Nat Hazards
DOI 10.1007/s11069-012-0443-7

ORIGINAL PAPER

An Australian pyro-tornadogenesis event

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Received: 2 May 2011 / Accepted: 3 October 2012

Abstract On 18 January 2003, fires had a devastating impact on Australia's capital, Canberra. A series of reviews and scientific studies have examined the events of that day and indicate that the worst impacts were due to a series of violent pyro-convective events and resultant pyro-cumulonmibi. These coupled fire–atmosphere events are much more energetic than normal fires. In one instance, an intense pyro-convective cell developed a tornado. We demonstrate that this was indeed a tornado, the first confirmed pyro-tornadogenesis in Australia, and not a fire whirl. Here, we discuss aspects of the formation, evolution and decay of the tornado, which was estimated to have been of at least F2 intensity, highlighting a process that can significantly increase the damage of a wildfire event.

Keywords Pyro-tornadogenesis · Pyro-cumulonimbus · Tornado · Wildfire

1 Introduction

On 18 January 2003, a number of bushfires, ignited by dry lightning storms on 8 January 2003, were driven by extreme fire weather conditions into the western suburbs of the city of Canberra. The evolution of the fire complex included a series of violent pyro-convective events over the rugged landscapes west and south-west of Canberra (in general terms centred at 148.8°E 35.4°S, see Fig. 1). This catastrophic fire event has been the subject of

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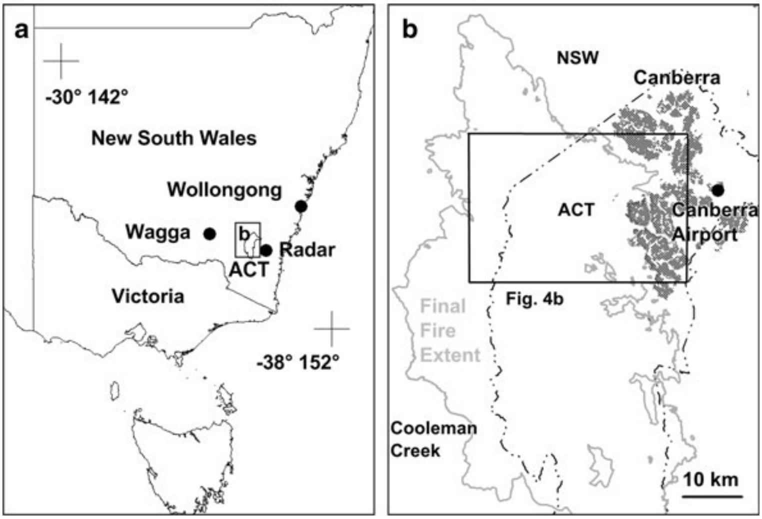

Fig. 1 Map showing the general location of Canberra and the fire-affected regions

administrative and judicial reviews (McLeod 2003; Doogan 2006) and of ongoing civil litigation. In his opening address to the Coronial Inquiry, the Counsel-Assisting the Coroner said[1]: "*One of the spectacular effects of this fire* [⋯] *was that the fires were of sufficient intensity and force to generate what was genuinely a tornado.* [⋯] *and that, of itself, as your Worship will hear, did some devastating damage*".

A number of alternative views were also forwarded. For example, Lambert (2010a) reports that a number of houses were impacted by airborne burning trees that had been torn from the ground and mentions anecdotal reports of wind speeds of 150–300 km h^{-1}, though he asserts that the damaging winds were intense indrafts into the convection column. The theoretical analyses of Raupach (1990) and Beer (1991), and experimental observations of wind-driven fires (Beer 1991), however, indicate that such intense indrafts into a fire's plume are not possible, except perhaps in the most extreme cases.

While Lambert was not claiming tornadic damage, it is clear that fires may produce localised strong winds. One form of this, reviewed by Countryman (1971), is the fire whirl. These form from the rising of unstable air, superheated by the surface. Countryman claims that fire whirl wind speeds may exceed 300 miles h^{-1}. Fire whirls are, however, linked to the surface and would not lift off along their path. Glickman (2000) defines a tornado as "A violently rotating column of air, in contact with the surface, pendant from a cumuliform cloud, and often (but not always) visible as a funnel cloud".

The fires have now been the subject of an unprecedented range of scientific studies, many of which confirm the incidence of a tornado. For example, Dold et al. (2005) discuss a number of unusual aspects of the fires and suggest the occurrence of either a tornado or a large fire-driven whirlwind; Fromm et al. (2006) note features including pyro-cumulonimbus (pyroCb) formation, the measurable impacts of the fire plume on the stratosphere and the formation of an F2 tornado, while Cunningham and Reeder (2009) discuss a mesoscale NWP simulation of the event that readily developed a tornado even when simplistic heat and moisture sources were used. In particular, Fromm et al. (2006) and

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[1] See page 2–3 of the transcript, Doogan 2006.

Cunningham and Reeder (2009) confirm the event as the first recorded instance of pyro-tornadogenesis in Australia.

This paper presents a detailed account of the event, including discussion of the precursor weather conditions, important aspects of the fire behaviour, field mapping of the tornado path, photogrammetric analysis and observations of the resultant damage in the worst affected regions and radar mapping of the tornado's progression.

2 Weather conditions

The fire weather conditions on 18 January were amongst the most severe ever recorded in the district. Air temperature adjacent to the fire-affected areas was above the 99th percentile of historical records and relative humidity fell to single digits. Figure 2 indicates that dew point temperatures dropped significantly, in two stages, in the afternoon (Mills 2005) and that the worst of the fire weather conditions corresponded to extremely low values of the Fuel Moisture Index (Sharples et al. 2009) indicating a fine fuel moisture content of approximately 2–3 %. Contemporaneous values of the Forest Fire Danger Index (Noble et al. 1980) were well above 100 (and well above the 99th percentile), indicating a strong potential for uncontrollable and catastrophic fire behaviour. A general account of the meteorology on 18 January is provided by Webb et al. (2004) and Taylor and Webb (2005).

The movement of a trough over the area resulted in critical levels of atmospheric instability. The 00 UTC sounding at Wagga (Fig. 3) indicates a c-Haines Index (Mills and McCaw 2010) at the 95th percentile level, low dew point temperatures throughout the

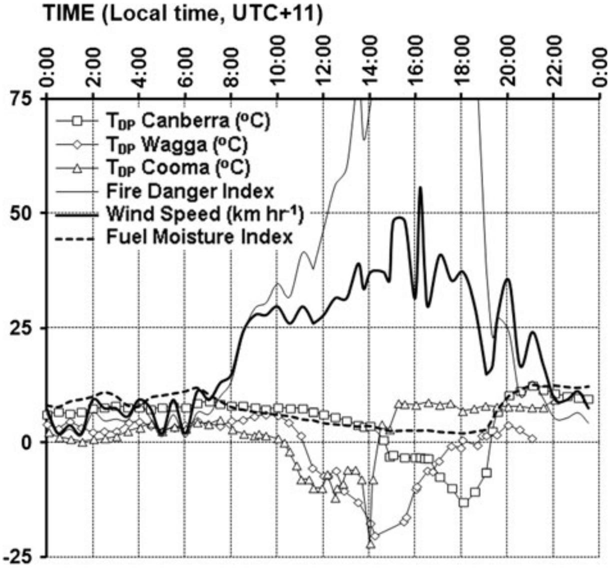

Fig. 2 Regional dew point anomalies at various stations and key fire weather parameters derived from Canberra Airport weather data, 18 January 2003. Note that the earlier arrival of the dew point depression event at Cooma (110 km to the south of Canberra) and Wagga (160 km to the west of Canberra) reflects the NW–SE orientation of and eastwards progression of the *trough lines* over this region

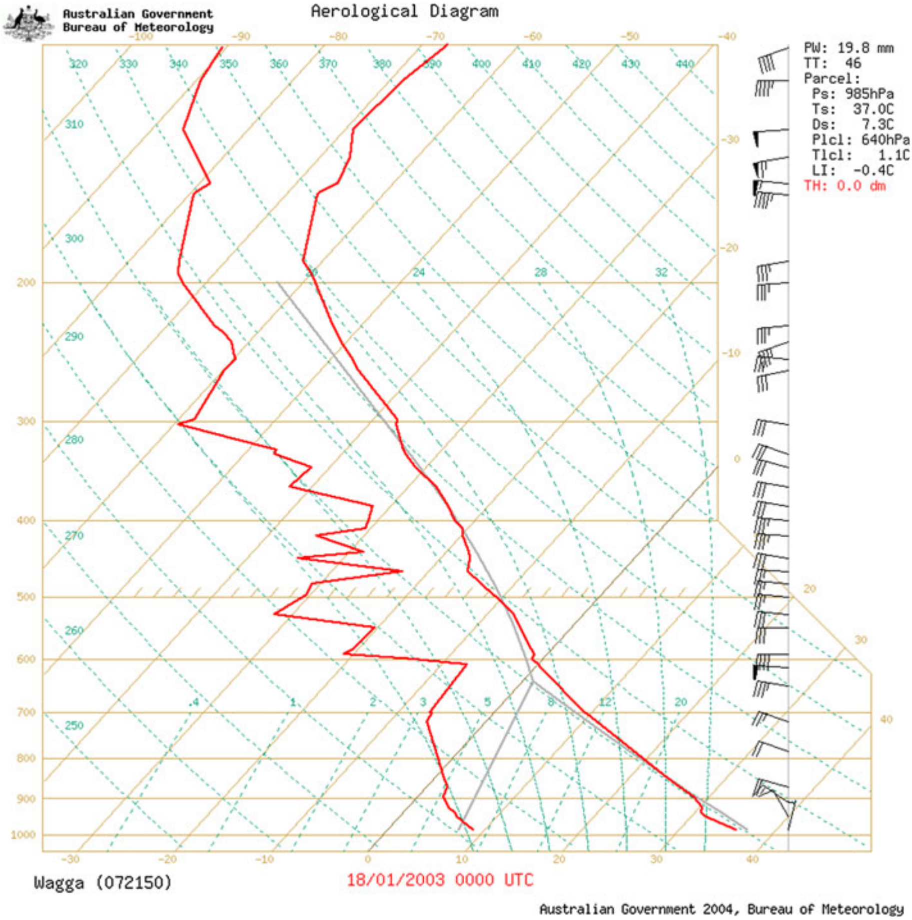

Fig. 3 Aerological diagram for Wagga at 11:23 local time on the 18th. The data indicate a Lifted Index of nearly 0, suggesting thunderstorm formation if there is a lifting mechanism (such as a large fire). It also shows a mid-level Haines Index of 6 and a Continuous Haines (c-Haines) Index of 11.5 (Mills 2005)

vertical profile, and suggests that once initiated, convective lifting of air could reach the tropopause at the 200 hPa level.

3 Fire conditions

McRae (2004) and Sharples et al. (2012) discuss a number of instances of atypical fire propagation observed on 18 January, apparently driven by the interaction of the extreme fire weather and the rugged terrain. Specifically, the atypical propagation was characterised by rapid lateral (i.e. in a direction transverse to the prevailing wind direction) spread of the fire in the lee of steep slopes and the production of extensive regions of active flame. The deep flaming zones that resulted are generally correlated with known formation sites of pyroCbs.

Radar data from the BoM show the complex chronosequence of pyroCb development (which is beyond the scope of this paper). However, the pyroCb (Fig. 4a) development is also corroborated by numerous photographs taken by air observers, fire-fighters and members of the public (such as in Fig. 4).

4 Field mapping

Shortly after the fire-run into Canberra, aerial observers mapped the reported tornado damage. The aerial mapping was augmented by field reconnaissance by the first author in the following months. The resulting map is shown in Fig. 4b and includes estimates of the temporal progression of the tornado drawn from fire crown scorch intensity maps derived from post-fire multispectral linescans (Cook et al. 2009).

One key observation from the destroyed Pierces Creek Pine Plantation is the distribution and orientation of uprooted or broken trees, which provide evidence of a moving, clockwise-rotating wind source. *Pinus radiata* (D. Don) trees were snapped off metres above the ground (Fig. 4c). This impact will be discussed further below.

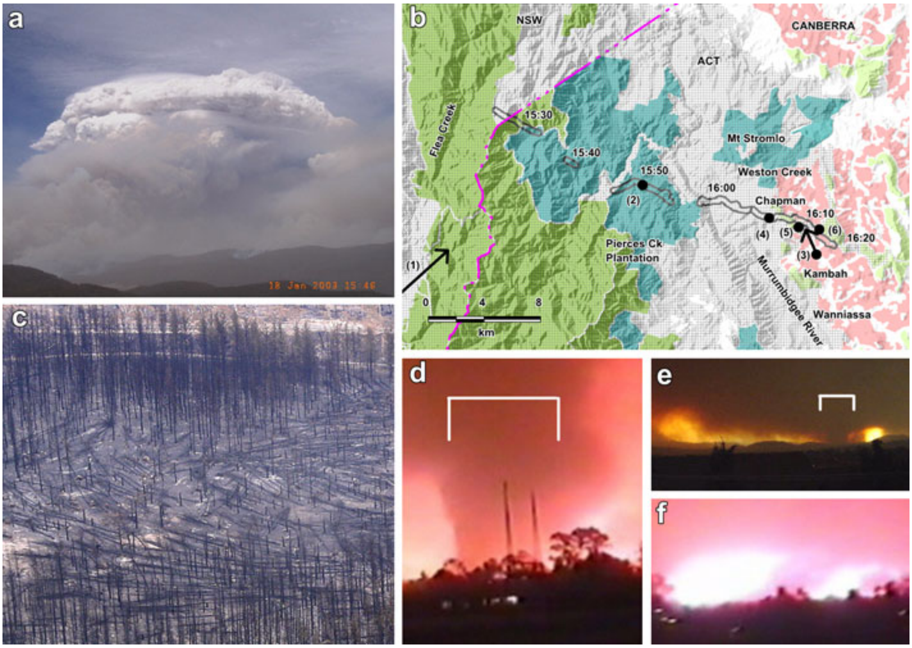

Fig. 4 **a** The pyroCb seen from the SW, above Cooleman Creek. **b** Track map of the tornado, showing estimated timing of its progression, national parks in *green*, pine plantations in *blue* and the burnt area in *grey*. Numbers in *brackets* refer to (*1*) Fig. 4a, (*2*) Fig. 4c, (*3*) Fig. 4d, (*4*) Fig. 4e, (*5*) Fig. 4f and (*6*) the location of the damaged police car. The *arrows* with (*1*) and (*3*) indicate camera orientation. **c** Tornado damage in the Pierces Creek Pine Plantation. **d** The tornado passing the suburb of Kambah. **e** The tornado approaching the suburb of Chapman. **e** A landscape-scale flashover on Mt Arawang as the tornado passes. The *brackets* in **d** and **e** indicate the vortex

5 Photogrammetric analysis

The analysis of photographs relied on knowing the location from which the photograph was taken treating X and Y measurements within the image as angular measurements from that location. By locating known reference points in both reference systems, it is then possible to take an object of interest in the image and identify its bearing from the photo point. If that bearing unambiguously matches a known location for the object, its real-world coordinates can be derived. Doing this for multiple images (from multiple times) permits calculation of averaged velocities. An example of this (for calculating vertical velocity) is shown in Fig. 5.

As the tornado approached the urban edge, two key pieces of photographic evidence were captured by members of the public. Firstly, a resident of the suburb of Wanniassa (Mr Jim Venn) took a photograph of the vista from his back deck. Analysis of this image showed the outline of a tornado (Fig. 4e). Photogrammetric analysis revealed that the line of sight to the tornado intersected the mapped damage path at only one location. It was thus possible to derive an accurately timed location of the tornado and subsequently to estimate the basal diameter of the tornado at 450 m. This estimate is consistent with the damage at the same point seen in post-fire photographs taken by air observers.

Secondly, a resident of the suburb of Kambah (Mr Tom Bates) took a 3-min video of the tornado passing north of Mount Arawang. Some still frames from the Bates video are shown in Fig. 4d, f. Considerably, more information was derived from this second case. After precisely locating the point from which the tornado was filmed, photogrammetry

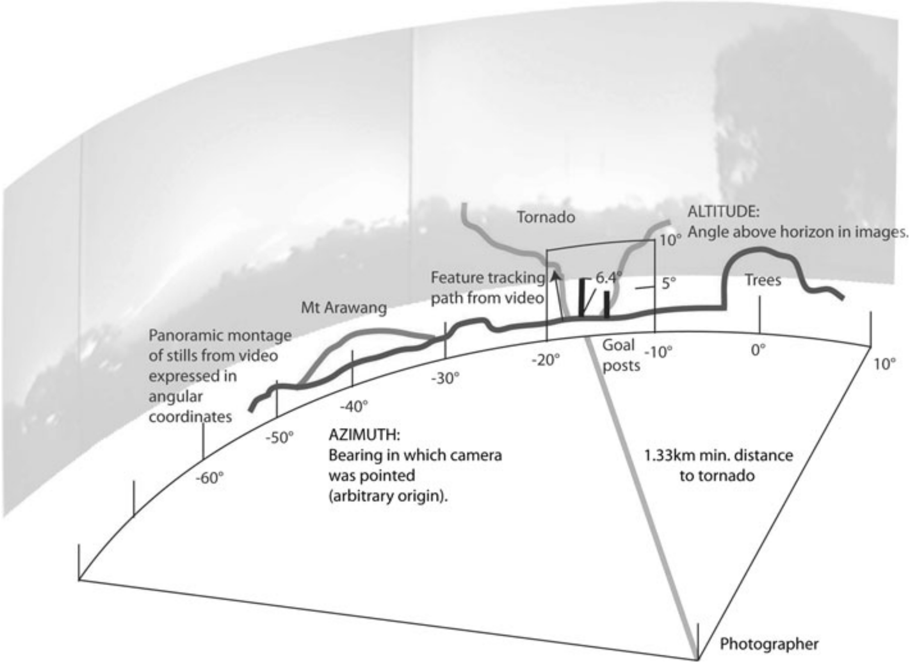

Fig. 5 A worked example of photogrammetric analysis, showing how an image is interpreted in angular coordinates and mapped onto real-world coordinates using the photographer's location and a known location for an object of interest

allowed the tornado to be traced along the mapped damage path for nearly 2 km over 3.3 min, at the end of which the basal diameter had shrunk to an estimated 160 m. The visible core is seen to be rotating clockwise in plan view with a translation speed of approximately 30 km h^{-1} and a vertical velocity of between 200 and 250 km h^{-1}. This vertical velocity, derived for (approximately) its lowest kilometre from the photogrammetric analysis, is consistent with the value of 216 km h^{-1} (60 m s^{-1}) derived from the numerical modelling of Cunningham and Reeder (2009).

Large debris, considered to be the steel roofing sheets from the 8 tonne roof of a water reservoir near Mt Arawang, was photographed falling from the sky over 1 km from the vortex. The Bates video also shows detail of the development of a number of spot fires on the lee-face of Mt Arawang. Their development is consistent with them being drawn into the air flow of the approaching tornado. At one point, all image pixels covering unburnt parts of the hillside saturate, suggesting a landscape-scale flashover event covering around 120 ha (Fig. 4f). The observation is consistent with the ignition of a premixed fuel–air composition that rapidly burns without igniting the surface fuels on the hillside (Arnold and Buck 1954; Dold et al. 2005).

6 Radar data

The radar data used were 0.5-degree elevation reflectivity data from the Bureau of Meteorology's Captains Flat weather radar (60 km south-east of the area of interest). The repeat time was 10 min, and it lacked Doppler capability. Figure 6 shows that the mapped damage path and its timing derived from analysis of fire spread closely align with the passage of such an area of enhanced radar reflectivity. We contend that the match is sufficient to support the thesis that it is the tornado that is shown by the radar. At that range, the beam was largely underneath the pyroCb and weakly reflected by particulates, but there was stronger reflectance from the tornado. The movement of the tornado along the centreline of the fire plume, and thus of the pyroCb, also confirms that the tornado was indeed a pyrogenic event.

7 Damage observations

Two reports from members of the public and emergency service personnel are particularly useful for estimating the intensity of the tornado. Firstly, a trailer behind an 8 tonne fire tanker was lifted off the ground, and secondly, nearby a 2 tonne police car was picked up and dropped into a stormwater drain. The police car also had its beacons and other external attachments stripped by the strong winds. Schmidlin et al. (undated) conclude that vehicles are rarely tipped over in F2 damage and about one in five are tipped over in F3 damage. The Enhanced Fujita Scale (Wind and Science Engineering Centre 2006; NOAA 2011) indicates that a tornado of EF2-EF3 intensity is required to lift and throw heavy cars.

The windthrow observed within the Pierces Creek Pine Plantation also provides a way of classifying the intensity of the tornado. Softwood trees, such as pines, will have their trunks snapped when subject to winds with a mean three-second gust speed of approximately 170–180 km h^{-1} (see Wind and Science Engineering Centre 2006: Appendix C). This is again consistent with a tornado intensity of at least EF2. More generally, houses in Lincoln Close, a street on the edge of the suburb of Chapman, suffered a mix of damage types (Fig. 7). Some houses were destroyed by fire, some exhibited only wind damage,

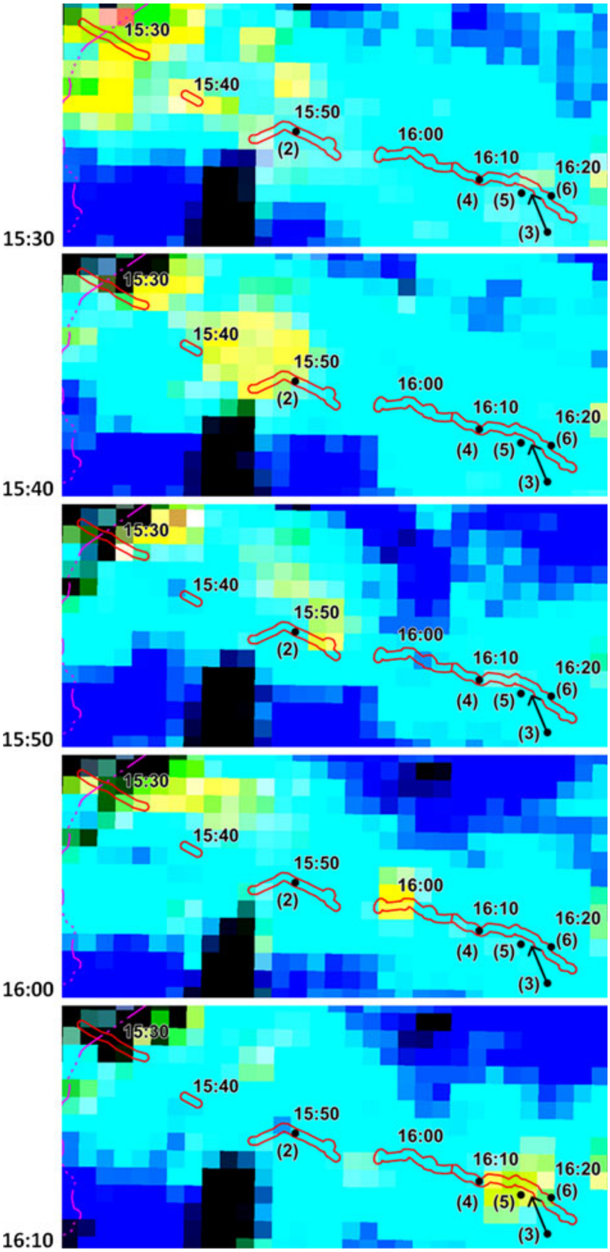

Fig. 6 The relationship between mapped damage path, timings based on fire isochrones and radar reflectance. In each of the five panels covering contiguous 10-min time intervals, the damage path polygon is shown with its timing based on fire spread reconstruction. The *colours* indicate reflectivity strength (increasing through *blue*, *cyan* and *yellow*). *Black* areas are terrain-induced reflectivity “holes”. The convective core of the event can be seen. In each panel, an area of stronger reflectivity (*yellow*) overlays the damage path. Numbers in *brackets* refer to (*2*) Fig. 4c, (*3*) Fig. 4d, (*4*) Fig. 4e, (*5*) Fig. 4f and (*6*) the location of the damaged police car. The *arrow* with (*3*) indicates camera orientation. The *dashed line* is the New South Wales border

Fig. 7 Aerial post-fire photograph of Lincoln Close, Chapman. A mix of damage types is evident—*F* fire only, *FT* fire and tornado, *N* none. This view to the north-west is from just north of Mt Arawang

some were burnt then damaged by wind, while others suffered wind damage and then were burnt (Webb et al. 2004).

The weight of data thus suggests that the tornado on 18 January 2003 was at least an EF2 event, but as most of the clear damage indicators occurred shortly before the tornado decayed, it is possible that it could have been rated as an EF3 event at its peak intensity.

8 Discussion

The events on the afternoon of 18 January 2003 comprise the first confirmed instance of pyro-tornadogenesis in Australia. The tornado lifted off along its track, as seen in Fig. 4b and discussed in Fromm et al. 2006. This distinguishes it from previously reported fire whirls (Countryman 1971 and Umschied et al. 2006) and meets the definition of a tornado given by Glickman (2000).

Agee and Jones (2009) define a taxonomy of tornado events. Fromm et al. (2006) report no obvious supercell characteristics for the pyroCb, and there is no evidence of a quasi-linear convective system. This infers a classification as a Type IIIa Landspout. Agee and Jones (2009) state that for these, “stretching of shear vortices in the planetary boundary layer by the updraft of non-supercells has, in extreme cases, produced F3 tornadoes”. They do not, however, consider pyrogenic tornadoes, and this assignment may need clarification.

Pyro-tornadoes are potentially an extremely dangerous companion to large wildfires, which can negate any fire suppression efforts and can pose an extreme risk to fire-fighting personnel and aircraft. Indeed, Hissong (1926) and Kuwana et al. (2006) describe two historical instances involving fire-induced vortices that resulted in multiple fatalities. For the case of the Canberra bushfires, it is estimated that a slight backing by the prevailing winds (towards westerly) could have produced storm damage well beyond that caused by the fire. Indeed, Fig. 4b indicates that the tornado path fortuitously ran between the suburbs of Kambah and Chapman, only directly impacting housing along a 200-m interval (Fig. 7).

If instead there was a one degree backing of the steering winds, the impact interval may have extended to a length of over 3 km. Extreme damage is frequently reported in the Mississippi basin from EF2 to EF3 tornados in communities that are well prepared through measures such as building codes, warnings and storm cellars. In this context, it is important to note that Canberra, in common with other Australian cities, has had no basis for requiring preparedness for tornadoes of such magnitude. While Australian cities in tropical regions are built to withstand tropical cyclones, the Australian Standard for wind actions explicitly excludes tornadoes (Standards Australia 2011).

Intense winds, strong enough to fell dozens of large eucalyptus trees and to cause severe damage to a number of structures (Lambert 2010b), were also observed in connection with the more recent "Black Saturday" bushfires in Victoria, Australia. Events such as those experienced in January 2003 and February 2009 in south-eastern Australia, whether occurring in connection with a tornado or not, highlight a need to include extreme pyrogenic winds into bushfire risk management frameworks as well as the bushfire research agenda adopted in south-eastern Australia and other fire-prone regions (e.g. Southern California).

Much effort has been expended in Australia in recent years on developing better approaches to elevated fire danger situations (Edwards 2010). This effort has focussed almost entirely on extrapolating "normal" surface conditions into exceptional situations. However, it must be realised that surface weather may have little bearing on the complex structure and dynamics of the thousands of cubic kilometres involved in a violent pyroconvective event. Fromm et al. (2010) discuss the growing prevalence of violent pyroconvective events in a number of countries. If these fires can produce thunderstorms, then it is prudent to expect them to be able to produce tornadoes, if the other requisite conditions are met. This paper has highlighted how extreme fire conditions can contribute to tornadogenesis and the level of damage that pyro-tornados can exact. Indeed, although the atmosphere was unstable and there was significant wind shear in the vertical profile (Fig. 3), the small CAPE value of 117 J kg^{-1} recorded on 18 January (Cunningham and Reeder 2009) indicates conditions that are by no means conducive to tornado formation. As such, and as pointed out by Cunningham and Reeder (2009) and Potter (2005), it is important to realise the effect that pyrogenic heat and moisture can have on convective dynamics in general and specifically in providing conditions more favourable to tornado formation. At times when fires can cause great damage and loss of life, pyro-tornadoes can be rare and short-lived associated events capable of similar levels of impact.

Acknowledgments The authors would like to thank Air Target Services Pty Ltd, Nowra, New South Wales; Clem Davis, Bureau of Meteorology (retired); Peter Deck of the ACT Ambulance Service; Christine Goonrey; NSW Rural Fire Service; Jim Venn; Tom Bates. The authors also acknowledge the two anonymous reviewers whose comments prompted significant improvements to the manuscript.

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