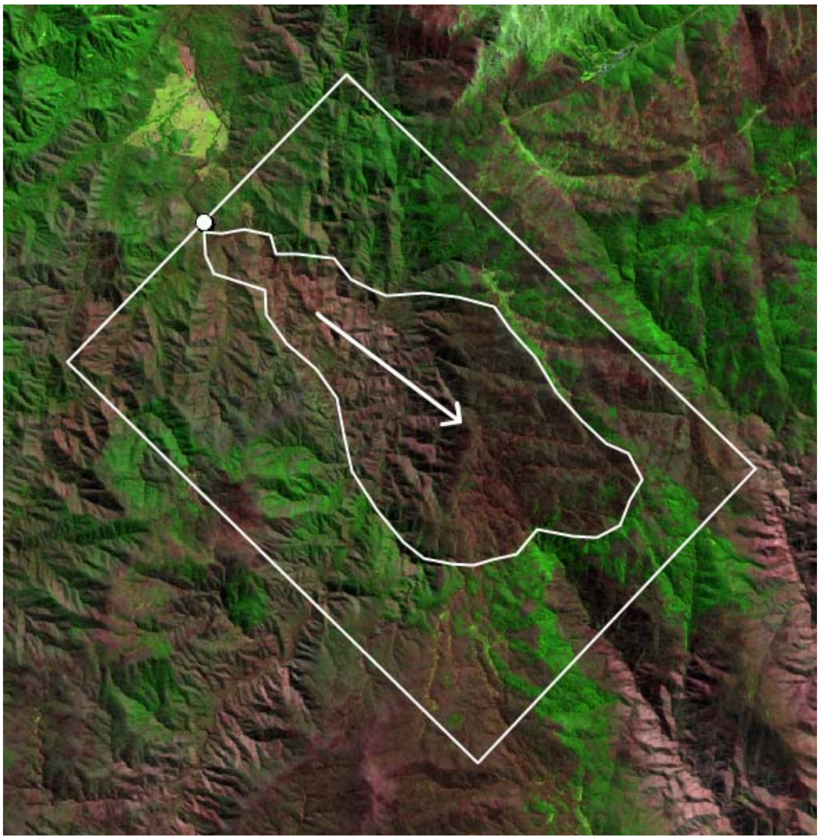


Figure 19. Threat footprint for extreme fire event, Tom Groggin, 26th January 2003. [Image: LandSat, USGS]

This footprint could be used as a primary input parameter for activation of the bushfire warning system.

Afterwards the fire will decay into a series of fires of large or very large scale. These need to be identified and their likely future spread analysed to generate new threat maps.

PREDICTION

At present we have little skill, nationally, for predicting the conditions conducive to an extreme fire developing. The material discussed below, under detection by a Situation Unit Analyst, is where this capability will come from. That material is oriented around a 2 to 6 hours window, but we need to be at least one shift ahead for a true prediction to be made.

At present the best guidance is an indication of the likelihoods of the possible transitions given the present state, defined by Fire Danger Rating and the largest scale-class of fire present on the landscape. An example is given below.

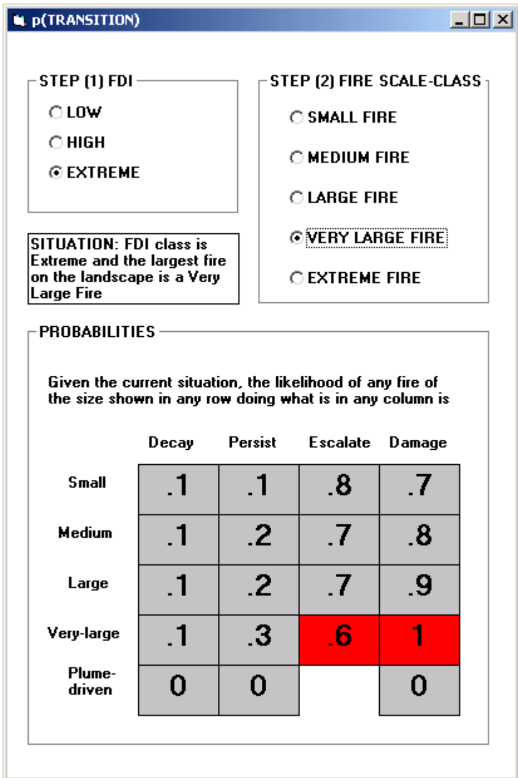
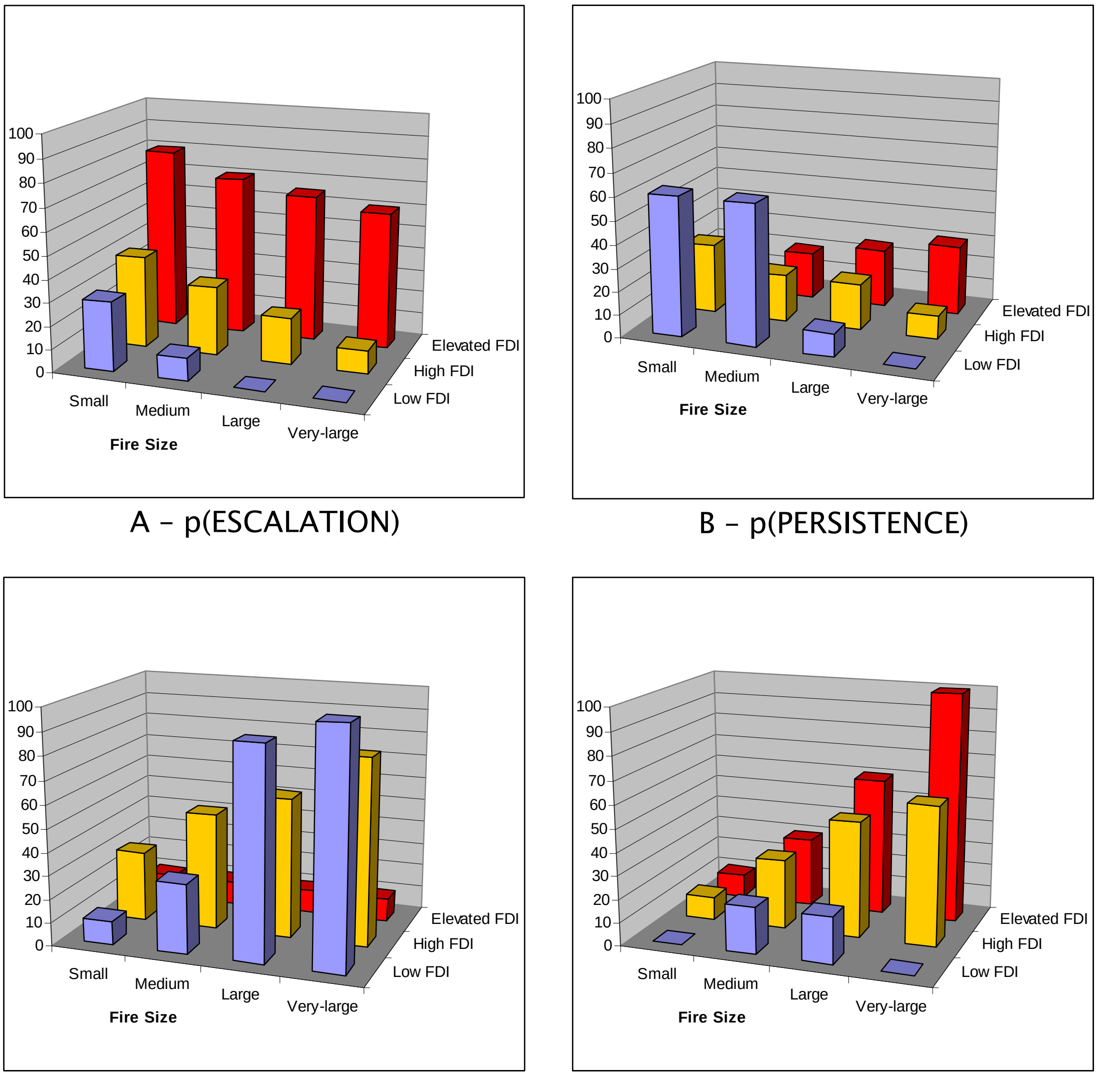


Figure 20. A sample screen from the TRANSITN.EXE program, showing estimated default transition probabilities.

Here, for the duration of the current shift, there is an assessment of a 60% chance of escalation, 30% chance of persistence at the current scale, and a 10% chance of decay. It is also assessed that there is a 100% chance of damage.

If the likelihood of escalation to an extreme fire is over, say, 20%, then a prudent IMT will put significant effort into preparing incident objectives for the protection of life should that escalation occur.



A – p(ESCALATION)

B – p(PERSISTENCE)

C – p(DECAY)

D – p(DAMAGE)

Figure 21. Graphs showing default transition and damage probabilities for a landscape that has a very large fire on it. The left-right axis is the size class of the fire being considered. The axis away from the observer is the fire danger range for the current sift. The vertical axis is probability. A is the probability of escalation, B is the prbability of persistence, C is the probability of decay, and D is the probability of damage.

In Figure 21 we can see that if we have a very large fire on a landscape, and that is the largest fire size present, and if we have a high fire danger, then during this shift we have a 10% chance of escalation, a 10% chance of persistence and an 80% chance of decay. There is a 60% chance of damage occuring. If there is elevated fire danger, then those probabilities are as seen in Figure 20. The guidance for IMTs is clearly quite different.

This is a default guidance only, and should be varies on the basis of knowledge of the incident. Note also the TRANSITN.EXE is adapted for use in rugged terrain. No equivalent is available yet for other terrain types.

DETECTION

Detecting an extreme fire is a challenge. In large part this reflects the size of such an event and the tendency for observers to move close in “to get a better look”. If the plume is to reach to 12 km above the ground, then an observer needs to be at least that far off to the side to see it properly.

This section should be read in conjunction with the handbook “Checklist for Fire Observers” and the chart “The Smoke-Spotters Guide”. Much of that material concerns the precursors of an extreme fire. This section will refer only to the confirmation of an extreme fire event.

Air Observers

The general appearance and geometry of the plume is what is being examined. The formation of a thunderstorm within the plume is diagnostic for an extreme fire and does not require verification. However the observer needs to be sure that it is a pyro-Cb not a towering pyro-Cu. An anvil or an overshooting top will suffice They also need to distinguish a thunderstorm approaching the plume from elsewhere. Another feature that may be visible is sheet smoke, but to be diagnostic it must be in the very high height range. (It may be difficult to distinguish between “high” and “very high” height ranges.)

The most efficient places for aerial detection are more than 5km away, to the left, right or rear of the main fire activity. As these locations do not assist with most goals of air observers, dedicated forays are essential.

In very windy conditions the plume from a developing extreme fire may travel a considerable distance downwind before it can reach the LCL and form a pyro-Cb. In such cases considerable care is needed to conclude that an extreme fire is forming. The main feature to look for is the cauliflower texture of the plume, as it pushes outwards against the surrounding as air as it rises towards the LCL.

The use of airborne remote sensing has been the single greatest benefit to understanding extreme fires. Thermal or multispectral linescanners provide the most useful information, as long as processing and delivery do not delay the data reaching the Situation Unit. FLIR pods are increasingly being used, but there is little experience in interpreting their output during extreme fires.

Smaller aircraft are buffeted by turbulence or lofted debris, and their pilots frequently decide that it is unsafe to fly close to the fires or plumes.

Larger, usually pressurised aircraft can work above these threats and this height gives them an improved overview, which is most important for intelligence gathering.

Ground Observers

If a ground observer is on the fire ground they will not be able to directly observe an extreme fire developing. Some features will be diagnostic if observed:

- lightning
- tornadoes
- hail

Other features are suggestive and require verification:

- A very dark, reddened sky in the afternoon.
- Very dense spot fire formation.
- The features of fire channelling.
- Fire balls or other unusual combustion phenomena.

The ground observer's main priority after seeing any of these features is, however, safety.

Of note are the indicative conditions given by Byram (1954).

> If a towerman or plane observer viewing a fire from a distance and at right angles to the wind reports that the smoke column tends to curve upward and become nearly vertical in its upper parts, the wind speed is undoubtedly decreasing with height. Such a fire could become dangerous if it burns into heavy fuel. If smoke column has started to "boil" or mushroom up, trouble has probably already happened on this particular fire, although its behavior is less serious if the towering smoke column is caused by a run upslope.

Situation Unit Analysts

The Situation Unit Analyst can examine a number of intelligence sources, including:

- Field reports, for key words or phrases suggesting the features listed above for field observers.
- BoM Weather Watch radar data, which picks up the moisture in the plume.
- Lightning detection system data, from sources as arranged by their agency.

- Satellite imagery, which shows plumes developing, but also suffers from elongated lag-times, which may be of little value for an IMT.

- Looking out the window – most of these events are so large that they are visible from quite some distance.

- Water vapour satellite imagery, which is a key precursor.

- Dynamic maps of FDI across that region, available from BoM data or from value-add sources (such as WeatherZone).

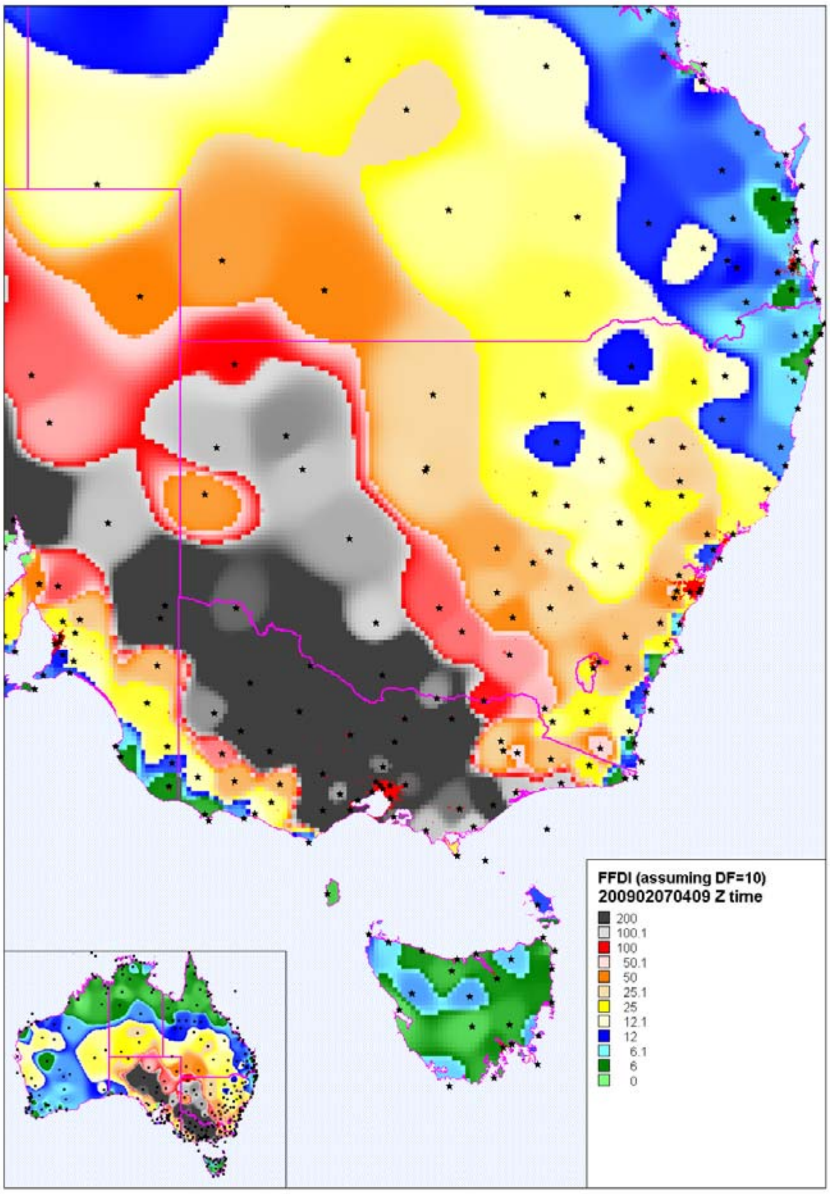


Figure 22. Map of FDI for 3:09pm AEDST on Black Saturday.

This table is designed to assist Situation Unit staff working in Control Centres. It lists key indicators and the sources from which they can be deduced. Key observations are suggested where possible. Analysts are required to use time-series data to extrapolate forward to give arrival times estimates.

Type	Indicator	Key Observations
FIRE WEATHER FORECAST		
	Fire Danger Rating	Elevated FDR is a pre-requisite
	Thunderstorm	Stability conducive to storms can promote violent pyro-convection
	Diurnal Weather Cycle	Maxima & Minima today & tomorrow / Graphical Fire Weather Explorer if available
WARNINGS		
	Fire Weather Warning	
	Damaging Wind Warning	
	Severe Thunderstorm Warning	
OBSERVATIONS (mostly from www.bom.gov.au)		
1) Automatic Weather Station Data		
	Subsidence Inversion	Major DP fall for stations above certain altitude (usually c.1500m). Rising MSLP.
	Low-Level Jet	Major DP fall for stations above certain altitude; elevated WSp. Elevated MSLP.
	Foehn Event	Downwind of ranges: (i) fall in DP; (ii) rise in T; and/or (iii) enhanced WSp.
	Wind Change	Progressive changes in WDir across region, often reflecting forecast.
	Thunderstorm	Erratic winds, rapid rainfall, drop in T.
	Rain	Increments in rain since 9am.
2) Radar		
	Plumes	Elongated return, oriented with WDir, stationary upwind edge (not diagnostic, could also be cloud).
	Wind Change	Either rapid swing in smoke plume or visible wall of lofted detritus on a seabreeze front.
	Thunderstorm	Distinctive rain-return footprint, synchronised movement of returns across radar.

3) Visible Satellite Imagery		
	Cold Front	Large, structured, southerly cloud band moving in a synchronised manner from west to east. Often includes Cb.
	Sea Breeze	Stratiform cloud mass progressively expanding inland from coast. Minor or no shadows even at low sun angles.
	Wind Wave Clouds	Elliptical clouds with smooth but diffuse edge (Lenticularis), aligned parallel to main ranges. Large shadows. Often stationary for hours.
		Bands of Cu aligned parallel to main ranges. Some shadows. Often stationary for hours.
	Pyro-Cb	Isolated large, tall cloud in area of fire activity. Lasts for 2 to 3 hours. (Cross-ref to other sources.)
	Foehn Wall	Downwind edge of cloud mass coincides with top of main range aligned across wind.
	Wind Change	Smoke plume swings around.
4) Infra-Red Imagery		
	Thunderstorms	Large, rounded white cloud-tops, either scattered or arranged in bands.
	Foehn Arch	Sharp upwind edge aligned with major terrain features, large, white, uniform cloud mass. Upwind edge may be stationary.
	Surface Thermal Anomalies	Enhanced black over cloud-free parts of the terrain prone to foehn effects.
		Reduced black over cloud-free parts of the terrain prone to sea breezes.
5) Water Vapour Imagery		
	Abrupt Surface Dryings	Elongated Dry Slots moving west to east
		“Bow Waves” ahead of sea breeze fronts
		Wind Wave features downwind of major terrain features (stationary).

6) MSL Analysis	
Thunderstorms	Approaching trough or cold front.
Foehn Event	Foehn nose ahead of approaching cold-front.
Subsidence Inversion	Established, stationary high pressure cell, elevated thickness.
Sea Breeze	Pressure gradient: coast higher than inland.
7) MODIS Imagery (NASA GSFC)	
Fire	Hotspots from Sentinel or University of Maryland
Thunderstorms, Foehn Clouds, Wave Clouds	Near-real time subsets, RapidFire (GSFC).

REACTION

If an extreme fire is detected or suspected it is important that an appropriate and timely set of responses occurs. This involves:

- Consideration of the need for verification
- Issuing of indicated watch-outs or red flag alerts
- Having the Incident Management Team revisit or revise the current Incident Action Plan, as required.

Extreme fires evolve rapidly and cause major escalation of threat to fire crews, the public and property.

Verification

It is an axiom of decision-making that the more important the decision, the better-informed the decision maker needs to be. Countering this, we have the information vacuum that frequently surrounds escalating fires. These two principles act to impede or prevent the sort of decision making that would mitigate fast-evolving threats.

Here we seek to make an information flow channel that includes the following:

- An observer, in the field or airborne, who is trained in recognising the features or precursors of an extreme fire.
  OR
  An analyst using remote sensing data sources, who is trained in recognising the features or precursors of an extreme fire.
- A recipient of that observation or analysis, in the Situation Unit of the Planning Section, who is in a position to trust that message and is trained in interpreting the features or precursors of an extreme fire. This includes the issuing of watchouts or red flag alerts.
- An IMT able to trust the material and trained in reacting to extreme fire related watchouts and red flag alerts.

Our concern is that, if forced channelling takes control of a corner of a fire upwind of crews, then we avoid conversations like this…

> "Control, this is Firebird 123. I'm reporting a forced channelling event making the fire dangerous upwind of Sector Mike, over."
>
> "Firebird 123 this is Control. What the hell did you just say?"

We need to reach a skill level where this is what happens…

> "Control, this is Firebird 123. I'm reporting a forced channelling event making the fire dangerous upwind of Sector Mike, over."
>
> "Firebrid 123 this is Control. Can you confirm an actual watch-out? over"
>
> "Affirmative, but based on what I'm seeing I'd also like to suggest a red flag for Sector Mike, over."
>
> "Received a red flag for Sector Mike, and will advise Incident Controller and Mike Leader of need for urgent action. Thanks. Out to you…."

Watchouts - Red Flags

It is best to consider two levels of alert to encapsulate the complexities of threat that may arise from escalating fires. A set of Watchouts has been developed to augment those already widely used to help fire crews stay safe – see Table 1. A set of Red Flag Warnings has also been developed to aid IMTs in ensuring timely, appropriate reactions – see Table 2.

Table 1. Recommended relevant Watchouts

1) Hot fire on lee-side of hill, lee wind field full of smoke 2) Fire flank follows dog-leg around lee-slope 3) Upwind edge of fire locked into break in slope 4) Dense "orange" plume of smoke on upwind corner of fire, at top of a lee slope 5) Fire jetting out of lee-slope eddy away from main fire 6) Intense spotting on fire flank 7) Lenticularis cloud in area 8) Parallel bands of clouds, transverse to prevailing wind direction 9) Geostationary clouds (forming on leading edge, decaying on trailing edge) 10) Foehn Wall behind ranges 11) Foehn Arch towards coast 12) Low-level clouds & smoke moving much faster than indicated by surface wind speed 13) Cloud Forms in convection column 14) Cloud forms while convection column still resisting mixing. 15) Cloud in convection column collapses 16) Cloud in convection column attains cauliflower texture	17) Cloud in convection column forms an anvil 18) Flank becomes headfire 19) Two convection columns converge 20) Convection column changes direction as it rises 21) Thunderstorm(s) approach fire 22) Tornado (attached to base of cloud) 23) Fire whirl (attached to ground) 24) Sudden non-diurnal rise in temperature and fall in DP 25) Fall in DP in second half of night at high altitudes 26) Sudden non-diurnal fall in DP mid-afternoon 27) Sudden non-diurnal fall in DP ahead of sea-breeze front 28) Clear night, continental air mass 29) Non-diurnal overnight escalation of fire behaviour, not linked to wind 30) Burnt area reburns as a crown fire or similar 31) Fire continues to accelerate up a canyon or gully 32) Elongated flames stay underneath canopy on steep slope 33) Ember storm

Table 2.

RED FLAG CONDITIONS		
Cause	**Implications**	**Recommended reactions**
1) Plume-driven fire observed or detected.	Extreme fire.	[A] Immediately set incident objectives to saving life and, if safe to do so, property.
2) Conditions conducive to plume-driven fire forecast.	Possibility of extreme fire forming.	[C] Ensure safety focus on all sectors. Set up observation capability. Develop fall-back IAP.
3) Passage of dry slot over fire forecast or detected.	Potential for violent escalation of fire.	[C] Ensure safety focus on all sectors. Set up observation capability. Develop fall-back IAP.
4) Thunder-storm approach observed, detected, or forecast.	Possibility of erratic fire behaviour with downbursts, etc.	[B] Immediately withdraw all resources from relevant sectors. Review incident objectives.
5) Wind change forecast, detected or observed	Wind changes can turn a flank into – longer – headfire, endangering crews working on direct suppression.	[B] Immediately withdraw all resources from relevant sectors. Review incident objectives.
6) Channelling event detected or forecast.	Dangerous fire behaviour around and downwind.	[B] Immediately withdraw all resources from relevant sectors. Review incident objectives.
7) Dew point depression event detected, observed or forecast.	Dangerous fire behaviour in areas affected.	[C] Review IAP, based on escalation of FFDI.
8) Foehn wind forecast or detected.	Localised dangerous conditions may occur.	[C] Ensure safety focus on all sectors. Develop fall-back IAP.
9) Unusual combustion observed.	Localised dangerous conditions may occur.	[C] Ensure safety focus on all sectors. Develop fall-back IAP.
10) Intense spotting observed.	Likelihood of a channelling event underway.	[B] Immediately withdraw all resources from relevant sectors.

		Review incident objectives.

Incident Management Team

In Table 2 the following codes are used for the urgency of the response:

[A] An extreme fire has occurred. This has an absolute priority, abandon all other actions;

[B] An extreme fire could occur soon. This is the highest priority, review urgency by sector and act immediately if required;

[C] Precursors of an extreme fire have occured. There is a high priority for review of safety in all sectors, and ensuring IAP options are developed on a just-in-case basis.

Some more detail on the first Red Flag is illuminating.

PLUME-DRIVEN FIRE DETECTED:

Detection requirements:

- Observers on ground in either cross-wind quadrant, >5km from fire, tasked to look for cloud formation before mixing starts within plume, and make a report to Situation Unit if a development occurs.
- Aerial observers tasked to assess and make a report to Situation Unit on plume dynamics every half hour.
- Situation Unit staff monitoring BoM radar for active returns above fire ground.
- A violent pyro-convection watchout is received from the field.

Required reaction - [A] absolute priority, abandon all other actions:

- Situation Unit staff advising Planning Officer of *potential* Red Flag situation and seeking a second source of intel as confirmation before advising on *actual* Red Flag situation. PO to immediately discuss with IMT.
- On confirmation the PO is to immediately meet with the IMT and declare the current IAP suspended and switch the Incident Objective to protecting life and, if it is safe to do so, property.
- It is essential that no backburns be lit, as these add to the event.

MONITORING

There is value from monitoring the large-scale evolution of an event once it is underway. Monitoring should aim to detect variance from expectations. The following may provide insight into potential changes of threat levels during the event:

- Pyro-Cb moves downwind without replacement: this indicates decay of event. If the fire is still extreme a replacement pyro-Cb would already be forming.

- Lightning detected: this indicates the mature phase of the pyro-Cb has been reached. New ignitions may occur. Pyro-Cb follow a similar life-cycle to normal Cbs.

- Radar returns move sideways with respect to wind: this indicates a severe channelling-driven escalation is underway. It is important to remember that events do not necessarily progress downwind.

- Radar returns ease: this indicates decay of the event, but secondary escalation may yet happen. It could indicate a lower moisture content in the plume.

- Plume moves in unexpected direction: this indicates that the best available Aerological Diagram does not represent the weather affecting the fire. Field observations are essential.

IMPACT

The range of potential impacts of an extreme fire is complex. They are, perhaps, best illustrated by discussion if what may happen when an extreme fire approaches.

From the point of view of an object under threat:

Iniitally the prevailling weather will be in place – largely as in the Fire Weather Forecast then in force, which will most likely be an elevated fire danger rating and rather intimidating.

- As the plume approaches, an indraught will develop, with the wind speeds dropping as this acts to counter the prevailling wind. There may be a lowering of the dew point if air is descending to feed the indraught.

- Medium-range spotfires may start across the local landscape. These will not be entrained, but will be running under the locally altered wind fields discussed above. As such they would not have their maximum potential rates of spread, but could quickly cause local damage, especially if the dew point has fallen.

- The arrival of the plume's leading edge may bring a number of possibilities. There is a likelihood of a period of low wind speeds as the plume arrives, with various flows in temporary balance. Upper winds deflected around the plume may then wrap around it and descend towards the ground in a turbulent lee flow. The plume may be pushed down onto the ground ahead of the fire, producing a marked darkening and new spotfires. There may be exotic turbulent processes: this includes fireballs and fire whirls. There may be a downdraught wind, such as is produced by a thunderstorm. This would dominate the wind field, producing a strong reversed wind flow for around ten minutes. The wind speed profile up to 10km ASL is the main determinant of what occurs. Damage patterns and level are difficult to foresee (on any timescale).

- The worst recorded features of onset involve tornadoes moving forward off burnt ground. These are large events, of up to half a kilometre basal diameter, and ignite large tracts of landscape as they move at high speed (measured at 35km/hr). Their ability to hold and circulate embers may be partially offset by their winds, which are too high to support fire spread. Wind damage is far more likely, until the next stage.

- After the onsets events, there is a period of consolidation. The terrain will be sheltered from the prevailling winds, and will be dominated by the indraught of what follows. The probably large number of spotfires will merge. They will be burning intensely, under elevated T, depressed RH and low wind speed. The landscape will be ignited in a patchwork fashion, with widespread but localised damage starting to occur.

- Behind the consolidation zone there may be the equivalent of a headfire, where the indraught and the prevailling winds coming in over burnt ground collide. Here vertical flames of 90m height have been observed in spotfires. More significantly is the new wind speed maximum blowing for a considerable distance over burning fuel. This picks up a large quantity of embers. In the right part of the plume an ember storm will form, causing considerable damage and allowing secondary embers to form in the urban environment. This drags the damage envelope into the urban area, and as it is a leapfrog type process it can persist for some hours after the plume has passed. Ember storms may flow in a turbulent manner, leading to erratic damage footprints.

- After the extreme fire event passes, the fire will usually decay into a set of large fires across the landscape. Each of these carries on-going potential to cause damage.

Some salient points of the damage potential are:

- The perspective form any given point close to events will be spectacular but limited. It will not be possible for an observer close-in to gain an overview of the event. It will not be possible to see the peak intensity approach.

- The environment will change a number of times during the passage of the event. It may be difficult for a lay observer to recognise when the peak threat has passed. The reduction in wind speed as the plume approaches may be particularly misleading.

- Damage may arise from unexpected sources.

- A number of the key events will impact the landscape in a patchwork manner.

- Damage may continue to spread into an urban environment for some hours after the plume has passed, as secondary ember storms continue to be produced.

These features need to be incorporated into planning for public warnings and for damage surveys.

PLUME DECAY

When an extreme fire develops there is a period of time within which much damage is done, people may die, and command, control, coordination and communications are degraded by the rapidly changing situation. Little is recorded from terrestrial sources to allow detailed assessment of the decay phase of an extreme fire.

Most extreme fires are recorded in a series of hourly satellite images using visible (daytime only), infrared and water vapor channels. Occasionally they are also recorded in data from more specialised satellites with longer return-times, such as Calipso and CloudSat. Importantly the high moisture content may be well resolved by any nearby weather radars, which give a ten-minute repeat cycle.

These permit the identification of some key elements of the decay phase.

Wx

Cloud imagery shows that almost all extreme fires last for around two hours and no longer than three hours, then decay. This is equivalent to the typical passage times of both trough lines and dry slots.

If it is a troughline, there may be storm cells that have formed independently of the fire, and the pyro-Cb may move off downwind with them.

Terrain

Where an extreme fire forms in rugged terrain, there is typically a strong association between the persistence of the fire and the complex interactions between terrain and weather. It is unusual for an extreme fire to move more than 5km out of rugged terrain before decaying.

Claims are often made that it is in the less daunting terrain that fuels have been managed and the fire trail network allows crews to get in and suppress the fires. Satellite imagery has shown that fires supporting pyro-Cb have rapidly decayed at the edge of rugged terrain, and it is unlikely the fire crews would have any impact in such a case.

As air masses, wind directions, fuel states and many other factors are correlated with the terrain change, it is of little value to consider causality. By whatever means it happens it is here that the protection of life and property may again become feasible.

CASE STUDIES

Australian Tier 1 pyro-Cb events:

(1) Big Desert 17 December 2002. The UTLS impact of this was detected by researchers in satellite data and later traced back to a fire event.

(2) Canberra 18 January 2003. This was the subject of a number of studies: Fromm *et al* 2006, Mitchell *et al* 2006, Dold *et al* 2005, McRae 2004, Sharples *et al.* (2012).

(3) Grampians Fire after 19 January 2006. The pyro-Cb from this fire sprayed the countryside downwind with lightning and started new fires.

(4) Wollemi 22 November 2006. With advance notice this fire was monitored through satellite data, including the CloudSat cross-section in Figure 3.

(5) Pilliga 29 November 2006. This fire grew overnight by 100,000 ha with few observations. A massive atmospheric injection merged with a dust cloud and a zone of stratiform clouds, generating considerable debate within the research community.

(6) Victorian Alpine Fires: (a) 6 December 2006

(7) Victorian Alpine Fires: (b) 14 December 2006. Smoke from this event was tracked around the globe in TOMS data.

(8) Victorian Alpine Fires: (c) 16 January 2007. This complex of slowly merging fires occasional exhibited intense convection. Operational meteorologists noted a number of lesser events, but some were clearly measurable in satellite data. It was in this series that sea-breeze fronts created pyro-Cbs away from the fires.

Australian Tier 2 pyro-Cb events:

(1) Berringa Fire 25 Feb 95. Well studied from a range of aspects, but no link to satellite data on the upper atmosphere: Chatto 1999.

(2) Victorian Alpine Fire, around 10 January 2007 - in fact there was a run of days of extreme convection and it is difficult to classify them succinctly.

There have been a number of pyro-Cb events with insufficient data for classification but which are porbably Tier 2 events, including:

(1) 10 January 2003 at Mt Cooke, WA

(2) 17 January 2003, overnight, ACT south of Canberra

(3) 23 January 2003 in Kosciuszko National Park, NSW

(4) 26 January 2003 in Victorian Alpine National Park near Omeo.

(5) 6 February 2007 at Yarrangobilly, Koscuiszko National Park, NSW.

(6) 17 December, 2009, Tinderry Nature Reserve, NSW.

Note that none of these events precedes 2002, despite the continuous global monitoring by satellite for over three decades. This is why Ash Wednesday, 1983, is not listed – it was at best a Tier 2 event.

Chisholm

The Chisholm Fire, approx 150km NNW of Edmonton, Alberta, Canada, escalated at 2300 on 28th May 2001 and formed a pyroCb at 0130 UTC on 29th May 2001, with violent pyro-convection abating at about 0500 UTC. See Figure 23.

This is the most intense event yet recorded, based on its impacts on the UTLS. Note that this does not necessarily correlate directly with "normal" fire severity parameters.

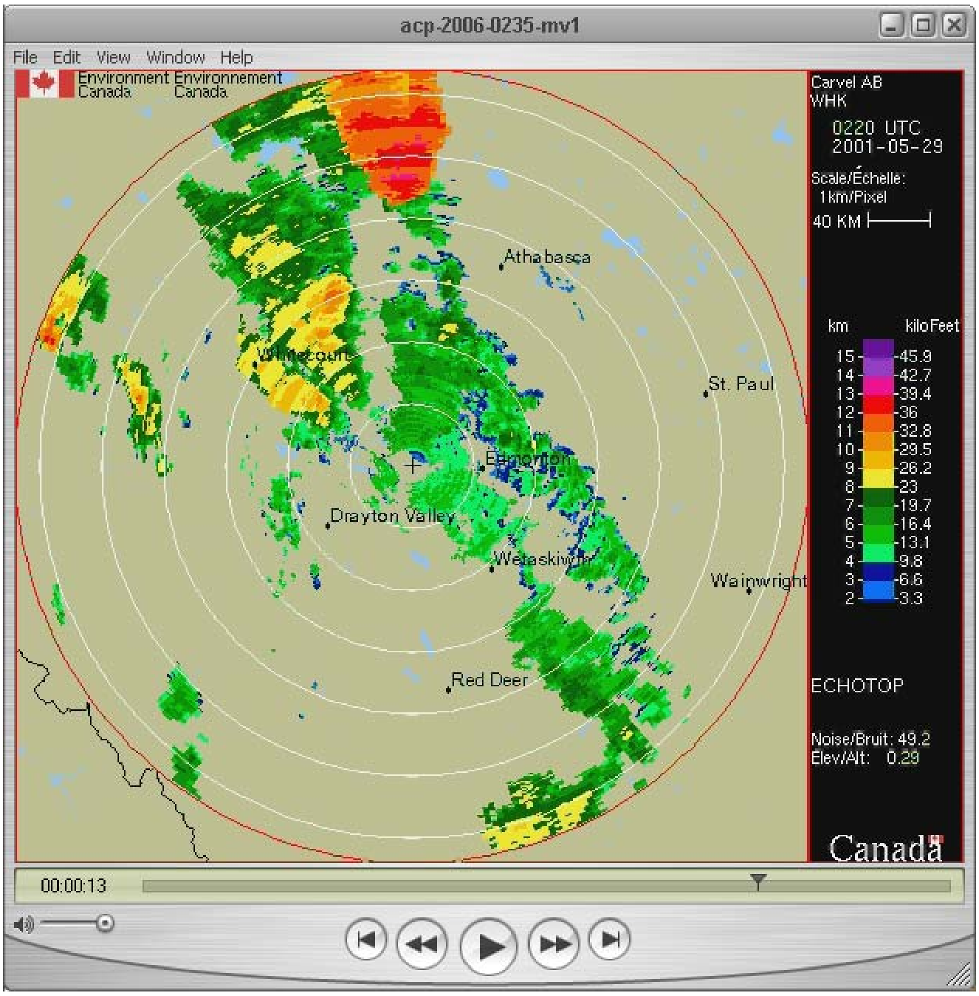


Figure 23. Radar screen of the peak formation of the Chisholm pyroCb.

Canberra

The Canberra Fires of the afternoon of the 18th January 2003 (McRae 2010) were only slightly less intense than the Chisholm Fire. After developing over 9 days, the fires broke containment lines on the afternoon of the 17th with escalating FDI. On the night of the 17th an extreme fire event burnt 26,000ha between 10pm and midnight. BoM weather data indicate that after that a foehn-like wind and a low level-jet occurred. On the afternoon of the 18th a series of extreme fire events occurred associated with the passage of a dry slot. Much of the deep flaming was driven by forced-channelling. Photographic evidence shows eruptive fire behaviour on the side of Mt Franklin and a large tornado linked to the massive pyro-Cb generated in the plume. It is important to note that most of the extreme fires rapidly grew out of small break-aways from previously held containment lines. Also there is little evidence relating to headfires – most of the considerable damage came from spotfire swarms coalescing and from ember storms. These events are now the most scientifically significant Australian fires on record.

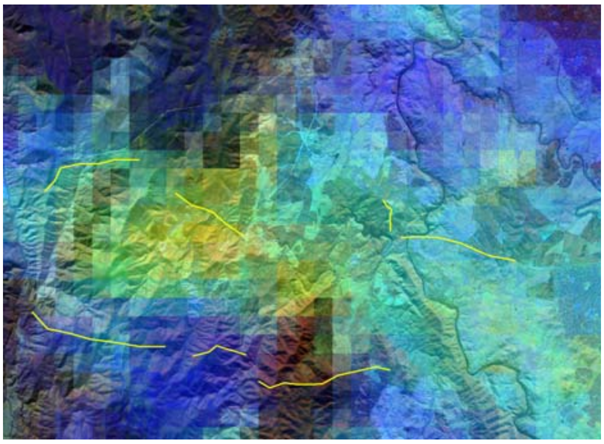


Figure 24. Radar image of the peak of the Canberra Fires over a post-fire linescan image.

Figure 25. The upwind edge of the McIntyres Hut fire, showing the top of a channelling-driven fire event (winds are from right to left). Prior to these fires there was no evidence of channelling affecting fire behaviour. [Photo: Stephen Wilkes NSWRFS]

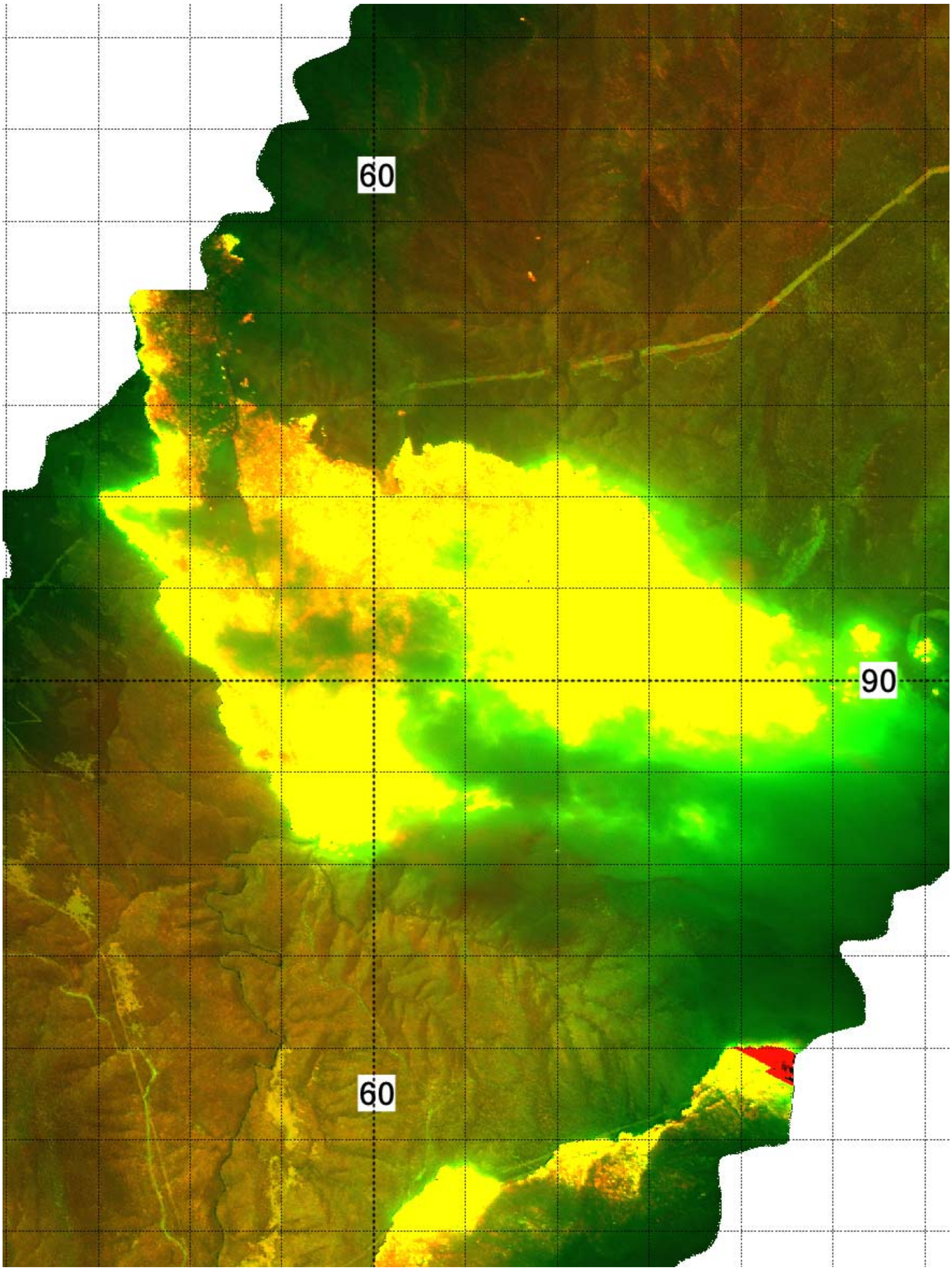


Figure 26. Extreme fire.

Figure 26shows a multispectral linescan of an extreme fire event underway. Yellow indicates the flaming zone. Note that a 1km map grid is superimposed on the image. Figure 25 was taken at grid reference 575 922.

Black Saturday

Black Saturday, 7th February 2009 was a day when a landscape with a number of fires was affected by the passage of a cold front and pre-frontal troughs which created the highest FDIs ever recorded in Australia. Many of the fires rapidly escalated into extreme fires causing massive losses of life and property. There were a number of instances of channelling-driven fire escalation.

As the weather systems passed from west to east the fires sequentially escalated, persisted as extreme fires for around two to three hours then decayed rapidly back to landscape fires which took much effort to make safe.

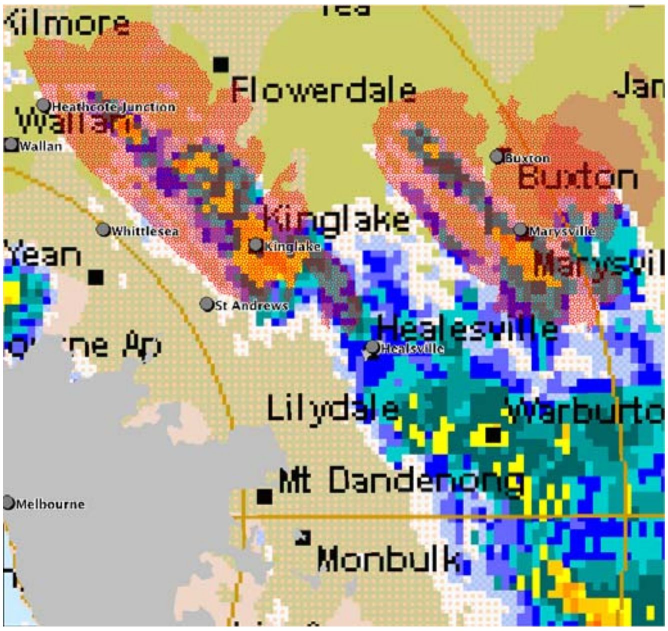


Figure 27. Radar data from Black Saturday. [Image: BoM]

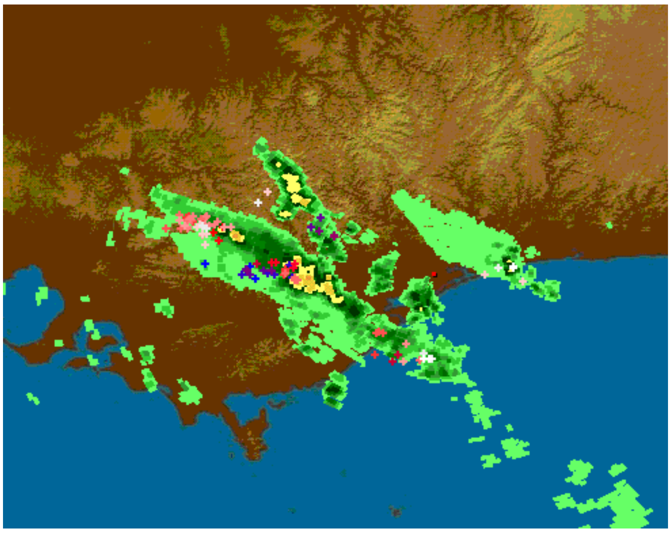


Figure 28. Radar and lightning data from Black Saturday. [Image: Weatherzone]

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APPENDIX – AEROLOGICAL DIAGRAMS

If you were to rise upwards through the atmosphere, there would be less and less air above you generating the air pressure that you would experience on your journey. Thus there is a relationship between height and air pressure. This relationship varies with the movement of weather systems. The civil aviation industry (now under the banner of the International Civil Aviation Organisation, ICAO) historically measured air pressure as a proxy for height, and so a standardised mapping of height onto pressure was developed.

Many properties of the atmosphere also change with pressure, with temperature being the primary one. A parcel with a constant amount of thermal energy will exhibit a varying temperature as its pressure changes. Changes in the environment of a parcel of air in which it does not exchange heat with its surroundings are called adiabatic. A graph with pressure/height as the Y-axis and temperature as the X-axis is an aerological diagram.

If we plotted a typical temperature profile of the atmosphere on such a graph it be awkward to use as the profile, the environmental lapse rate (ELR), would move along a diagonal off the left-hand margin and much detail would be obscured by its severe inclination.

To make a graph useful, what would otherwise be vertical lines of constant temperature are **skewed** sideways. This allows the ELR to sit in the middle of the graph, making key details visible. If we make height a linear trend, the pressure changes in a **logarithmic** manner. This gives us a skew-T log-P Aerological Diagram. A blank graph is shown in Figure 29, while an example from a blow-up fire day is shown in Figure 30.

On such a graph, for a given combination of height and temperature, there is a single solution for the dry adiabatic lapse rate and the moist adiabatic lapse rate.

The moisture content of the air is an independent variable. To handle this we can also plot a trace of the profile of the dew point temperature with height. For a given combination of height and DP there is a single solution for the mixing ratio (the weight of water in a kilogram of air). As a parcel of air rises the mixing ratio is conserved up to the height where the air becomes saturated.

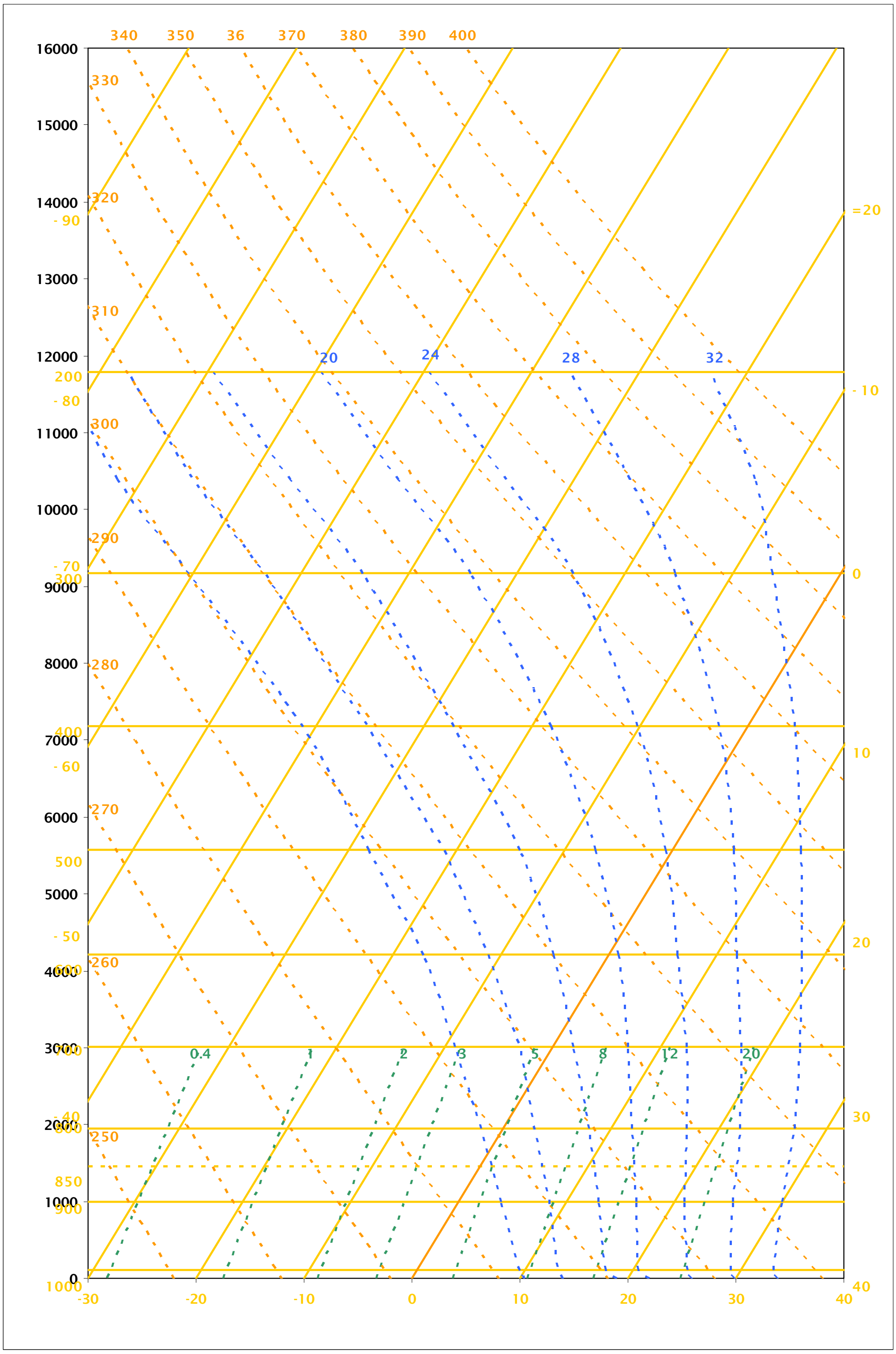

Figure 29. A blank skew-T log-P diagram.

Orange lines show equal temperature and pressure, green lines equal mixing ratio, blue lines equal MALR and red lines equal DALR.

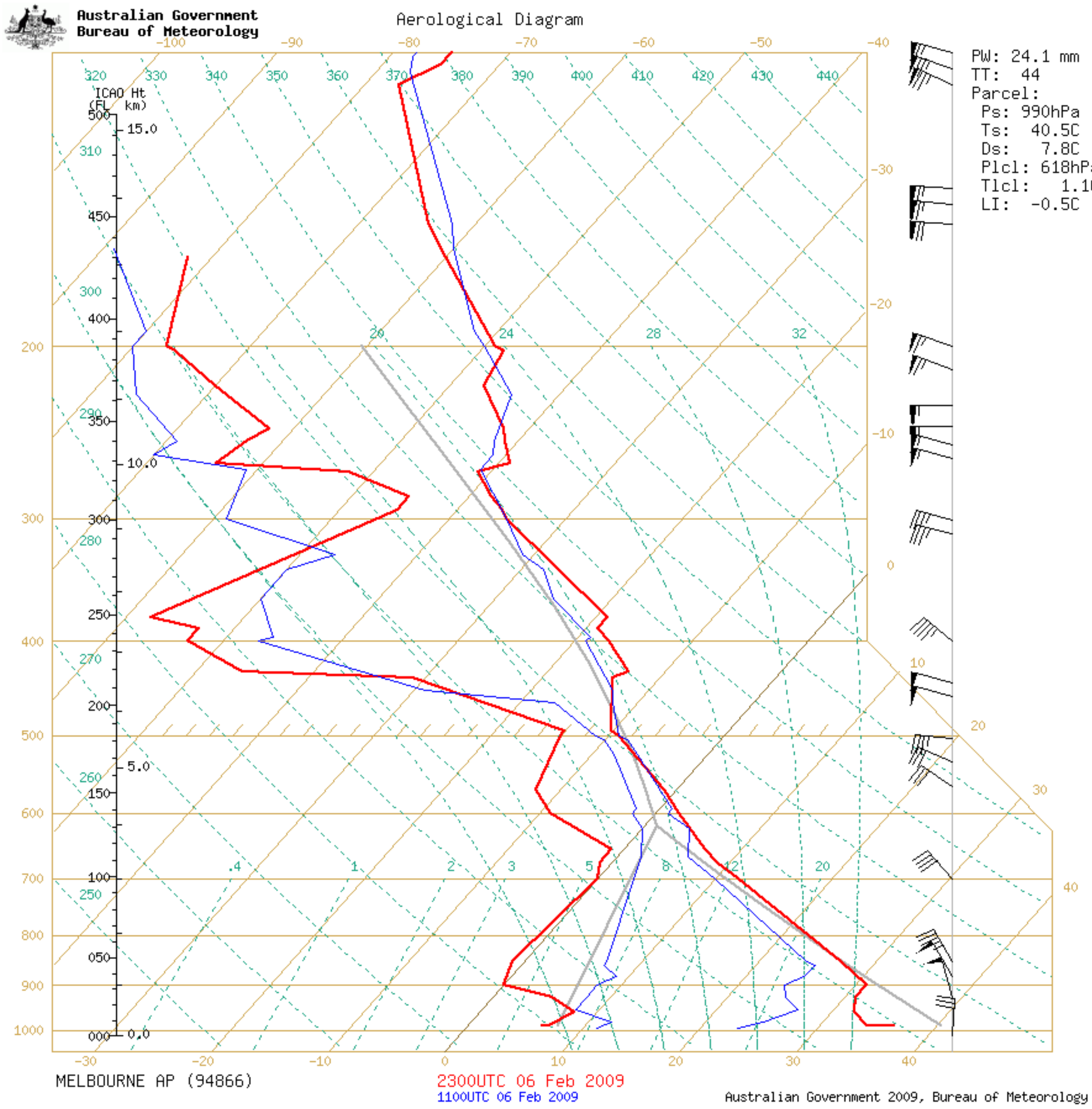

Figure 30. An actual Aerological Diagram from Black Saturday. [BoM]

Figure 30 shows an actual diagram, using a simpler but more standard colour scheme. Note that it also shows the winds at various heights in the standard depiction using wind barbs.

A wide range of indices can be generated from key points on these graphs, covering stability, precipitation and air pollution (smoke) dispersal.

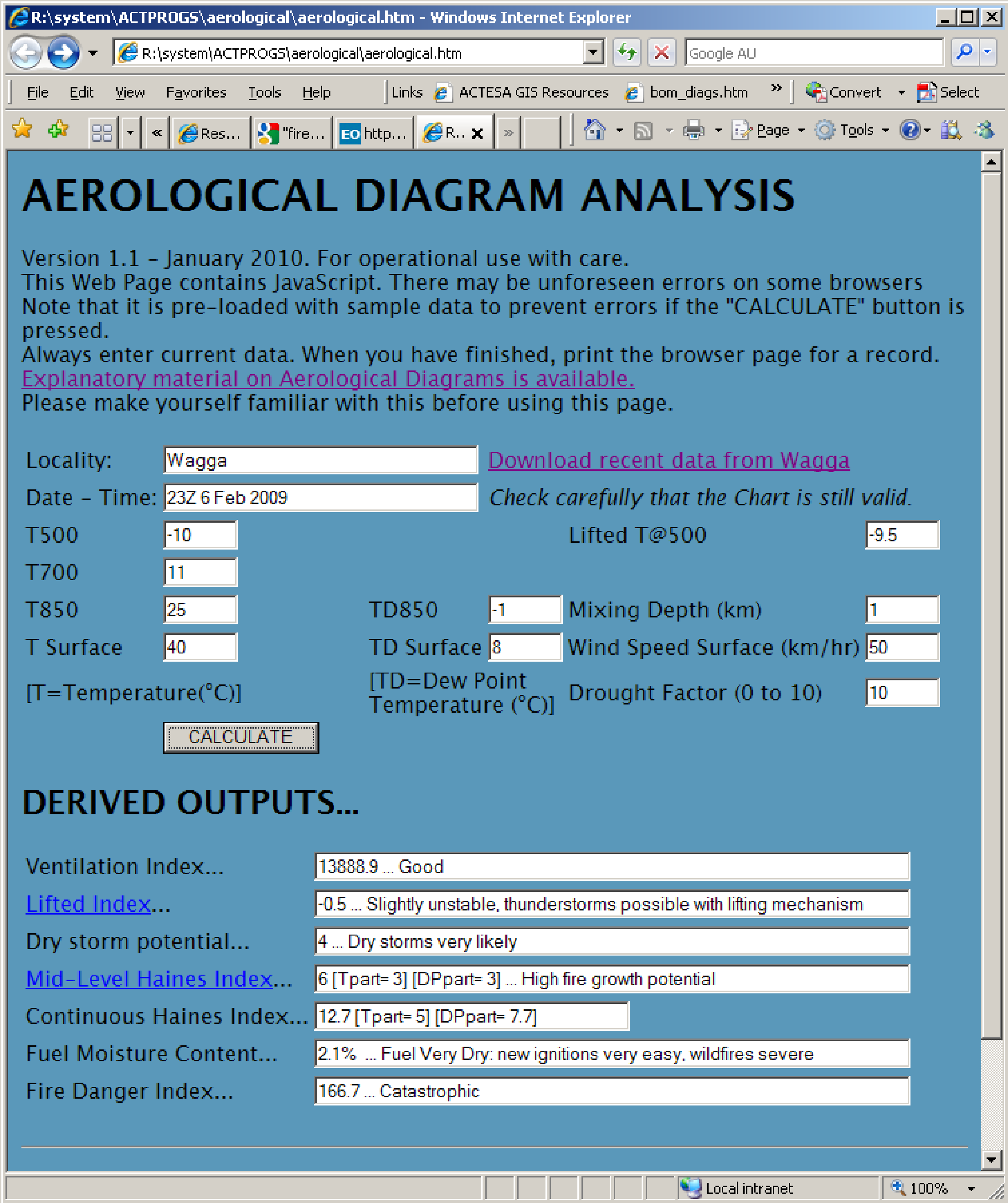

Figure 31. Sample screenshot of AEROLOGICAL.HTM

AEROLOGICAL.HTM is a web page designed to facilitate calculating and interpreting key indices.

PRODUCTS
FROM THE HIGHFIRE PROJECT

TOOLS	#1	Interpretation of Smoke Plumes	Dec 2009
	#2	Using an Aerological Diagram	Jan 2010
	#3	How to Model Wildfires	Jan 2010
	#4	Estimation of Formation Parameters of a Thermal Belt During Bishfire Operations	Jan 2010
	#5	Summary of Process Leading to Variance from the Diurnal Fire Weather Cycle in the high Country	Feb 2010
	#6	The Smoke Spotters Guide	May 2010
GUIDES		Checklist for Fire Observers	July 2009
		Guidelines On Red Flag Warnings And Watch-Outs For Fire Crews Operating In Rugged Landscapes	July 2009
		A Handbook on Wildfire Behaviour Prediction	Aug 2009
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SOFTWARE		AEROLOGICAL.HTM	
		TRANSITIONS.EXE	

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