HAZARD NOTE

ISSUE 48 JUNE 2018
TOPICS IN THIS EDITION | FIRE IMPACTS | FIRE SEVERITY | FIRE WEATHER

EXTREME FIRE BEHAVIOUR: RECONSTRUCTING THE WAROONA FIRE PYROCUMULONIMBUS AND EMBER STORMS

ABOUT THIS PROJECT

This research was conducted as part of the *Coupled fire-atmosphere modelling* project.

AUTHORS

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SUMMARY

The Waroona bushfire, 100 km south of Perth, burnt 69,000 ha, destroyed more than 160 homes and caused two fatalities in Yarloop in January 2016. During the first two days of the fire, which hit both the towns of Waroona and Yarloop, there were four periods of extreme fire behaviour: two involving massive pyrocumulonimbus (bushfire thunderstorm clouds) and two major ember showers. Pyrocumulonimbus developed over the fire on the evening of 6 January and around midday on 7 January. Destructive ember showers occurred on two consecutive evenings: at Waroona on 6 January, and then Yarloop on 7 January. The Yarloop ember storm destroyed the town. None of these four episodes matched the time of highest fire danger as measured by fire danger indices. This *Hazard Note* is based on a case study that examined the meteorology and fire reconstruction in parallel, and identified the dynamic processes behind the extreme fire behaviour, providing valuable knowledge to apply during future events.

▲ **Above:** FIREFIGHTERS BATTLING THE WAROONA BLAZE. PHOTO: DEPARTMENT OF FIRE AND EMERGENCY SERVICES WA.

CONTEXT

Extreme fire behaviour can threaten the lives of local residents and firefighters, destroy properties and infrastructure and severely damage natural environments. Pyrocumulonimbus clouds are an indication of extreme fire behaviour, and due to their convective nature they can produce gusty, erratic winds that may result in changeable and very rapid fire spread in any direction. Understanding the triggers and factors that produce extreme fire behaviour will enable predictive tools to be developed that can help mitigate its impacts.

Following the Waroona bushfire, an independent review was completed by Euan Ferguson on the response to the fire. The *Report of the Special Inquiry into the January 2016 Waroona Fire* noted two opportunities for the Department of Fire and Emergency Services WA and Department of Biodiversity, Conservation and Attractions to engage with the CRC and the Bureau of Meteorology to investigate the causes of and effects of pyrocumulus weather occurrences on bushfire behaviour, and the prediction of lightning strikes.

BACKGROUND

During the first two days of the Waroona bushfire, there were four episodes of extreme fire behaviour. Two separate pyrocumulonimbus (pyroCb) events developed; both were associated with unusually fast fire runs given the prevailing surface wind speeds. The first pyroCb on 6 January developed a smoke plume over 14 km high and ignited new fires downwind. The second pyroCb on 7 January occurred earlier than the normal timing of surface-based thunderstorms. Two evening ember storms also occurred: the first impacted Waroona when the incident management team believed the fire to be several kilometres further east, and the second resulted in the destruction of Yarloop and caused two fatalities.

The extreme fire behaviour at the Waroona fire was unexpected and did not coincide with the time of day of highest fire danger, as measured by the Forest Fire Danger Index. Surface conditions of temperature, relative humidity and wind gave no indication that the environment was conducive to extreme fire behaviour.

A collaborative case study on the Waroona bushfire has identified the dynamic interaction processes between the fire, the local topography, local fuels and meteorology that contributed to the observed, extreme fire activity.

BUSHFIRE AND NATURAL HAZARDS CRC RESEARCH

The limitations of surface-based approaches to fire prediction using the McArthur grass and forest fire danger indices are widely recognised in Australian fire management. The emphasis on surface meteorological inputs provides a limited picture of the three-dimensional, time-evolving environment that drives a bushfire. In particular, interactions between the fire, the atmosphere and surrounding topography can drive processes such as wind modification and plume dynamics in the vicinity of a fire. However, these processes are complex and manifest differently at different fires, making them hard to define and difficult to simplify into a predictive process. The team examined case studies to gain insight into the contributing factors and the dynamic processes that drive extreme fire behaviour. The study of the Waroona fire benefited greatly from collaboration across different fields of expertise. This collaboration allowed the overlaps between the fire behaviour and surrounding meteorology to be explored at different stages of the fire.

RESEARCH FINDINGS

The four extreme fire behaviour episodes at the Waroona fire are detailed here.

Pyrocumulonimbus events

During the late afternoon of 6 January, a pyroCb developed over the fire, with a dense, rotating smoke plume extending to higher than 14 km. The pyroCb produced an extensive cirrus anvil (anvil-shaped thunderstorm cloud), evidence that it had accelerated upwards so powerfully that it had 'punched' into the stratosphere. Lightning from the pyroCb ignited new fires downwind of the main fire front and a density current outflow (a downdraft carrying heavier, cooler air in the compensating downwards column of the pyroCb) was observed at the nearby Wagerup Automatic Weather Station (AWS).

This gust outflow from the pyroCb downdraft recorded at Wagerup AWS on the evening of 6 January shows the potential impact of dry (or hybrid) microburst environments when a fire is burning. Dry microbursts can produce strong, downdraft winds and have been associated with fatalities at other fires; the Waroona pyroCb outflow, seen on radar and AWS observations, illustrate the hazard associated with the phenomenon. Thunderstorm and pyroCb outflow boundaries are regions of enhanced turbulence and are therefore conducive to transporting large quantities of embers, as well as unusually fast and erratic fire spread.

On 7 January, a pyroCb developed in the late morning, which is unusual timing for surface-driven thunderstorm activity. This study shows that two processes drove the pyroCb. The first was high energy release along a 20 km fire line spreading in heavy vegetation that had been unburnt for 20 years. The second was rapid forward spread driven by the movement of above surface winds down to the surface, via a process called 'momentum entrainment', within the fire plume. This circulation process involved the downward motion of faster, higher energy air from a 'wind maximum' – a fast channel in the atmosphere – located one to three kilometres above the surface. Doppler radar velocity scans showed strong, fire-induced, low-level convergence. This pyroCb featured two short-lived pulses of cloud to the upper levels of the atmosphere when energy release from the fire was sufficient to overcome a weak elevated temperature inversion.

Although pyroCbs occurred on both days

WHAT IT MEANS

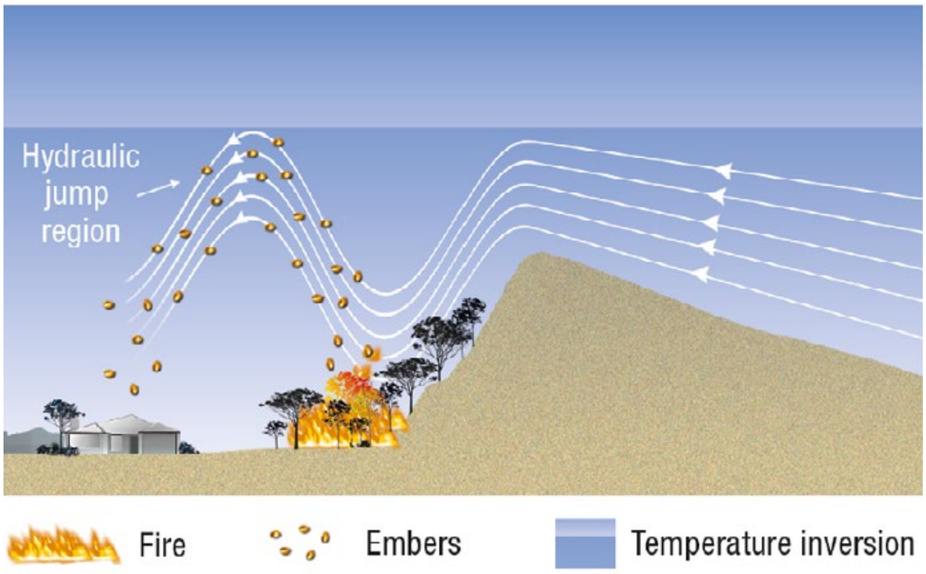
Pyrocumulonimbus (pyroCb) is a cumulonimbus (thunderstorm) cloud that forms over a bushfire. PyroCbs develop in unstable atmospheres and are triggered by the heat energy released by the fire. They can produce lightning, hail and tornadoes. PyroCb are usually associated with large (often crown) fires, high energy release, high flames and indicate extreme fire behaviour. Due to their convective nature they can produce gusty, erratic winds that may result in changeable and very rapid fire spread in any direction.

Density current outflow is the downdraft from the pyroCb. The pyroCb has an updraft and compensating downdraft. Condensation and evaporation processes make the downdraft air denser (heavier) than the surrounding air, so the downdraft accelerates downwards until it hits the surface, where it spreads out as a turbulent flow, producing gusty winds in any direction.

Downslope winds form in the lee slope of mountain ranges in the evening and overnight. They occur when a cooler air mass moves up the windward slope, and is 'squeezed' between the hilltop and a temperature inversion above the ridge. Once on the (warmer) leeward slope, the air accelerates downwards in a highly turbulent, gusty flow. Downslope winds occur regularly in favourable locations during spring and summer and are known colloquially as 'gully winds' in Adelaide and 'scarp winds' in Perth. Downslope winds can produce a hydraulic jump, an atmospheric wave with rapid up and down motion, which, if corresponding with a fire plume, can rapidly lift and deposit many embers (see figure 1, page 3). Even without a hydraulic jump, the turbulence in gully winds can rapidly transport firebrands locally.

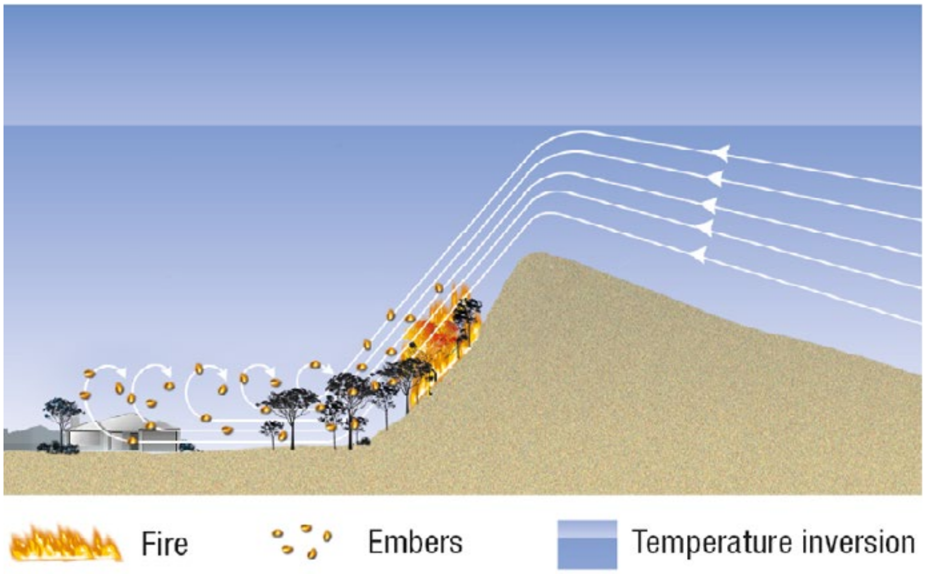
▲ **Above:** EXTREME FIRE BEHAVIOUR DURING THE WAROONA FIRE.
PHOTO: DEPARTMENT OF FIRE AND EMERGENCY SERVICES WA.

FIGURE 1



▲ **Above:** HOW A HYDRAULIC JUMP CAN SPREAD EMBERS AHEAD OF A FIRE FRONT.

FIGURE 2



▲ **Above:** HOW DOWNSLOPE WINDS SPREAD EMBERS AHEAD OF A FIRE FRONT.

END-USER STATEMENT

While our current fire behaviour models perform well under a broad range of conditions, they have been shown to be incapable of representing the complex fire behaviour that can occur when large bushfires interact with the atmosphere. Fires of this type tend to be particularly dangerous and have resulted in extensive damage and loss of life. Having a sound understanding of factors that trigger coupling between a fire and the atmosphere, together with the ability to predict fire behaviour in real time, would better place fire managers to respond to fires of this type and to minimise impacts on the community. This case study is an important step in better understanding extreme fire behaviour.

– Dr Lachlan McCaw, Principal Research Scientist, Department of Biodiversity, Conservation and Attractions Western Australia

in favourable environments, the triggers and thresholds were different. On 6 January, a sea breeze front triggered the pyroCb, which developed in the late afternoon, at a similar time as non-fire thunderstorms. In contrast, on 7 January, the pyroCb developed in the late morning, against normal daily thunderstorm trends.

On both days, vertical wind shear (changes in wind direction and speed with height) contributed to the coherent structure and rotation of the fire plume, which enabled strong plume updrafts that injected smoke and other pollutants into the stratosphere.

Ember shower in downslope winds

On both evenings, the Wagerup AWS showed an increase in wind speed consistent with downslope winds in the area, which is known to experience gusty ‘scarp’ winds during the evening and overnight. An important aspect of the dynamics of downslope winds in driving ember showers is their highly turbulent nature near where the base of the hill meets the coastal plain. When co-located with a fire, downslope winds produce an environment that is highly conducive to spotting and ember showers, particularly if vegetation is favourable for firebrand production. High resolution modelling shows the presence of a hydraulic jump adjacent the scarp. The hydraulic jump is an atmospheric wave with rapid up and down motion that can enhance localised lofting and deposition of many firebrands over an area (see figure 1, above). The high velocities in the hydraulic jump mean that embers are more likely to be deposited while still alight (that is, large numbers of embers can be transported significant distances within the ember’s burnout time).

On the evening 6 January, Waroona was reported to be under ember attack around 9pm. The ember attack is likely to have been due to lightning ignition of a new fire closer to the town, which was subsequently driven by the density current outflow from the pyroCb. Local downslope winds and a hydraulic jump produced the mechanism for localised lofting, transport, and turbulent dispersion of firebrands, which resulted in the ember attack over Waroona.

The evening ember storm on Yarloop on 7 January was also driven by downslope winds, similar to the ember attack over Waroona. Dense, long-unburnt vegetation just to the east of Yarloop contributed significantly to the intensity of the fire, as well as being a source of firebrands. Doppler radar velocity scans show significant vertical fire plume development and localised convergence at the time Yarloop was destroyed by the ember storm.

HOW IS THE RESEARCH BEING USED?

The case study’s findings have helped identify the drivers of the unexpected extreme fire behaviour at the Waroona fire.

▲ **Above:** THE RAPID SPREADING OF THE WAROONA FIRE WAS CAUSED BY UNUSUAL WEATHER PHENOMENA. PHOTO: DEPARTMENT OF FIRE AND EMERGENCY SERVICES WA.

The lessons relating to pyroCb development and impacts and ember transport in downslope winds can be applied to bushfires in many other locations around Australia. This study will help to raise awareness of situations in which extreme fire behaviour may not occur at the same time or place as the maximum observed fire danger index.

This case study has been presented at many forums that included numerous operational personnel, such as fire behaviour analysts, meteorologists embedded with fire and other agencies, fire weather forecasters and fire managers. In reaching this audience, the researchers have shared the study's findings with operational decision-makers, equipping them to better identify potential risks at future fires and mitigate destructive impacts.

This study builds on previous CRC research on mountain waves (see *Hazard Note* 24) and ember transport in plumes, by showing a specific case for downslope winds. The impact of downslope winds at the Waroona fire shows how a highly turbulent low-level wind environment can be conducive to destructive ember showers.

This research could be applied to develop a predictive tool that identifies environments and localities that are favourable for winds conducive to the development of ember showers. This is likely to complement other CRC research, including the project *Improved prediction of severe weather to reduce community impact*, which is developing tools for predicting pyroCb and for ember transport in smoke plumes. Both projects highlight the need to identify environments and situations when normal daily patterns of fire danger are unlikely to apply, in order that risks can be communicated to fire managers and the community.

FURTHER READING

Peace M, McCaw L, Santos B, Kepert J, Burrows N and Fawcett R (2017), Meteorological drivers of extreme fire behaviour during the Waroona bushfire, Western Australia, January 2016. *Journal of Southern Hemisphere Earth Systems Science*, http://www.bom.gov.au/jshess/docs/2017/Peace.pdf

Kepert J, Tory K, Thurston W, Ching S, Fawcett R and Yeo C (2016), Fire escalation by downslope winds, *Hazard Note* 24, Bushfire and Natural Hazards CRC.

FUTURE DIRECTIONS

This project will continue until 2020. The next phase of the research, currently in progress, is to run simulations of the Waroona bushfire with the coupled fire-atmosphere model ACCESS-Fire. The project has substantially developed the ACCESS-Fire model, which was originally created by Monash University and the University of Melbourne. This model couples the Australian Community Climate and Earth-System Simulator (ACCESS) Numerical Weather Prediction model and a range of fire spread prediction models, such as the McArthur, Rothermel and CSIRO grass and forest models. ACCESS-Fire can simulate large fires with full coupling to the atmosphere. In the coupling process, fire spread and vegetation burnt is calculated at each time step. The energy released by the fire is passed to the atmospheric model as a heat and moisture flux, which changes the atmosphere, particularly the nearby winds. The model results show how the energy released by a fire can modify the surrounding atmosphere, as well as resolve the complex interactions with local terrain. This develops the understanding of dynamic fire behaviour and enables predictive tools to be developed that can be used to mitigate the impacts of large fires. The project's researchers plan to continue collaborating on ACCESS-Fire with colleagues at the University of Melbourne.

The Bushfire and Natural Hazards CRC is a national research centre funded by the Australian Government Cooperative Research Centre Program. It was formed in 2013 for an eight-year program to undertake end-user focused research for Australia and New Zealand.