The Breath of the Dragon - Observations of the January 2003 ACT Bushfires

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Abstract

A band of dry thunderstorms crossed southeast Australia on the afternoon of January 8, 2003. Much of the area was in a high level of drought. A vast number of fires were started in the high country. Three were in or adjacent to the ACT, and four more were not far away in NSW. One of these made a major run in the first hours, with three medium range spots. Over the following days, almost all fires continued to expand, due to their remote locations, the full flammability of 1000-hour dead-and-down fuel and an extraordinary, protracted spell of easterly winds with high FFDI. On the 17th, hot, dry NW Winds returned and caused all extant fires to break their containment lines and make major runs, reaching rural properties.

On the 18th some of the most extreme fire behaviour ever witnessed occurred, and was closely scrutinised by modern remote-sensing technology. This gave insight into some unexpected processes, centred on the interaction of mountainous terrain, unstable air and a landscape covered with large fires. These fires are estimated to have burnt 90,000 ha in three hours, with enormous energy release. They evolved into plume driven fires with the passage of a trough. One of these reached the edge of the city of Canberra, where it encroached on nine suburbs, killing four people and destroying valuable assets and over 500 houses. Many lifelines of the city were disrupted. The suburban impact was exacerbated by a severe tornado.

The fires have been painstakingly reconstructed through analysis of linescans, thermal scans, satellite images, weather radar, and photographs by air observers. Descriptions are given of weather, fire runs, plume fires, lee slope ember storms, ember storms caused by forced channelling, pyro-cumulo-nimbus development, grassfire behaviour under gales-force winds and spotting characteristics.

A wide-range of issues arising from this event have been, and still are, being reviewed and debated in enquiries by a range of jurisdictions.

HEAT RELEASE

Table 1. Energy budget, ACT bushfires, p.m. 18/1/03 only

Area burnt in 12 hours	$9.0*10^4$	ha
Fuel loading	$3.0*10^4$	kg/ha
Energy content	$2.0*10^4$	kJ/kg
Fuel consumed	$2.7*10^9$	kg
Energy released	$5.4*10^{13}$	kJ
Blast energy TNT[1]	$4.7*10^3$	kJ/kg
TNT equivalent	$3.5*10^5$	t
Time period	$4.3*10^4$	s
Power	$1.3*10^9$	W
Earthquake equivalent of fire	5.7	M(Richter)
Newcastle earthquake, 10:27, 28/12/1989	5.6	M(Richter)
Average tornado	4.5	M(Richter)
Domestic energy usage	$2.0*10^7$	kJ/person/annum
ACT usage	$6.0*10^{12}$	kJ/annum
ACT usage in 12 hr	$8.2*10^9$	kJ
Ratio of fire to ACT domestic energy usage	$6.6*10^3$	

It was assumed that:

- 90,000 ha burnt in that period.
- 30 t/ha was the average fuel loading, including heavy and fine fuel
- This fuel had an energy content of 20,000 kJ/kg.

These results are quite startling.

WIND TERRAIN INTERACTIONS

Fire behaviour modelling needs to include wind-terrain interactions. When this happens, some interesting phenomena emerge. This could be the basis for an entire study in its own right.

A deep low point in the terrain can act to funnel winds. This need not be symmetrical, like a gorge, but may be asymmetrical like a monocline. The important feature is a departure from the trends in the surrounding land surface. Many gorges are parts of dendritic drainage networks, and tend to meander with respect to the bulk wind direction. This results in a complex mix of local patterns, but little in the way of large-scale interactions.

In the montane landforms in the southeast, there can be pronounced lineaments that do lead to large-scale interactions with the wind. The structure of these has been shown to be of immense significance in blow-up fire events.

Figure 1 shows an example of an asymmetric wind-terrain interaction event. This event is forcing rapid flank expansion of the fire. In this phenomenon, which could be called lee-slope channelling, the eddy winds formed in the lee slope of a prominent high point recirculate significant quantities of embers, which burnout the lee slope. The recurrent part of the eddy also sheds embers into the bulk wind flows, which cause a rapid and intense progression of fire immediately downwind.

In this figure, the transition of colour in the linescan can be interpreted. Indications from elsewhere in the event showed that it was taking up to 2 hours for the observed colour

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[1] Based on $W_{TNT} = \alpha * W_f * H_f / H_{TNT}$, where α=0.03

sequence to evolve (in the representation of thermal infrared data). This indicates a flank expansion rate of 0.5 km/hr. However the downwind behaviour of the expanding flank appears quite severe, and features extensive spotting within 200m of the main flank.

In terms of symmetrical interactions there is an existing body of research that needs to be brought into the Australian context.

Kossmann et al (2001) discusses pressure driven and forced channelling, where a valley carries a wind direction different to the bulk. This is due to, respectively, pressure gradients and terrain interactions.

As the 2003 fires burnt in complex terrain, we examined linescan data to see if channelling may have been detected.

Figure 2 shows a likely example of forced channelling driving a severe fire to the south under northwest bulk winds. The deeply incised lower gorge of the Cotter River (which includes the Bendora Dam) appears to have carried an ember-laden eddy. The interaction of this with channelling seems to have resulted in a corkscrew effect pushing the embers upstream to the south. Of significance is that the western edge of the fire closely corresponds to the break in slope at the top of the inner gorge. Even though the upper slopes are steep and rugged, the eddy was contained to the lower gorge, ruling out a slope driven effect. On the downwind side of the eddy the result is totally different, with the flaming zone spilling out catastrophically. At 14:50 it covered over 12 km^2, while at 15:40 it covered a non-overlapping area over 15 km^2. This indicates the consumption by fire of over 18 km^2 in one hour off an effective headfire width of 3 km. However, unlike an elliptical spreading fire with a 3 km front, this geometry gave a far more circular hot area, able to create a more vigorous convection column.

A number of other instances of channelling may be inferred, as shown in **Figure 3**.

In summary, channelling is a form of wind-terrain interaction that operates on large scales, produces large flaming zones and contributes to extreme convective behaviour.

CONVECTION

One of the more extraordinary features of these fires was the convection. A NOAA MODIS image was taken of the area at about the time of peak convective development. A part of this is shown in Figure 4. This image shows the massive convection forming downwind of the fire activity. The maximum height recorded for a cloud top was 16 km above sea level, above ground at 1600 m ASL.

It is apparent in this image that there is a significant difference between lower winds (NW) and upper winds (W). The wind shear may have contributed to the formation of the tornado that hit the urban interface.

In the heat release section it was concluded that over $5*10^{13}$ kJ was released by the fire activity in a short period of time. Many of the convection columns passed through the condensation level, and often significantly so. As a rule of thumb a similar amount of heat would be released through the latent heat of condensation. From the image we could conclude that cloud covers 1500 km^2 of ground and that much of has been lifted by up to 10 km.

CONVECTIVE PHENOMENA

A series of interesting phenomena arose from the convection:

- Canberra was showered with charred foliage. Analysis of these revealed considerable quantities of leaves clearly from *Eucalyptus pauciflora* and less obviously from species like E. radiata or perhaps *E. dives*. Most interesting was material from understorey species such as *Tasmannia lanceolata*.

- The large-scale pulse of smoke sent to the tropopause by the convection was tracked by NASA's TOMS satellite as moving coherently as far as the Andes in about a week.
- At least two large-scale rotating events were observed. One in Tidbinbilla Nature Reserve was perhaps a very large fire whirl, and its core was filled with incandescent gas, perhaps flame. The other has been described an F2 tornado on the Fujita Scale [which says "Significant tornado; winds at 180-253 km/hr; Considerable damage. Roofs torn off frame houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light object missiles generated."]
- It overtook the main firestorm on the urban interface at Chapman. Its mapped path is shown in Figure 5. In doing so the pattern of damage caused evolved from fire then wind to both, then to wind then fire.

FIRE BEHAVIOUR

For much of the time from ignition until the severe runs on the 17th and 18th most of the fires were backing in heavily timbered, remote areas through mountainous terrain. Their behaviour was primarily exceptional in the difficulty of suppression, which reflected the rapid involvement of heavy fuel. At times heavy fuel contributed to rates of spread, and it frequently made suppression difficult for handtool crews and reduced the effectiveness of aerial waterbombing. Whenever the backing fires reached upslopes they made localised hot runs, which often caused short range spotting. The only intense activity early on was the initial run of the McIntyres Fire soon after ignition as it burnt out of a canyon.

RATE OF SPREAD

As mentioned there were few events of interest until the 17th. The combined fires made at least 9 major runs as a result of short distance spotting to just outside containment, with numerous longer-range spots making runs. Some of these were major uphill runs, but many runs also were over undulating or even downhill country. Using the intensity of radar returns as a measure of the duration of fire escalation, the activity was: Broken Cart Fire: 6 km run in 4 hours [1.5 km/hr]; Stockyard Fire: 23 km in 11 hrs [2.1 km/hr]; Bendora Fire: 13 km in 6 hours [2.1 km/hr]; and McIntyres Fire: 5 km in 8 hours [0.6 km/hr].

On the 18th things were much different. It is also harder to interpret the indirect evidence to hand. The 13:00 radar composite shows very little activity, while that for 14:00 shows rapid escalation. BoM reconstructions show clearly a peak in convective activity off Stockyard Fire at 14:40, Bendora Fire at 15:20 and McIntyres Fire at 15:50 [but there is a time lag for heat release to result in a radar return]. This equates to a northwards vector of about 25 km/hr for the trigger, compatible with the conclusion that it was a trough line. In terms of measurement of rate of spread:

- Lateral flank expansion as measurable in places at up to 5 km/hr.
- Forward rates of spread of over 10 km/hr are inferable from linescan overlaps.
- In places, where intense fire runs crossed large range, such as shown in

A 

B 

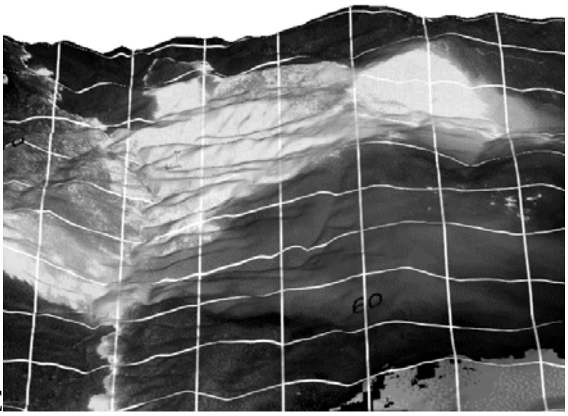
C 

Figure 6. (A&B) Extreme fire behaviour as Broken Cart Fire burns onto Brindabella Ranges. Analysis of linescans of this event indicates that it effectively climbed a vertical kilometre in one lick. The trees in the foreground are 25 m tall *E. dalrympleana*. (C) A reconstruction of a view from the south, with a linescan overlaid on a high-resolution digital elevation model. A one-kilometre grid is also overlain. The fire was travelling from left to right. The low point to the left is on the Goodradigbee River, with the Brindabella Range to the right. The brightest area is the flaming zone.

- , linescans indicate that the traverse was effectively made in one lick. Here Broken Cart Fire is crossing the Brindabella Ranges south of Mt Franklin.

INTENSITY

Some extraordinarily intense fire behaviour occurred on the 17th and 18th when the fires made runs. Unfortunately the linescans do not permit detailed scrutiny of this aspect of fire behaviour. Air observers felt that their safety was jeopardised when they approached the worst fire runs, and so observations are limited.

In the lead up to the 17th, the fires' intensities were generally more subdued. An enduring theme from this period is the difficulty of suppressing these fires, even when they were backing downslope. A possibility is that the antecedent rain-free period had made large downed fuel fully flammable. Crews equipped for fine fuel driven fires would have found it harder to be effective. There are models that handle large fuels (up to 1000 hour dead and down), and it is seen as desirable to revisit these for local conditions.

SPOTTING

The distribution of spotting was interesting. The McIntyres Fire put out 3 significant spot fires in its initial run, although some have claimed that at least one of these may have been independent lightning ignitions. The maximum distance was about 6 km.

Between the 8th and the 17th, with most fires backing, there was little spotting. The exceptions occurred when uphill runs were underway, where spots of up to 2km occurred. It is of note that these were during the exceptional spell of significant fire growth to the west, and resulted in the Bendora Fire and Stockyard Spur Fire fires becoming established in NSW.

On the 17th, with the onset of strong westerly winds, the picture was quite different. Once the Broken Cart Fire broke its NE containment it spotted downwind up to 20 km. This event was captured by a NOAA MODIS satellite image and hotspot analysis. The Bendora Fire made a hot uphill run to the border and spotted up to 6 km into the ACT. The Stockyard Fire underwent a valley burnout (See Figure 2) and this spotted to the east by up to 9 km, although the data for this area are ambiguous. The McIntyres Fire was burning within an unburnt inclusion in rugged country, and spotted to about 5 km outside containment.

On the 18th the picture was radically different. Despite faster rates of spread, the spotting distances were reduced. Lee slope burnouts acted through significant short-range lateral spotting. Some of the more severe headfire runs were characterised by short-range spotting storms. The linescans and the few photographs taken of these show them mostly burning back rapidly towards the main fires.

Of course on the 18th extensive ember storms occurred. Where these were observed on the urban edge the swirling embers were igniting anything in their path. It is possible that the surface air flow adjacent to the fire was a horizontal vortex driving embers back into the fire down low and drawing them out higher up (although there is no information on how high up).

In grasslands there is little evidence of formation of coherent headfires on the 18th. Cheney & Sullivan (1997, pp28-29) discuss whether winds can be so strong as to "blow-out" a grass fire. There is post-fire evidence that this happened, with paddocks being burnt by large numbers of small overlapping elliptical fires.

PLUME FIRES

To understand the airflow around the fires on the 18th, we need to discuss possible drivers of those fires.

In normal fires there is a precarious balance between wind-driven lateral transport of heated air and embers and buoyancy-driven vertical transport. An increase in the former consumes more fuel and in turn increases the latter, restoring the balance.

I would like to suggest that in plume fires this relationship is broken. Once the heat release exceeds a threshold, the plume continues to expand as it rises and resists the efforts of surrounding air to turbulently mix with it and dilute its excess heat. It is then pushed ahead of the upper winds, in effect dragging the surface fire across the terrain in the direction of the upper winds. With the different airflow around the plume, the path taken by embers and firebrands is altered, and they tend to stay recirculating within the plume, building up the ember density.

Evidence for this is limited. Field reconnaissance around Mt Stromlo post-fire showed no evidence of wind-terrain interaction left in charred pine needles. Also linescan images show a lack of this as well.

The massive convective uplift requires a replacement airflow, as noted by other authors on this matter. This may bring in dry upper air. The dew point inside the plume may be much lower than indicated by nearby weather records.

The absence of tools to predict the formation of such plume fires was an issue on the day. It appears that the precursors include, but are not limited to, extreme Fire Danger Rating and a Haines Index of 6. The passage of a trough over the fires is clearly resolved in Bureau of Meteorology radar reconstructions (prepared for the Coronial inquiry). In these the activity level "explodes" sequentially from south to north, in accord with being triggered by a trough passing overhead.

It appears that plume fires are promoted by having a more circular than elongated hot area driving the convection. Where ever flank expansion was amplified by lee-slope or forced channelling this condition was met.

The greatest concern arises from the western edge of the McIntyres Fire. Here a breakout on the evening of the 17th was in place on the western side of the Goodradigbee River, adjacent to a large burnout area. Analysis of the linescans indicates that within 2 hours the flaming area was in excess of 20 km^2. A worrying interpretation is this is that, given the precursors, plume fire development may be promoted by a breakout adjacent to a largely contained fire.

Plume fire development will likely be enhanced by any amplification of instability. Three such processes may have been in place on 18/1/03:

1. The passage of a trough.
2. Wave clouds (lenticularis), such as in the lower left corner of Figure 4, indicate the formation of mountain waves, and the various vertical air movements that they may generate.
3. The release of latent heat of condensation when the saturation level is reached.

Significant post-fire discussion has centred on the importance of fuel loads. While high loadings may be needed to get a fire going and may hinder suppression, analysis of topography and vegetation suggest the most intense burning was not necessarily correlated with high fuel load vegetation types – see Figure 7.

DISCUSSION

It was fortunate that we were able see linescan taken of the fires while they were exhibiting extreme behaviour. Other data sources, including air observer photographs, SENTINEL maps, MODIS images and BoM radar images provide objective evidence of the same. These data sources together open new possibilities in fire analysis.

They show some key issues:

1. The high level of drought made large downed fuels fully flammable. Reliance on fine-fuel based models caused significant operational difficulties. The switch to new models must proceed as rapidly as possible.
2. Mountainous terrain interacted with wind to produce extraordinary fire behaviour due to two forms of channelling. Firefighting in mountainous areas must be supported by an understanding of these processes. Channelling appears to have aided the formation of plume fires.
3. Plume-driven fires developed in at least 7 instances. They also occurred in adjacent fires in NSW. We do not have the tools to forecast this, and desperately need those tools.

These issues need to be addressed. Fire behaviour such as experienced as a concern for fire managers in all of Australia's more vertical regions. We need to examine what is known overseas, we need to conduct research, and we need to develop the tools to predict their occurrence and to allow those in the field to recognise their occurrence.

REFERENCES

Cheney, P. & Sullivan, A. (1997). *Grassfires: fuel, weather and fire behaviour*. CSIRO.

Kossmann, R., Sturman, A. & Zawar-Reza, P. (2001), *Atmospheric influences on bush fire propagation and smoke dispersion over complex terrain.* Proceedings, 2001 Australasian Bushfire Conference, Christchurch NZ.

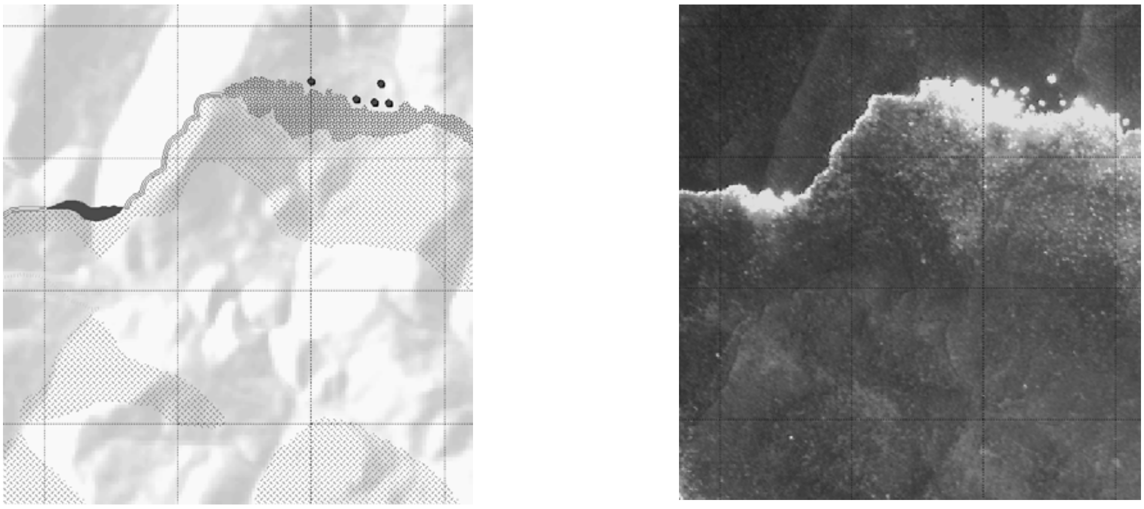


Figure 1.*Lee slope channelling*: Broken Cart Fire, 18/1/03. With winds approaching from the top left, the fire edge is working its way significantly to the upper right under the control of a lee slope eddy.

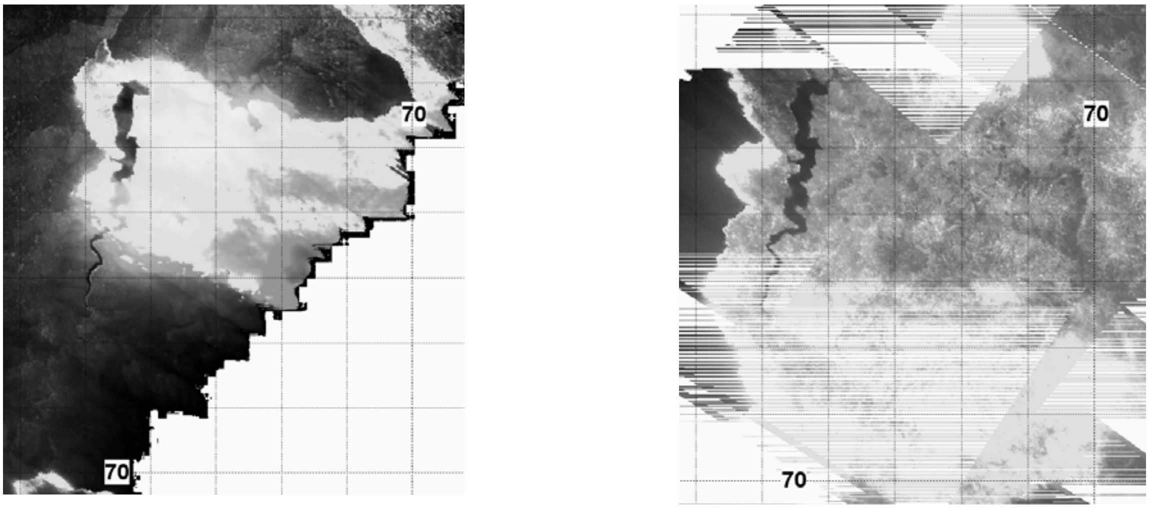
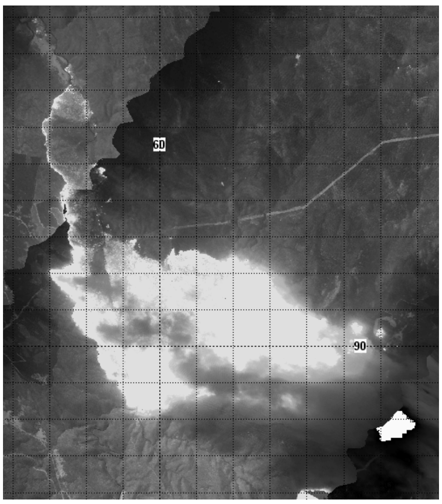
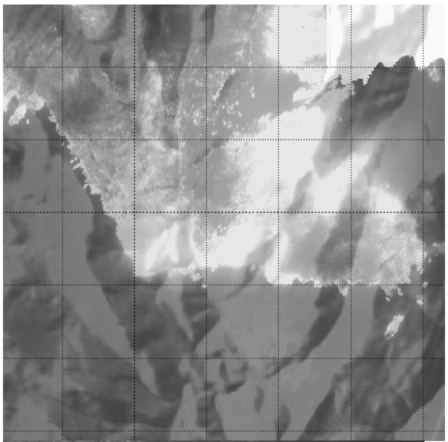


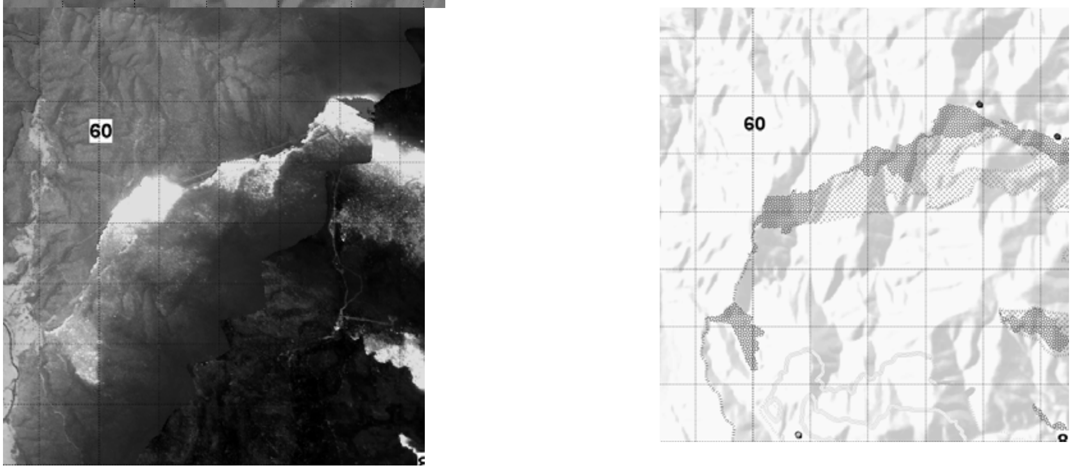
Figure 2. Forced channelling causing a valley burnout: Bendora Fire 18/1/03. In the first linescan extract, taken at about 14:50 the origin of the event is evident in its northwest corner, indicating less than 2 hours for the evolution of a flaming zone 3 km north to south and in excess of 5 km west to east. In the second extract, taken at about 15:40 the flaming zone has moved generally southwards as a block for 4 km. This indicates a flank expansion of nearly 5 km/hr.



(A) Forced channelling, Flea Creek area, McIntyres Fire, 18/1/03. This features the western edge following the break in slope, the downwind spillover and the massive flaming zone (5 km by 8 km with intense spotting). This developed in less than 2 hours from a 30 ha starting point.



(B) Lee slope channelling, Glendale Depot, Stockyard Fire, 18/1/03. The lee slope of a NW-SE oriented ridge has caused the flank to deviate southwards by over 2 km. An additional terrain interaction is occurring on the downwind ridge, and cooler cores of at least 2 significant spotfires are visible.



(C) A complex series of lee slope channelling events of the northern flank of Bendora Fire on 18/1/03.

(D) Lee slope channelling, southern flank Uriarra run of McIntyres Fire 18/1/03.

Figure 3. Other instances of channelling from 18/1/03.

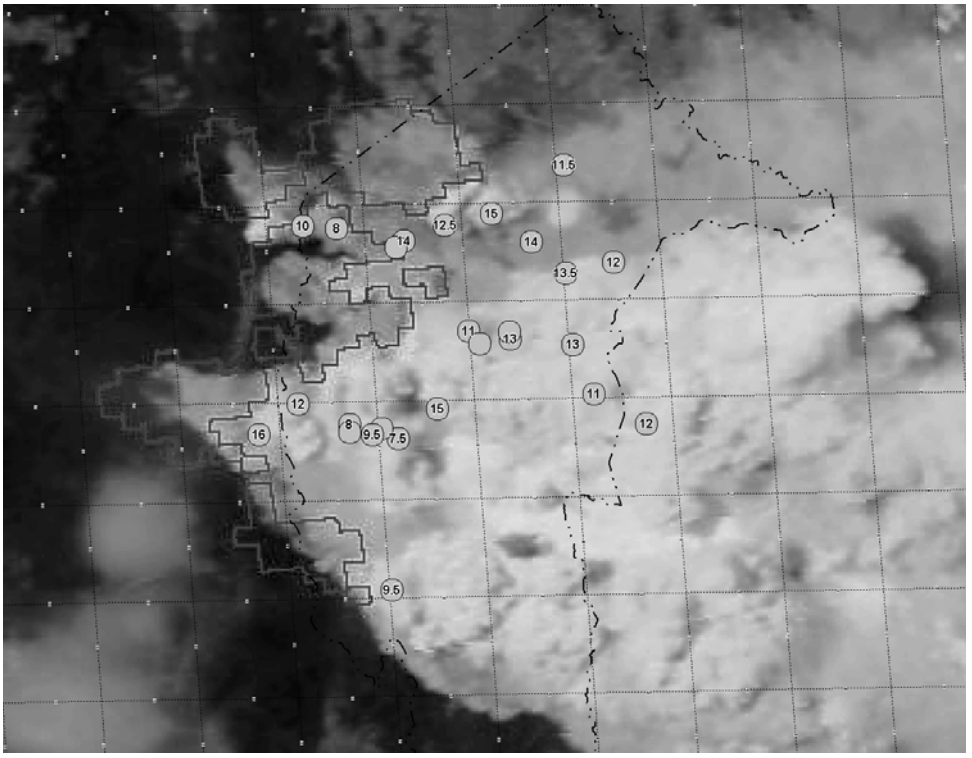


Figure 4. MODIS imagery of ACT and region, 14:00 18/1/03. This also shows a 10km grid (slightly skewed in this projection); the ACT border; automated fire mapping (by NOAA) and labelled circles showing inferred peaks of convection, with heights in km.

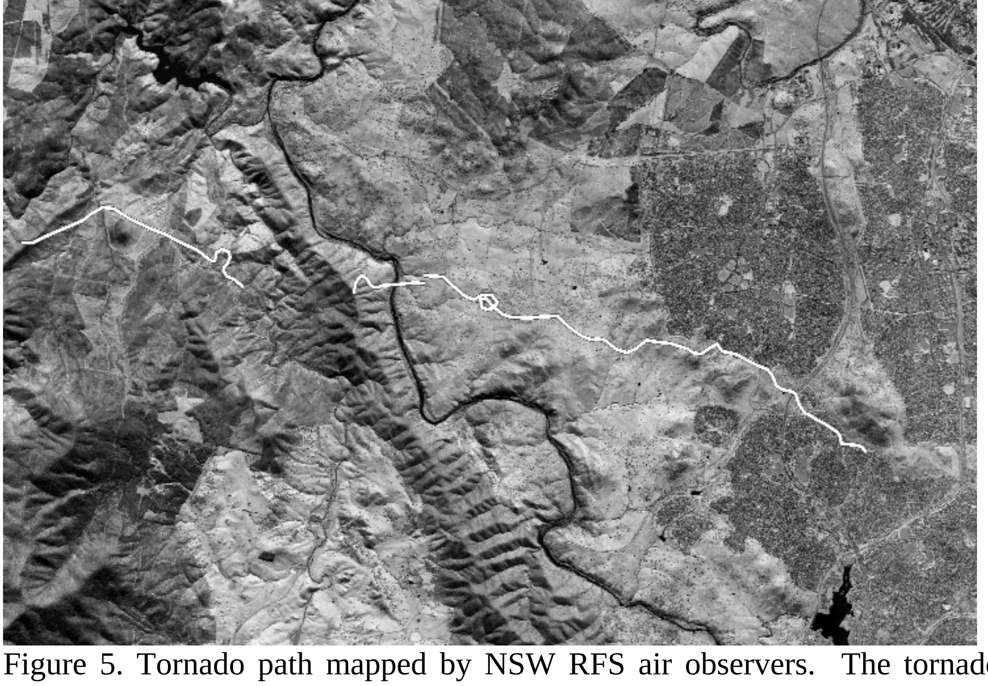


Figure 5. Tornado path mapped by NSW RFS air observers. The tornado crosses pine plantation, grazing land and eventually urban lands. The direct path length is 16km. This mapping is confirmed by post-fire mapping of extreme damage on the ground.

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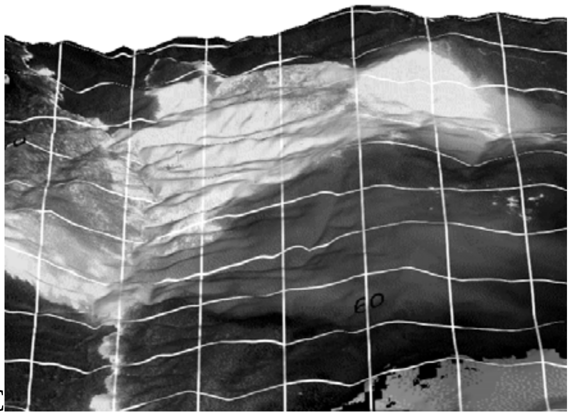

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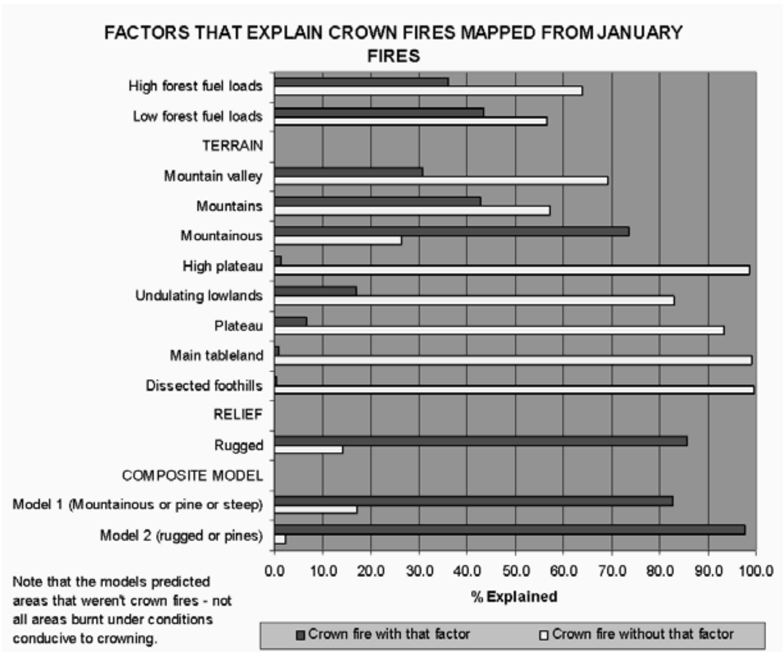

Figure 7.