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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 pyroconvective events and resultant pyro-cumulonmibi. These coupled fire-atmosphere events are much more energetic than normal fires. In one instance an intense pyroconvective cell developed a tornado, the first confirmed pyro-tornadogenesis in Australia. 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.

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An Australian pyro-tornadogenesis event

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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 pyroconvective events and resultant pyro-cumulonmibi. These coupled fire-atmosphere events are much more energetic than normal fires. In one instance an intense pyroconvective cell developed a tornado, the first confirmed pyro-tornadogenesis in Australia. 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 comprised a series of violent pyroconvective events over the rugged landscapes west and southwest of Canberra (in general terms centred at 148.8°E 35.4°S, see Figure 1). This catastrophic fire event has been the subject of administrative and judicial reviews (McLeod, 2003; Doogan, 2006) and of on-going 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

[1] See page 2-3 of the transcript at http://www.courts.act.gov.au/BushfireInquiry/Submissions/Transcripts.htm

reports of wind speeds of 150-300 km h-1, though he asserts that the damaging winds were intense indrafts into the convection column.

However, 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 (pyro-Cb) 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 sources were used. In particular, Fromm et al. (2006) and Cunningham and Reeder (2009) confirm the event as the first 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.

2. Weather conditions

The fire weather conditions on 18 January were amongst the most severe ever recorded in the district. Air temperature outside 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 also dropped significantly twice in the afternoon (Mills, 2005) and that the worst of the fire weather conditions corresponded to values of the Fuel Moisture Index (FMI) (Sharples et al., 2009) below 2, which indicates a fine fuel moisture content of approximately 2-3%. Contemporaneous fire danger indices 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 00UTC sounding at Wagga (Figure 3) indicates a c-Haines Index (Mills and McCaw, 2010) at the 95th percentile level, low dew point temperatures throughout the vertical profile, and suggests that once initiated, convective lifting of air could reach the UTLS at the 200 hPa level.

3. Fire conditions

McRae (2004) and Sharples et al. (submitted) 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 pyro-Cbs.

Radar data from the BoM clearly shows the complex chronosequence of pyro-Cb development. The pyro-Cb (Figure 4a) development is also corroborated by numerous photographs taken by air observers, fire-fighters and members of the public (such as in Figure 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 RHDM in the following months. The resulting map is shown in Figure 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 clear evidence of a moving, clockwise-rotating wind source. *Pinus radiata* trees were snapped off metres above the ground (Figure 4c). This impact will be discussed further below.

5. Photogrammetric analysis

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 revealed a clear image of the tornado (Figure 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 450m. 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 three minute video of the tornado passing north of Mount Arawang. Some still frames from the Bates video are shown in Figures 4d & 4f. Considerably more information was derived from this second case. After precisely locating the point from which the tornado was filmed, photogrammetry allowed the tornado to be traced along the mapped damage path for nearly 2 km over 3.3 minutes, at the end of which the basal diameter had shrunk to an estimated 160m. The visible core is clearly seen to be rotating clockwise in plan view with a ground speed of approximately 30 km h^{-1} and a vertical velocity of approximately 250 km h^{-1}. Large debris, considered to be the 8 tonne roof of a water reservoir, can be seen falling from the sky over 1 km from the vortex.

The Bates video also shows detail of the development of a number of spot 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 120ha (Figure 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. Damage observations

Two reports from members of the public and emergency service personnel are particularly useful for estimating the intensity of tornado. Firstly, a trailer behind an 8 tonne fire tanker was lifted off the ground, and secondly, 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 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 & 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 (Figure 5). Some houses were destroyed by fire, some exhibited only wind damage, 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.

7. Discussion

The events on the afternoon of 18 January 2003 comprise the first confirmed instance of pyro-tornadogenesis in Australia. It is important to distinguish the event from a large fire whirl (such as reported in Umshied et al., 2006) as it was attached to a cloud base and lifted off the ground a number of times, whereas whirls are attached to the ground. The correlation between radar returns of peak convective activity and reconstructed peak fire intensity confirms that the tornado was indeed a pyrogenic event.

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 the west) could have produced storm damage well beyond that caused by the fire. Extreme damage is frequently reported in the Mississippi basin from EF2 and 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 has had no basis for requiring preparedness for tornadoes of such magnitude.

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 southeastern Australia highlight a serious shortcoming in current state-of-the-art bushfire risk management frameworks as well as in the bushfire research agenda adopted in southeastern 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 pyro-convective event. Fromm et al. (2010) discuss the growing prevalence of violent pyro-convective events in a number of countries. If these fires can produce thunderstorms, then it is prudent to expect them to produce tornadoes as well. This paper has shown some of the circumstances under which this might happen. 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.

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FIGURES

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

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 the trough lines over this region

Fig. 3 Aerological Diagram for Wagga at 11:23 on the 18th. The data indicates a Lifted Index of 0, suggesting thunderstorm formation if there is a lifting mechanism (such as a large fire). It also suggests a mid-level Haines Index of 6 and a Continuous Haines (c-Haines) Index of 12.2

Fig. 4 (a) The pyro-Cb seen from the SW, above Cooleman Creek. (b) Track map of the tornado, showing estimated timing of tis progression, and the burnt area in grey. (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 flash-over on Mt Arawang as the tornado passes

<<Note: A=top left; B=top right; C=botton left; D=botton center; E=center right; F=lower right>>

Fig. 5 Aerial post-fire photograph of Lincoln Close, Chapman. A mix of damage types is evident

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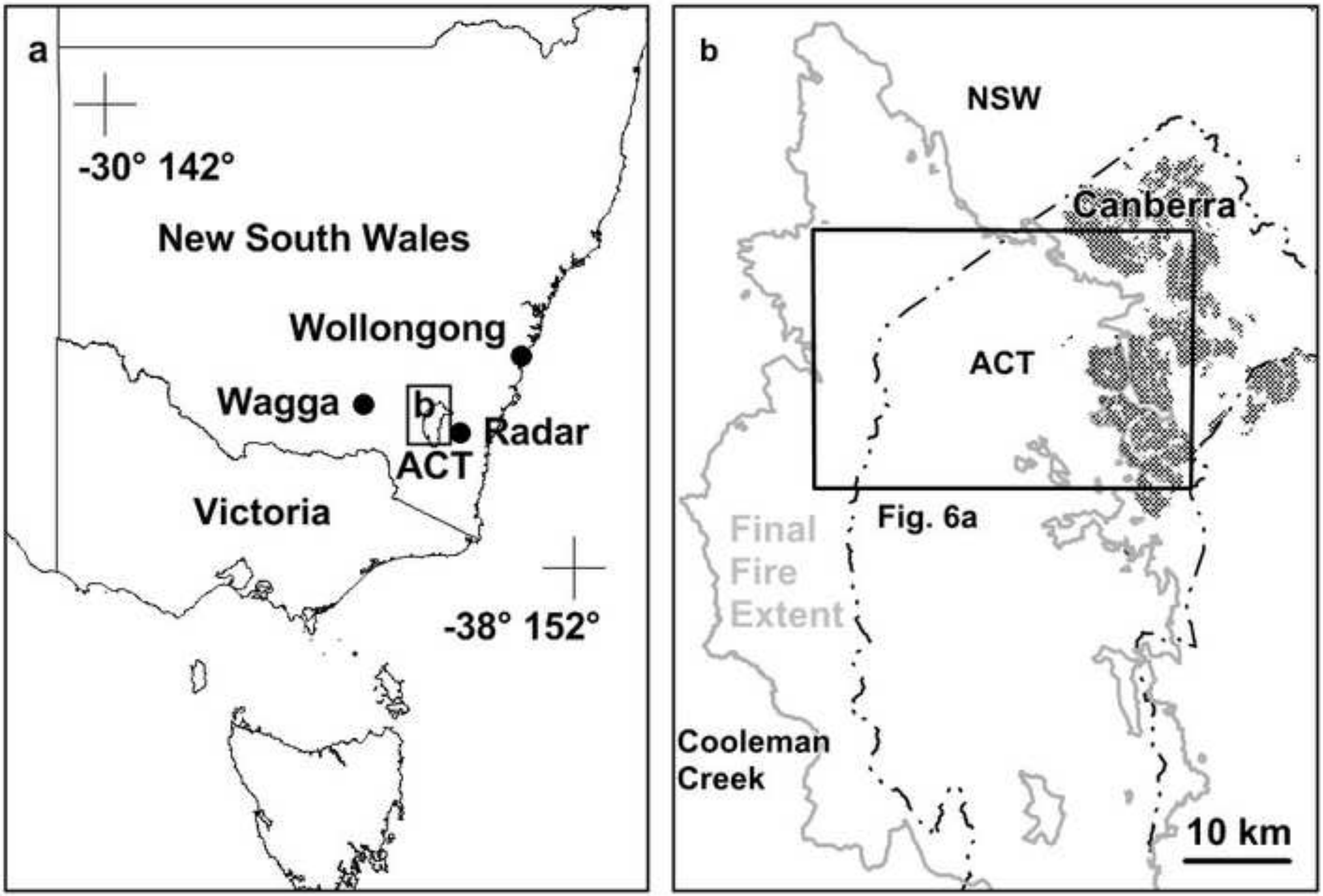

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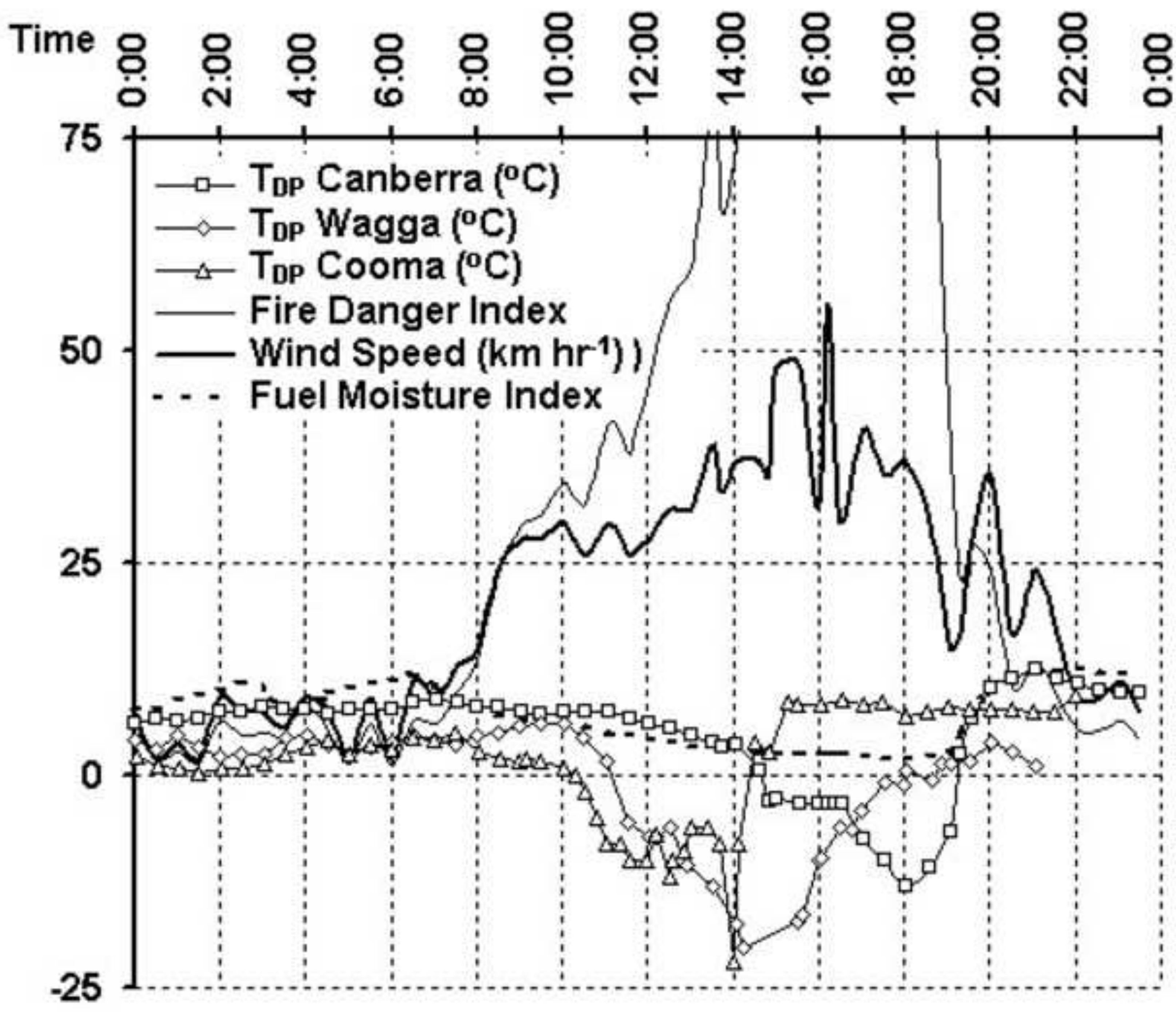

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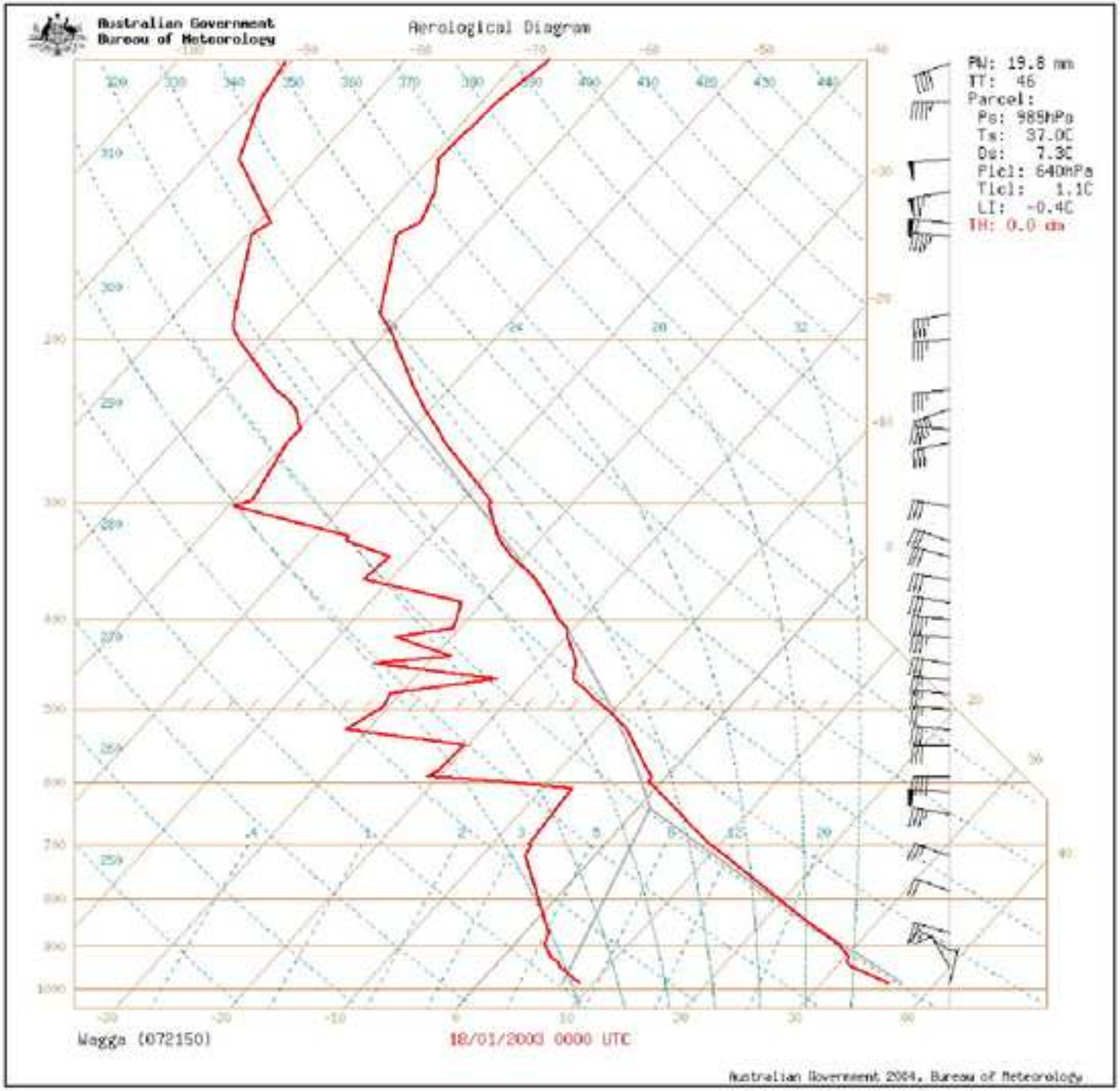

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Table 1. Weather data from Canberra Airport Automatic Weather Station, 18 January 2003.

Time (local)	Temp-erature (°C)	Relative humidity (%)	Dew Point Temp-erature (°C)	Wind speed: mean & gust (km hr^{-1})	Wind Direction (° true)
15:00	36.9	10.8	-2.7	48 65	310
15:30	36.1	10.8	-3.3	48 78	310
16:00	36.3	10.7	-3.2	31 60	310
16:30	36.0	10.8	-3.4	30 48	300
Extreme	37.1	6.0	-13.0		
at time	14:37	18:04	18:04		