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LESSONS LEARNED FROM A MULTIDISCIPLINARY INVESTIGATION INTO THE WAROONA FIRE

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ABSTRACT

THE WAROONA FIRE

The Waroona fire burnt over 68,000 ha and destroyed more than 160 homes in southwest Western Australia in January 2016. This conference paper is an abbreviated and less technical version of a longer case study that has been submitted to the Journal of Southern Hemisphere Earth Systems Science (Peace et al., 2017). More detail and supporting analysis is contained in the JSHESS version and interested readers are directed there.

Our investigation revealed processes that contributed to four episodes of extreme fire behaviour and the findings are highly relevant to other fires where extreme fire behaviour may develop. This study draws on two reports that highlight the difference between observed FDI's and fire activity at Waroona (Bureau of Meteorology, 2016 and McCaw et al., 2016).

There were two pyroCb events; both were associated with anomalously fast fire spread in the prevailing winds; one ignited new fires downwind and the other was against normal diurnal timing. Two evening ember storms occurred; the first impacted the town of Waroona and on the second evening, there were two fatalities when the fire made an unexpected run and produced a destructive ember storm over the town of Yarloop.

EXTENDED ABSTRACT

THE WAROONA FIRE

The Waroona fire burnt over 68,000 ha south of Perth on 6 and 7 January 2016, with devastating consequences for the towns of Waroona and Yarloop and the broader community of Western Australia. Figure 1 shows the fire perimeter and nearby localities. The meteorology and fire behaviour have been closely examined in a multidisciplinary case study and processes have been identified that are likely to have contributed to the extreme fire behaviour that was observed (Peace et al., 2017). This paper is an abbreviated and less technical version of the longer case study.

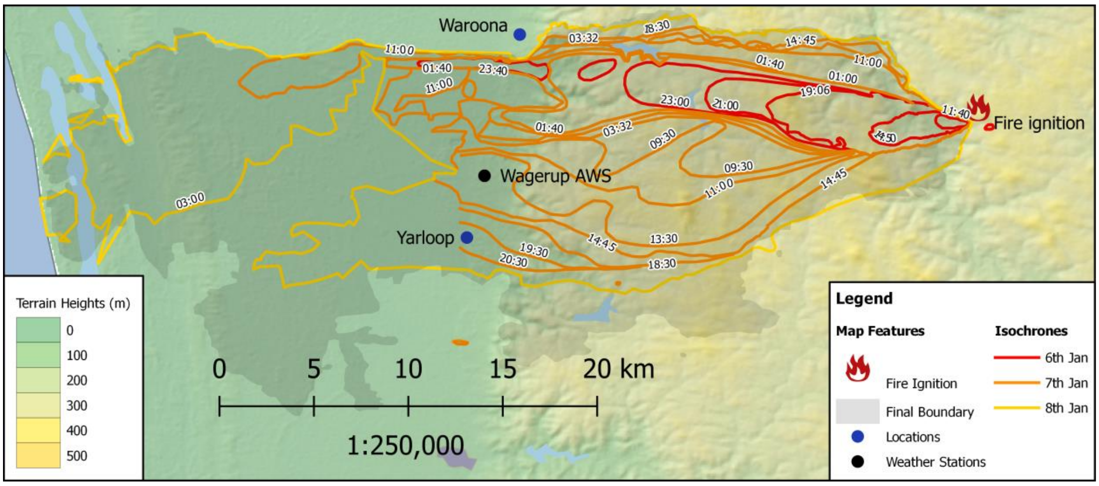

Figure 1: Reconstruction of the spread of the Waroona fire, modified from McCaw et al. (2016). This case study focusses on the first two days of the fire (red and orange isochrones show 6 and 7 January respectively).

FOUR EPISODES OF EXTREME FIRE BEHAVIOUR

During the first two days of the fire there were four separate periods of extreme fire activity. PyroCb developed over the fire on two separate occasions; the first was late afternoon on 6 January and the second at around midday on 7 January. Two destructive evening ember showers occurred; the first over the town of Waroona on 6 January and the second, on 7 January, destroyed the town of Yarloop. None of the four episodes of extreme fire behaviour occurred when fire danger indices (FDI's) were at their daily peak. Times in this paper are quoted as Local Time (LT) in order to easily reconcile events with diurnal trends.

PYROCB ON 6 JANUARY

Figure 2 shows a satellite image of the pyroCb on 6 January. The pyroCb development was triggered by local convergence on the leading edge of a sea breeze front (for more detail see Peace et al., 2017). The pyroCb plume extended to above 14 km and it produced an extensive cirrus anvil, a feature consistent with stratospheric intrusion. Observers saw lighting from the pyroCb ignite a new fire downwind of the main fire front, closer to the town of Waroona, although no time or location is recorded.

Figure 2: High resolution visible image from Himawari satellite at 1810 LT 6 January 2016.

The downdraft outflow from the storm hit passed across the nearby Automatic Weather Station (AWS) at Wagerup refinery, where a peak in wind speed and wind gust and a marked drop in temperature was recorded just before 1900LT (see Figure 3). The gust outflow recorded at Wagerup AWS illustrates the danger of pyroCb (or dry convective microbursts) produced in a fire environment as the outflow boundary produces increased wind speed and enhanced turbulence. Consequently, the gust front provides a local environment which is favourable for anomalously fast and erratic fire spread as well as transport of large quantities of embers. Pyroconvective dry microbursts have been associated with fatalities at other fires (including the Dude Fire (Goens and Andrews, 1998), the Yarnell Fire (Yarnell Serious Accident Investigation Team, 2013) and the Waldo Canyon Fire (Johnson et al., 2014).)

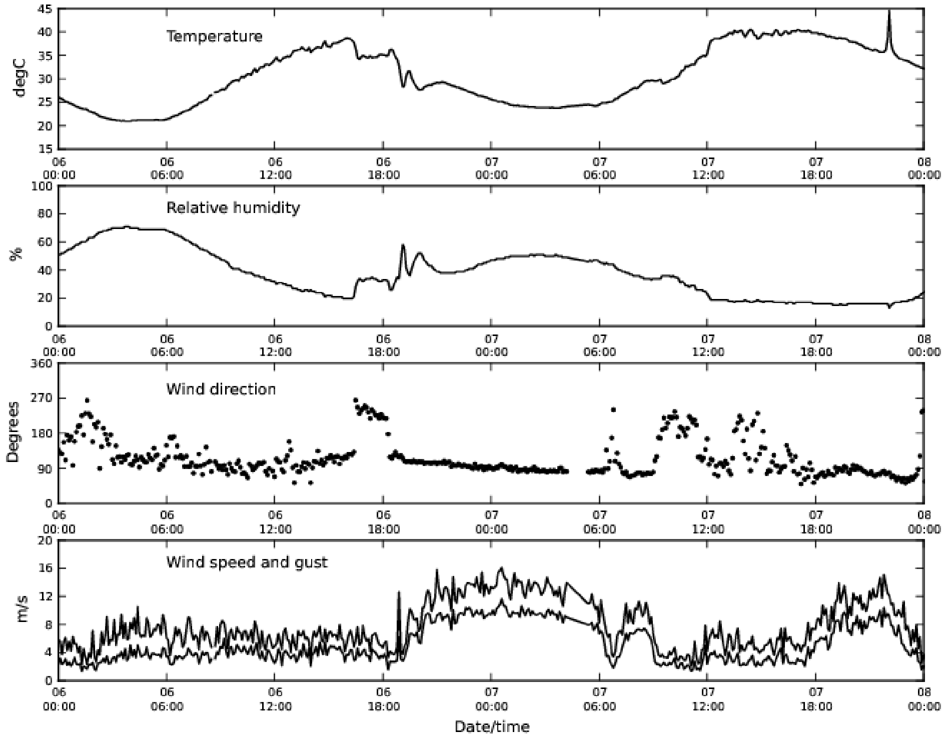

Figure 3: Observations from Wagerup Automatic Weather Station from midnight 6 January to midnight 8 January 2016.

The environmental near surface winds were relatively light during the pyroCb event and the rate of spread of the head fire does not reconcile with the observations at nearby AWS (see McCaw et al., 2016 for further detail).

PYROCB ON 7 JANUARY

On 7 January, a pyroCb developed over the fire during the late morning, against normal diurnal trends (e.g. Peterson et al., 2016). Features of the storm that can be seen in Figure 4 include a low level smoke layer, a deeply turbulent vertical plume and a cirrus outflow layer near the top of the atmosphere.

Figure 4. Pyrocumulonimbus over the Waroona fire on 7 January 2016 (Photo provided by Tracey Vo, Channel 9 Perth).

The late morning development of pyroCb on 7 January is unusual. We attribute it to two factors; firstly, high energy output resulting from the long fire front, which was nearly 20 km long and spreading in heavy, 20 year old fuels and secondly, rapid forward spread and resulting high energy release driven by momentum entrainment of the morning low level wind jet (the wind maximum was located around 1-1.5km above the surface).

The late morning convection featured two transient pulses that overcame a weak elevated temperature inversion, and strong updrafts produced a pileus cloud cap above the pyroCb. Strong, fire-induced low-level wind convergence along the fire-line can be seen in the wind velocity fields on Doppler radar. It is likely that heavy fuel loads and the low-level convergence were key factors in meeting the threshold for deep convection to occur.

THE EMBER STORMS AT WAROONA AND YARLOOP

At around 2100LT on the evening of 6 January, the Incident Management Team received reports that the town of Waroona was under sustained ember attack. The source of the embers is likely to have been a new spot fire that was started by a lightning strike closer to the town than the main fire front. The analysis described in Peace et al., (2017) indicates that the new fire was probably driven towards Waroona by a density current outflow produced by the thunderstorm downdraft, assisted by channeling along a local gully.

On the evening of 7 January, the town of Yarloop was destroyed by an ember storm. The ember storm was described as "*…the whole thing exploded in a massive downdraft*" (in Ferguson, 2016). Heavy, long unburnt fuels to the east of the town were a significant contributing factor to the intensity of the fire, as well as being a source of fire brands. However, the change in fuels does not fully explain the exponential increase in fire activity.

Close examination of velocity scans from the Doppler radar show the smoke plume doubled in vertical extent from below 4 km to nearly 8 km in around 20 minutes. In addition, localised convergence can be seen on radar at the time Yarloop was destroyed by the ember storm.

THE DYNAMICS OF DOWNSLOPE WINDS AND EMBER STORMS

Analysis of the observations and Numerical Weather Prediction output (see Peace et al., 2017) suggests that the evening ember storms over Waroona and Yarloop were caused by the fire interacting with downslope winds.

Downslope winds occur along lee slopes during the evening and overnight period under favourable conditions. A temperature inversion above the mountain top acts as a stable lid, effectively squeezing the airstream as it moves up the windward slope, into a narrow channel above the topography. On the downward slope, the squeeze is released and the airstream accelerates and develops into highly turbulent flow. Under certain circumstances a hydraulic jump can develop, which takes a wave form located above the base of the slope, with rapid up and down motion in the jump region.

The slopes of the Darling Scarp are known to experience downslope winds, (locally known as 'scarp winds') and on both evenings, Wagerup AWS shows an increase in wind speed consistent with downslope wind development (see Figure 3). An important aspect of the dynamics of downslope winds in driving ember showers is that downslope winds are extremely gusty, so that, when co-located with a fire, the environment is highly turbulent and conducive to ember transport, particularly if local fuels are favourable for firebrand production.

Two conceptual models (with and without a hydraulic jump) are presented in the schematics in Figures 3 and 4. The schematics are not intended to be to scale and have been produced to provide a visual representation, rather than an accurate scientific depiction of the physical processes. Figure 5 depicts a downslope wind environment without a hydraulic jump; the gusty and turbulent downslope winds enable transport of firebrands to adjacent properties. Figure 6 shows a downslope wind environment with a hydraulic jump present; the firebrands are lofted and rapidly accelerated upwards a distance of several hundred metres, then deposited rapidly downwards onto properties.

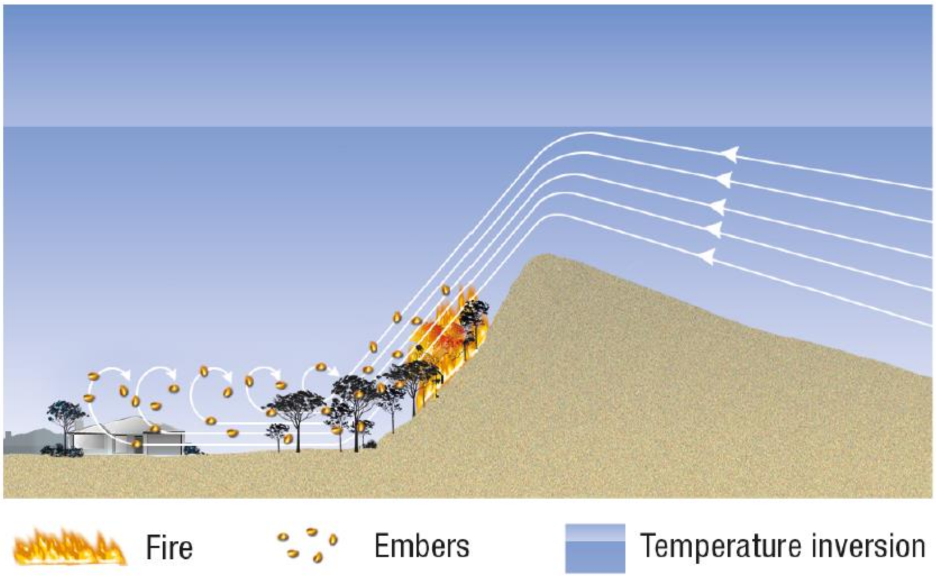

Figure 5. Schematic showing how downslope winds can transport embers from a fire burning near the base of the hill (without the presence of a hydraulic jump).

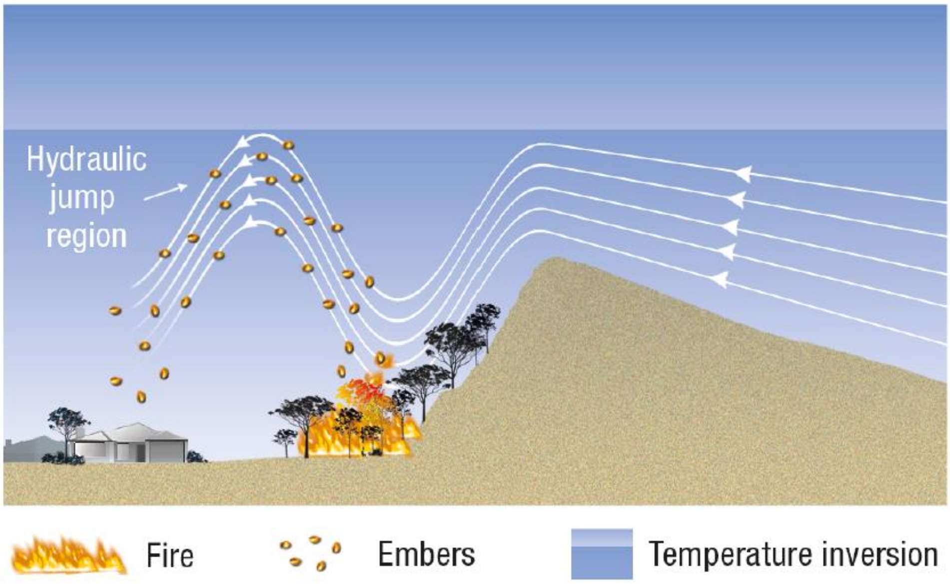

Figure 6. Schematic depicting transport of embers by downslope winds where the embers are lofted by the hydraulic jump then deposited on properties.

The presence of a hydraulic jump provides an enhanced mechanism for lofting and deposition of large numbers of firebrands over a local area. A feature of both models of downslope wind transport is that the transport of embers occurs quickly over a short distance in the vertical plane, and this permits large numbers of fire brands with burnout times of a only a few minutes to travel distances of hundreds of metres to a few kilometres (Ellis (2013) reports burnout times up to seven minutes). In comparison, embers lofted vertically in a traditional fire plume are likely to have a longer transport time and therefore more likely to extinguish before deposition.

A simple 'back of envelope' calculation, using wind speeds of 50-80km/h (typical for a downslope wind regime) and a firebrand burnout time of 2-3 minutes, suggests embers may travel up to 2-4 km before extinguishing. Importantly, the embers in downslope winds can be produced and transported in large numbers when fuel types are favourable and this is consistent with the description of the ember attack on Waroona and Yarloop.

LESSONS LEARNED FROM THE WAROONA FIRE

There are several findings from the Waroona fire that may be applied to future events to help identify situations where an escalation to extreme fire behaviour is possible. Advance warning of such circumstances may enable mitigation efforts that allow lives and properties to be saved. This section is intended to be of use for fire weather forecasters and for fire managers in the context of operational decisions and planning at fire grounds.

FDI PEAK

The timing of the extreme fire behaviour at Waroona was against normal diurnal trends in the fire danger index (FDI). The normal peak in FDI occurs mid-afternoon, whereas the four episodes of extreme fire behaviour at the Waroona fire were in the late afternoon, early evening, mid evening and late morning. This timing discrepancy has been seen at other fires, but there are limited operational tools for identifying such situations correctly in advance and the knowledge gap presents opportunity for development of robust predictive aids.

Both of the pyroCb episodes produced extensive crown fires and defoliation. A correlation between the development of a significant plume or smoke column over a fire and transition to crown fires has not been established in the scientific literature. However, anecdotal evidence suggests links between likelihood of defoliation or crown scorch and an unstable atmosphere, even in benign wind and temperature conditions.

A contributing factor to the extreme fire behaviour is likely to have been limited overnight fuel moisture recovery in the hot, dry conditions.

Fire managers periodically describe prescribed fires that are much more active than expected in the prevailing meteorological surface conditions. Atmospheric stability is a contributing factor in some cases, but including this information into operational risk assessments is difficult. However, there is a need for more information on how the vertical structure of the atmosphere may affect fire behaviour. This may include greater use of available tools such as C-Haines (Mills and McCaw 2010), FireCape (following Potter, 2005) and Mixing Height. However, these are subjective and it would be of benefit to have improved approaches on how to interpret the information and relate it to likely fire activity, especially in a quantitative way.

ENTRAINMENT

Entrainment in this context describes the process by which a fire plume brings down elevated higher momentum air to the back of the head-fire, which consequently increases the rate of spread above that expected given the prevailing surface winds. At the Waroona fire, there are two occasions when this seems to have occurred; during the morning pyroCb event and during both evening ember storms.

The effects of dry air from above the surface impacting a fire have previously been described, for example at the Wangary fire (Mills, 2008). A region of dry air was identified over the Waroona fire ground on the evening of 7 January at around the same time the fire activity escalated. However, increase in fire activity cannot be directly attributed to the dry air, as there will be a time lag due to the delayed response of fine fuels to changes in atmospheric humidity. In contrast, the response of a fire to entrainment of momentum will be almost instantaneous. At going fires, data describing the airmass above a fire should be examined and the potential for entrainment should be assessed, recognising that the impacts of momentum entrainment on fire behaviour will be dominant over moisture.

DOWNSLOPE WINDS

A key finding from the examination of the Waroona fire (Peace et al., 2017) is that turbulence associated with downslope winds produced the transport mechanism for the ember storm over Yarloop that resulted in two fatalities. Any fire burning in a downslope wind regime has the potential to develop very rapidly and produce ember showers and highly anomalous fire spread. This is highly relevant for Australian fires as there are many locations where downslope winds occur, including the Mount Lofty Ranges in South Australia and the Darling escarpment in Western Australia. The environments that are favourable for downslope winds are also often favourable for enhanced rainfall and therefore heavy loads of flammable vegetation, thus exacerbating the risk to life and properties.

Predicting the potential for development of downslope winds can be assessed through the strength of the pressure gradient across a region in combination with the structure of the temperature and moisture profiles above topography. In addition, Numerical Weather Prediction (NWP) forecast models are run at sufficiently high resolution over Australia to coarsely resolve the downslope wind mechanism. In forecasting operations, examining NWP cross sections of wind vectors and potential temperature can identify the presence of stronger, elevated winds.

Forecasting techniques should be complemented by local knowledge of downslope wind regimes. 'Hot spots' in downslope winds typically form near gullies, and knowing the locations where winds are strongest may be critical information at fire grounds. Downslope winds develop near the lee slopes of ranges. Therefore, the risk of escalation for fires may not be identified, as a conventional risk assessment may identify the windward slope as more exposed to stronger winds and consequently having higher fire risk.

Fires burning in elevated terrain are affected by topographic processes due to the fire behaviour being impacted by unstable atmospheric environments and by fire modified winds (e.g. Sharples, 2009). The effect of topographic wind modification and fire interaction is typically assessed over high terrain, specifically over steep mountain ranges. However there are cases of extreme fire behaviour triggered by wind flow over terrain with elevation of just a few hundred metres (e.g. Kepert et al. 2016).

PYROCUMULONIMBUS

Two separate pyroCb events developed over the Waroona fire. While in both cases the fire was burning through heavy fuels beneath a conditionally unstable atmosphere, the trigger and the mechanism driving each event were slightly different. In both cases, the energy released by the fire triggered PyroCb development in an environment that was marginally unfavourable for non-fire thunderstorms. On the 6 January, the trigger for thunderstorm development was the passage of a sea breeze front, This demonstrates that wind change boundaries near fires should be closely monitored to assess their potential for triggering an increase in fire activity. The radar data showed the pyroCb updrafts and downdrafts separated by a considerable distance (Peace et al. 2017). The evidence that has been examined suggests that the downdraft produced anomalous fire spread speed and direction and drove a spot fire that was ahead of the main fire front closer to the town of Waroona.

On 7 January pyroCb developed late morning, against normal diurnal trends. The pyroCb development has been linked to the long fire line of 10-20 km, which combined with a deep flaming zone in heavy fuels to produce a high instantaneous energy release over a large area. Long fire lines should be a watch-out for deep pyrocumulus or pyroCb. Doppler radar data showed strong convergence in the fire modified winds and it is likely the convergence played a role in triggering the two pyroCb pulses that occurred. Radars are not always in fortuitous proximity to large fires, but any fires near radar should be closely monitored on both reflectivity and velocity scans, and skilled interpretation may assist in critical decisions (e.g. McCarthy et al. 2016).

The timing of the extreme fire behaviour and the ferocity with which it burnt took experienced fire managers by surprise. The fire reconstruction (McCaw et al., 2016) describes discrepancies between the observed and predicted spread rate at several stages of the fire. These discrepancies were found by examining field observations such as leaf freeze and comparing calculated spread rates. Fire prediction tools currently used operationally in Australia are focused on near-surface conditions. Therefore, they have no capacity to capture the potential for pyroCb development, or fire plume interaction with downslope winds; which are the processes that led extreme fire behaviour at the Waroona fire.

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