Operational prediction of extreme bushfires

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Abstract

Fire behaviour is changing as new modes of fire spread dominate in south-eastern Australia, making extreme bushfires significant risk drivers during bad fire seasons. This is linked to changes in climate and landscape hydrology. A Hierarchical Predictive Framework has been developed specifically to predict the risk of extreme bushfires in south-east Australia. It uses temperature anomalies and the accumulation of river drying events to predict seasonal risk. If that risk is raised, a Blow-Up Fire Outlook model looks at fire weather forecasts and fireground context for specific risk prediction. This guides operational intelligence gathering to support decision-making by incident management teams. The Hierarchical Predictive Framework is based on over 20 years of archival data on extreme bushfires and their context. It is intended to work alongside, but not replace, existing operational systems. Tools like the framework can help keep fire crews safe in the face of risks like branched troughs and the rapid rise in prominence of foehn-driven fires in Australia, as well as the rapidly growing threat from fires that spawn pyrocumulonimbus clouds (pyroCbs).

Introduction

Through the 1980s and 1990s, fire agencies in Australia put significant effort into using the El Niño-Southern Oscillation Index as a seasonal outlook tool. It measured reversing seas surface temperature gradients across the equatorial Pacific Ocean that affected weather patterns on a hemispheric scale. This work was supported by development efforts by the Bureau of Meteorology[1] and by the media in the reporting on approaching fire seasons. It worked well and is still widely used.

El Niño years were hot and dry (although not necessarily windy) and produced bad fire seasons. La Niña years were the opposite and these 2 states typically defined the maximum and minimum conditions facing fire services. After the 1997 El Niño event, the climate across the south-east regions of Australia began changing. In places like Canberra, the average temperature has risen over 3 degrees Celsius, while summer temperatures have risen by more (see Figure 1). This upward trend has major annual variations imposed on it, so a year that falls on the trendline may now exceed the pre-1997 El Niño peaks while a year warmer than the trendline may set new records.

Widespread firefighting operational challenges were experienced during the Australian summer bushfires in 2019–20 and suggest that the fire climate ‘rule book’ has been rewritten. New fire types are occurring with increasing frequency. PyroCbs are fire thunderstorms that form in violent pyro-convective plumes and these are increasing in frequency (McRae 2022) (see Figure 2). While fires driven by the foehn effect (hot, dry winds coming off higher terrain) were novel a decade ago (Sharples *et al.* 2010), they are around half of the major events that occurred during the Australian summer bushfires in 2019–20. It is clear that new tools are required.

To support adaptation, a Hierarchical Predictive Framework (HPF) has been developed. This takes lessons from recent research into extreme bushfires that have occurred and draws on long-established knowledge to show strong linkages that allow effective predictive services. Figure 3 shows the framework. It operates on a range of temporal scales, each requiring different concepts. As the fire season gets closer, the scale shrinks and new concepts are applied,

1. Bureau of Meteorology ENSO Outlook, at www.bom.gov.au/climate/enso/outlook/.

producing a nested set of alerts leading up to the tools needed by an Incident Management Team to keep communities and fire crews safe.

The framework has been applied retrospectively to assess its performance. Levels 1 and 2 have been applied to more than 2 decades of data. Level 3 has been partially assessed using data from the Australia's 2019–20 bushfires land temperature anomalies. This paper describes the framework and reports the results of analysis. It shows that the hierarchic approach works well and that the HPF may be an effective operational predictive tool.

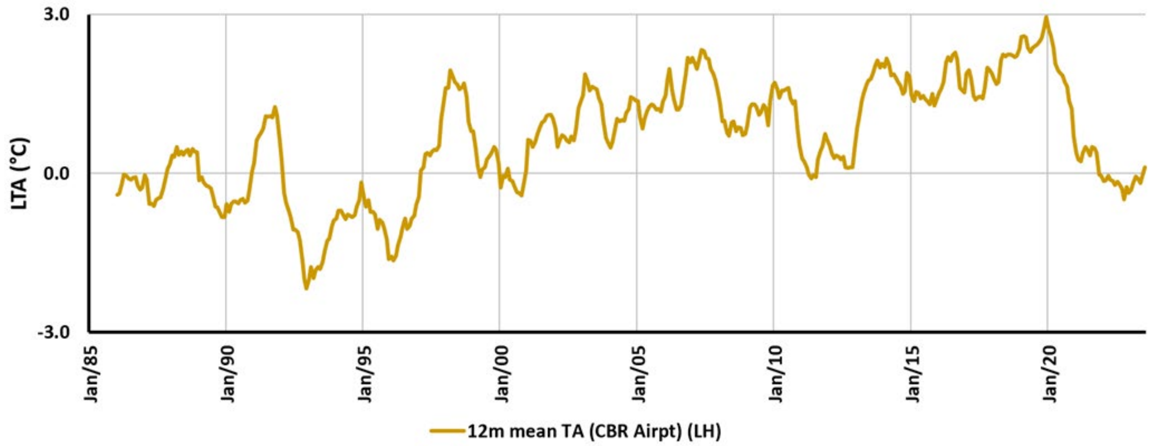


Figure 1: Trends in land temperature anomalies at Canberra airport.

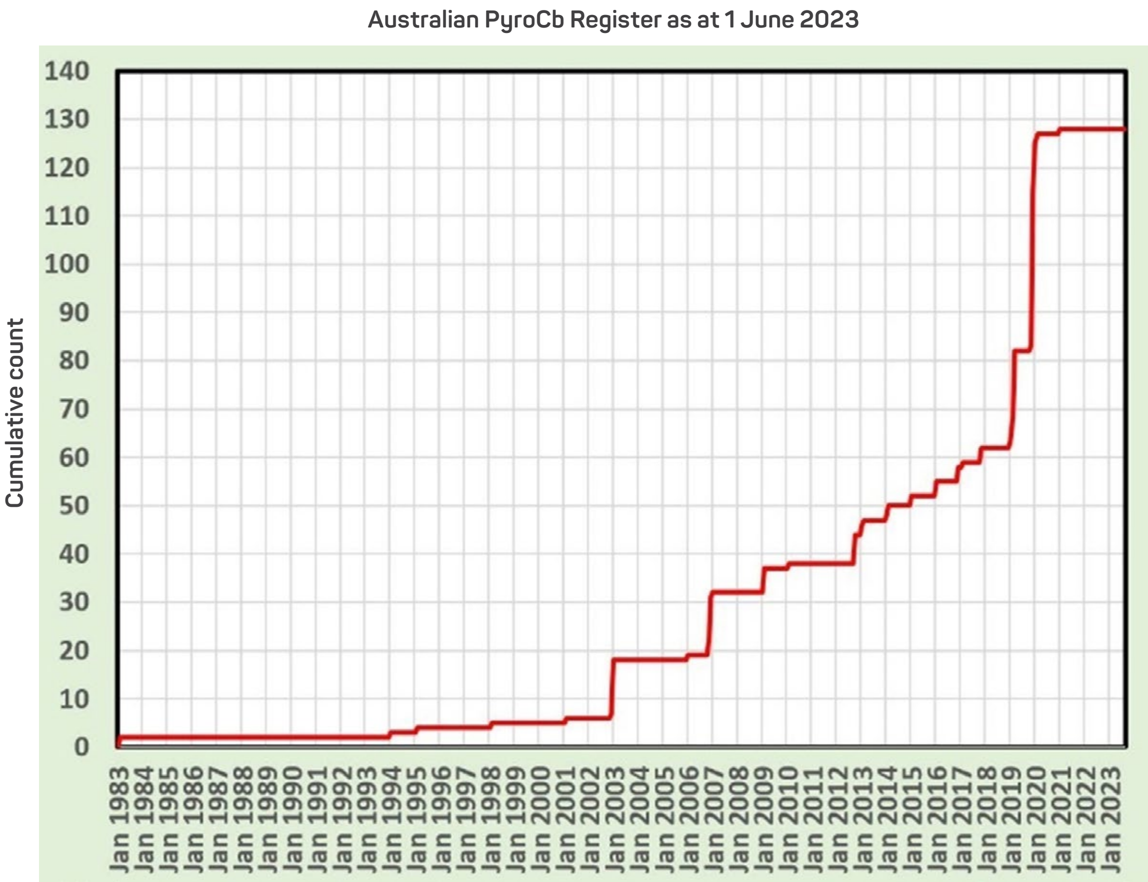


Figure 2: The Australian PyroCb Register, at www.highfirerisk.com.au/pyrocb/register.htm.

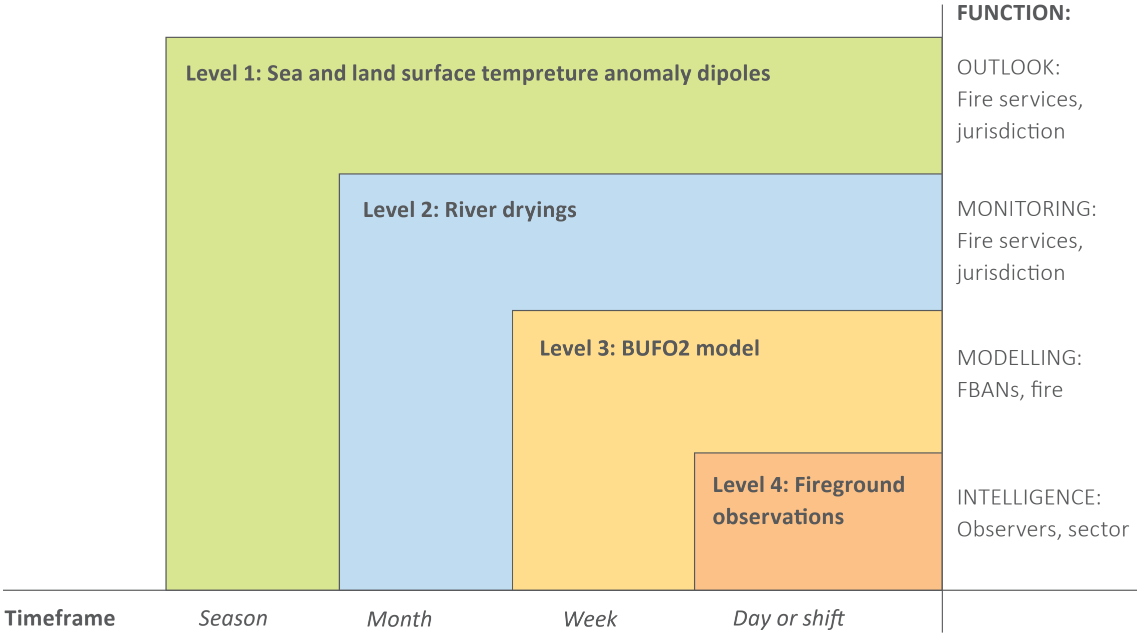


Figure 3: Schematic structure of the HPF showing the linkages between spatial and temporal scales.

Method

With the goal of predicting the potential for the most damaging class of bushfire, the HPF presented here is based on observations of environmental variables. These are brought together in a way that uses 4 levels to provide closer scrutiny if that potential increases. It is designed to support fire service operations.

Level 1

A Level 1 alert is an early monitoring stage alert. Sea surface temperatures (SSTs) started being recorded after the 1983 El Niño event. This was based on buoy and satellite imagery. A climatology of expected SSTs was developed and this is subtracted from the latest observations to derive SST anomalies. Maps were produced by the US National Oceanic and Atmospheric Administration and have been available online. The HPF uses SST anomalies averaged over a 12-month period.

Most blow-up fire events in eastern Australia are in the forests near the coast as well as in the highlands between Melbourne and Brisbane and into Tasmania. A convenient central reference site was selected at Canberra airport within the Australian Capital Territory. Land temperature anomalies are averaged over 12 months in the same way as the marine ones using a Bureau of Meteorology climatology. The difference between the 2 averaged anomalies is termed the 'Canberra Dipole' and is the basis for a Level 1 alert that is issued if the dipole is positive and increasing heading into or during summer.

Figure 4 shows that there has been a radical swing from the heat of bushfires in the 2019–20 fire season into the flooding conditions of the following years. At the time of writing, the black line showing the Canberra Dipole is climbing and there is a potential for a Level 1 alert in either the next summer or the one after. Events from early 2002 leading up to severe bushfires in Canberra in January 2003 suggest that a 9-month lead-up may be required from the current similar situation, suggesting March 2024 is the earliest date.

When positive, the dipole shows the potential for land temperature anomalies to affect synoptic patterns that produce complex trough systems onshore that are involved in most extreme bushfire events. An example is shown in Figure 5, which is an image taken 5.5 hours before the end of 2019. Overlaid are isobars derived from observed air pressure (QNH[2], black lines), inferred trough-lines (based on observed QNH and wind vectors, black dashed lines) and the sea breeze edge (based on dew point temperature gradients, white dotted line). The complexity of the trough system affects fire weather.

It must be remembered that the bushfires in 2019–20 in New South Wales included severe drought, heatwave and raised dust events. The dipole also shows, when negative, the potential for flooding events. Thus, the dipole gives insight into some of the most elevated risks faced by communities.

Level 2

A Level 2 alert relates to the assessment of soil hydrology. Many tools have been developed to assess the dynamics of moisture exchange between soil and fire fuel lying on the ground and these have long been used operationally. This includes a Drought Factor used in the McArthur Forest Fire Danger Index and equivalent measures in Mount's Soil Dryness Index. In recent

2. QNH is an observed measure of air pressure and is different to modelled sea level air pressure.

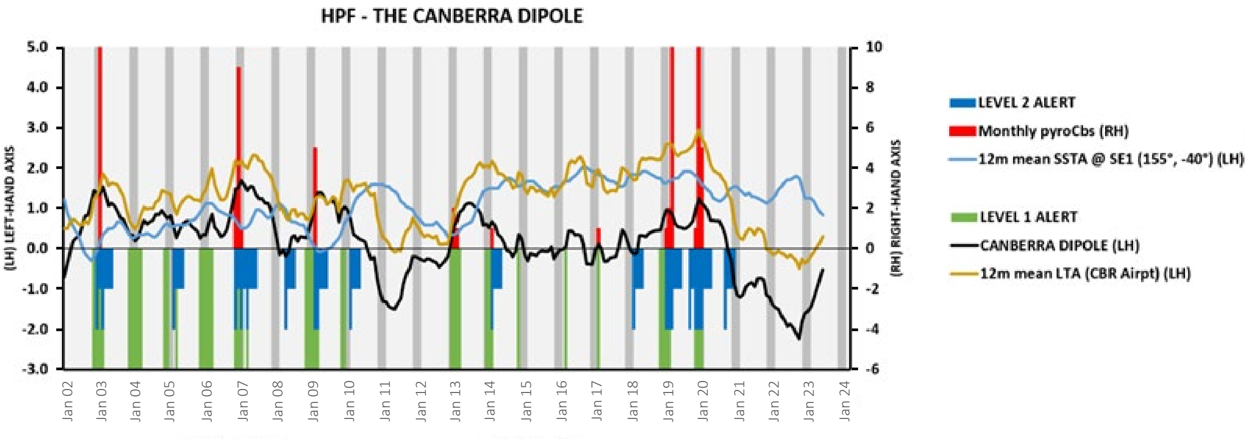


Figure 4: A sample plot of the Canberra Dipole showing the transition from negative values towards zero and positive values in the coming months. Level 2 alerts distinguish the accumulation phase from the ensuing residual phase.

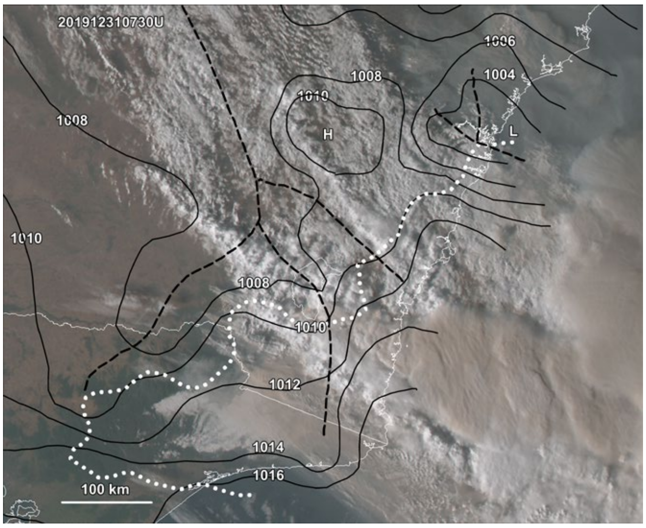


Figure 5: A Himawari-8 satellite image of extreme pyro-convection over south-east Australia.

decades, satellite-based systems have been developed. While these show the flammability of fine fuel, they say little about larger fuel types.

As a drought progresses, deeper layers of the soil profile dry out. Eventually, it is all dry and rivers stop flowing. At this point, all fire fuels—from fine fuel to logs—are flammable on a day of raised fire danger. This is reflected in a formal operational concept (Figures 6a and 6b) developed by ACT hydrologist, Dr Vitaly Kulik, after the 1983 Gudgenby Fire in southern ACT (Kulik 1990). The HPF Level 2 applies that concept to a set of un-dammed reference rivers across the southeast (see Figure 7). If river drying occurs while a Level 1 alert is in place, a Level 2 alert is issued. A Level 2 alert continues for some time after new river dryings cease (the residual phase) and until their levels consistently climb, thus indicating water flowing from the deep subsoil into the stream. If river drying occurs without a prior Level 1 alert, both Level 1 and 2 alerts are issued.

Hydrological Forecast No. 1997/98 - 11
BUSHFRE POTENTIAL FOR: 1 January to 8 January inclusive
REGION: ACT and southeast ACT

Gauging station	Catchment	River Flow (l/s)	Bushfire potential level	Estimated time to next level#
410731	Gudgenby River U/S Mt Tennent	10? ??	>100 sq cm	CRITICAL
410734	Queanbeyan River U/S Tinderry	25 ??	10–100 sq km	1 week
410738	Murrumbidgee River U/S Mt MacDonald	584 ??	>100 sq km	CRITICAL
410761	Murrumbidgee River U/S Mt MacDonald	250? ??	>100 sq km	CRITICAL

• Data not available *
? Some data missing; extrapolated from available data
Estimate assumes no significant rain occurs within the catchment
U/S Upstream of:

Figure 6a: A sample operational bushfire hydrology forecast issued on 30 December 1997 by Ecowise Environmental for the ACT Bushfire Service.

Figure 6b: Subsequent bushfire activity in the hills surrounding Canberra that is rapidly suppressed.
Image: Rick McRae

No.	Site code	Name	Latitude	Longitude	Owner	1st date on record	Minimum level (m)
1	216002	Clyde River at Brooman	-35.4681	150.2394	NSW DILW	8/07/1960	0.17
2	212021	MacDonald River at Howes Valley	-32.8611	150.8611	NSW DILW	9/02/1976	-0.20
3	41000261	Goobarragandra River at Mac's Crossing	-35.4183	148.4357	NSW DILW	13/06/2012	0.86
4	225219	MacAlister River at Glencairn	-37.5162	146.5665	Vic DELWP	7/04/1967	0.25
5	220004	Towamba R at Towamba	-37.0715	149.6593	NSW DILW	5/04/1970	0.35
6	212260	Kowmung River at Cedar Ford	-33.9481	150.2431	NSW DILW	17/05/1968	0.17
7	204014	Mann River at Mitchell	-29.6931	152.106	NSW DILW	10/05/1972	0.35
8	204051	Clarence River at Paddys Flat	-28.7198	152.4198	NSW DILW	26/03/1976	0.60
9	207015	Hastings River at Mt Seaview	-31.3683	152.2425	NSW DILW	31/05/1984	0.55
10	208001	Barrington River at Bob's Crossing	-32.0284	151.4671	NSW DILW	31/01/1944	0.47
11	410535	Murrumbidgee River above Tantangara Reservoir	-35.7706	148.5703	Snowy Hydro Ltd	2/05/1960	0.45
12	401554	Tooma River above Tooma Reservoir	-36.1	148.26	Snowy Hydro Ltd	19/09/1968	0.44
13	215208	Shoalhaven River at Hillview	-35.1845	149.9536	NSW DILW	6/11/1973	0.37
14	410734	Queanbeyan River at Tinderry	-35.6144	149.35	Icon Water	2/08/1966	0.65
15	403221	Reedy Creek	-36.3109	146.6012	Vic DELWP	11/11/1964	0.25
16	218007	Wadbilliga River at Wadbilliga	-36.257	149.6926	NSW DILW	12/06/1974	0.65
17	410731	Gudgenby River at Tennent	-35.5722	149.0683	Icon Water	12/11/1964	0.35

Figure 7: Metadata for the set of usable hydrological stations.

Source: Bureau of Meteorology

At this point, the HPF shows that there is sufficient heat and dryness in the seasonal and regional contexts to support extreme bushfire development.

Level 3

A Level 3 alert is issued when analysis of conditions raise concerns about extreme fire activity. If a Level 2 alert is issued, the next step is for Fire Behaviour Analysts attached to fires to determine if conditions are conducive to a Blow-Up Fire Event (BUFE). A BUFE occurs when a fire forms deep flames and when it stops being a line of fire and becomes an area of fire with a large firefront (see Figure 8). The convection column above this large fire behaves differently, allowing a coupling of the fire with the atmosphere above. This causes a switch from quasi-steady-state fire behaviour (where if you know the terrain, the fuel and weather you usually know what the fire is likely to be doing) to dynamic fire behaviour (where you need to know the terrain, the weather including the stability and the fire itself; fuel loading is not a key element).

Since fires in Canberra in 2003, it has been clear that firefighters are routinely dealing with 2 types of fire. Quasi-steady-state fires have been well predicted by McArthur meters and also the Australian Fire Danger Rating System. Dynamic fires have had limited validated predictive tools available; especially the Continuous - Haines Index (Mills & McCaw 2010) and the Blow-Up Fire Outlook model (McRae & Sharples 2013, 2014).

Extreme bushfires, as defined by Sharples *et al.* (2016), develop dynamic fire behaviour and form one or more BUFEs. A BUFE requires deep flaming with 7 known causes:

- Strong winds, creating deep flaming zones.
- Wind change, causing a fire flank to form a new, larger fire front.
- Eruptive growth, which requires canyon-like landforms.
- Vorticity-driven Lateral Spread, when fire interacts with eddy winds and spreads in 2 directions at once.
- Dense spotting, reflecting changes in fire intensity as spot fires merge.
- Use of accelerants, in accord with Incident Action Plans, forming certain fire patterns.
- Interior ignition, a problem in the vegetation mosaics of the Boreal Forests.

A common element is low fuel moisture for dead-and-down fuel, which allows easy fire spotting. Damaging BUFE occurrence is not strongly related to fire danger nor to fuel loads, apart from the need for a prior fire with the potential to have high intensity. Some new ignitions or break-aways escalate in this way almost immediately (e.g. Kilmore East fire on Black Saturday 2009 and the Bendora fire breakaway on 18 January 2003, west of Canberra, shown in Figure 8).

Figure 8 shows a linescan 2 hours after a spotover (shown by the arrow) of a long-held containment line (dashed line) near Bendora Dam in New South Wales on 18 January 2003. Active flaming is shown in yellow and the map grid has one kilometre

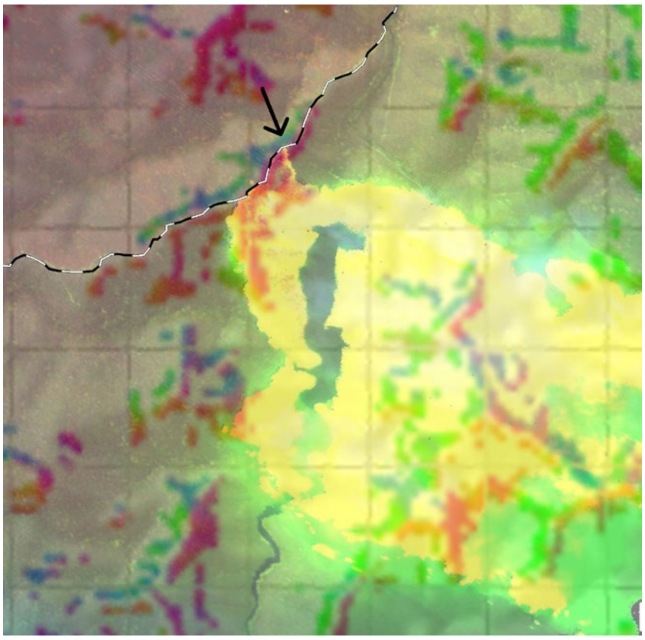


Figure 8: An example of a minor breakaway rapidly causing deep flaming and a Blow-Up Fire Event.

Image: NSW Rural Fire Service

spacing. Overlaid is a landform model of areas prone to Vorticity-driven Lateral Spread (VLS). The red colour indicates VLS generators under the then-prevailing northwest wind. Note the intense spotting on the southern edge.

A revised model for BUFE formation, the Blow-Up Fire Outlook 2 (BUFO2) has been developed. This takes inputs on the fire, the terrain, the atmosphere and the surface weather and produces a single-time or time-series outlook for steady-state fire behaviour, a BUFE, a pyroCb or a foehn-effect fire. Inputs can be from forecasts several days in advance and up to the current operational shift time. The model may lead to a Level 3 alert. A trial version of BUFO2 is included on the HPF webpage.

There are many useful sources of data on fires that are relevant. A good example for pyroCb monitoring is the NASA WorldView. Normal Bureau of Meteorology sources are used for weather data and weather balloon data is from the Bureau or from fire agencies. A range of terrain analyses for forested parts of Australia can be found on the HighFireRisk website. The VLS terrain analysis maps are also important.

Level 4

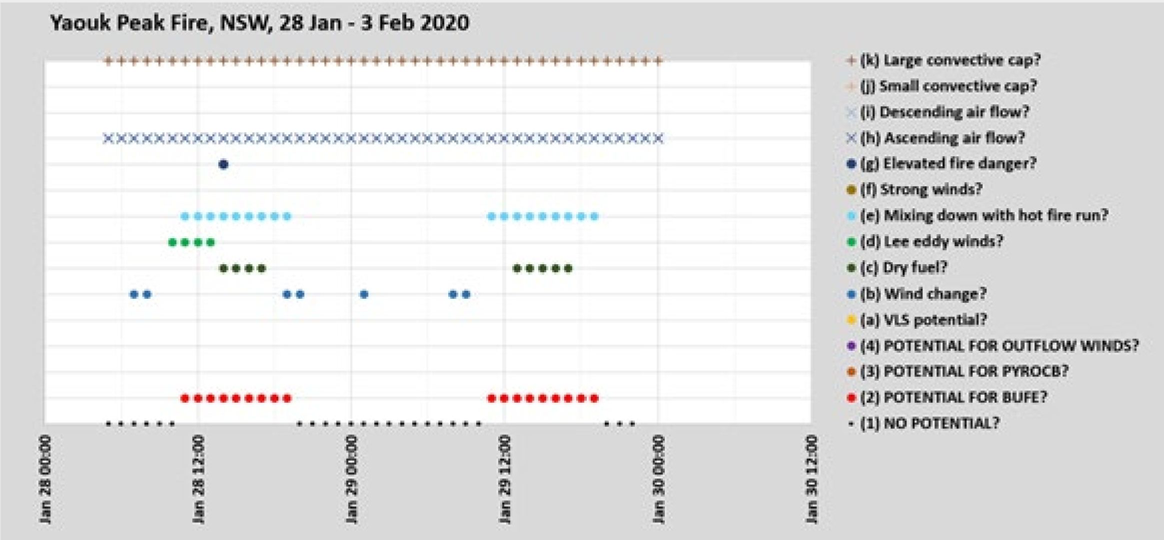
A Level 4 alert is a trigger to take action. As the Level 3 alert is a cue to collect field observation data to create intelligence products that can drive changes to an Incident Action Plan, a resulting Level 4 alert is an unambiguous and formally defined trigger to act. In such times, the baseline objective for incident management teams and fire divisions should be to save lives. BUFEs typically last for around 3 hours and may span an area ranging from 5km by 5km up to 70km by 20km. The summer bushfires in 2019–20 produced at least 170 BUFEs, allowing

Worked example of the BUFO2 model run as a time-series

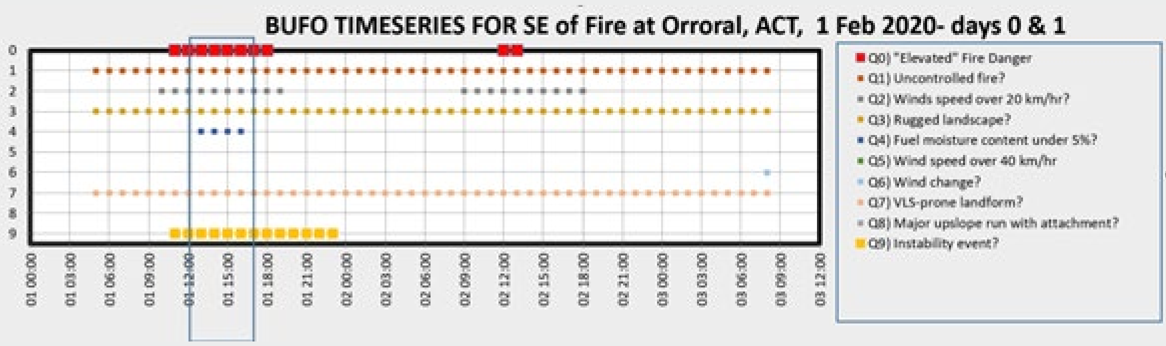
BUFO2 is a spreadsheet that tests data on forecast conditions at a fire for the potential for key events to occur. These are checked to see if all precursors of dangerous fire development are expected.

The Yaouk Peak Fire was burning in NSW just south of the ACT. An analysis on 28 January showed that BUFEs could occur on the next 2 afternoons, as shown by the red dots in row 2 below. These indicate an uncontained fire under a stable profile (so not likely to form a pyroCb). Dry fuel in the rugged terrain meant that a hot uphill fire run could mix down dry air aloft, increasing fire intensity (a form of feedback loop) and perhaps form a BUFE.

As this fire was being burnt out within a containment block, avoiding hot runs and subsequent mixing down, a BUFE did not form.



However, 2 days later a long-range breakaway merged with the ACT Orroral Valley fire. Being an unstable setting, this formed a pyroCb (event 2020k in the Australian PyroCb Register). The plot below used an earlier version of the model. The outlined window is a typical VLS event. The following afternoon lacked the low fuel moisture required for VLS.



Different combinations of the fire's setting can produce different outlooks for how the fire might evolve. It is operationally significant that very different behaviour can form under the same fire danger and fuel loads. The risks to fire crews and the allowable tactics can also be very different.

the first statistical estimates of these sizes to guide Incident Management Team decision-making.

BUFO2 is not a spread model. It is a risk model to assess the likelihood of high-consequence events on the fireground. It is important to note that the aim is not fire-spread prediction. There is no headfire and fire progression is by means of medium-range spotting and lateral spread. There are no opportunities to intervene to halt the fire's spread. Ground or air observers need to look for the lead-up steps occurring such as a fire heading into terrain that is able to form deep flaming through VLS or eruptive growth, or to confirm the initiation of an event by noting changes in the smoke plume or clouds around it. Most importantly, in the future, it may be possible to use these forecasts and observations to avoid the onset of a BUFE. For example, if an area should not be allowed to burn when fine fuels are fully flammable, then it could be burnt at an earlier, safer time.

The HPF is currently in a draft form and is waiting an operational testing when the next Level 1 alert is issued.

Results

The performance of the HPF against records spanning more than 20 years is summarised in Figure 9, which shows that areas in the plot are proportional to the number of months included. A Level 2 residual phase is after river dryings stop accumulating and accounts for the delay in restoration of deep drainage when rainfall resumes.

The goal of Level 1 and Level 2 alerts is to indicate times when the more demanding Level 3 modelling is required while not missing any such times, and this has been achieved. When the modelling is required, most fires will not pass the stricter Level 3 BUFO2 test, in most cases due to a lack of any mechanism for achieving deep flaming. It is anticipated that fire behaviour analysts would get to know the local conditions needed for a Level 3 alert.

A limited operational trial of drafts of the Level 3 model during the summer bushfires in 2019–20 yielded 13 alerts issued to fire agencies. Apart from one early successful BUFE prediction,

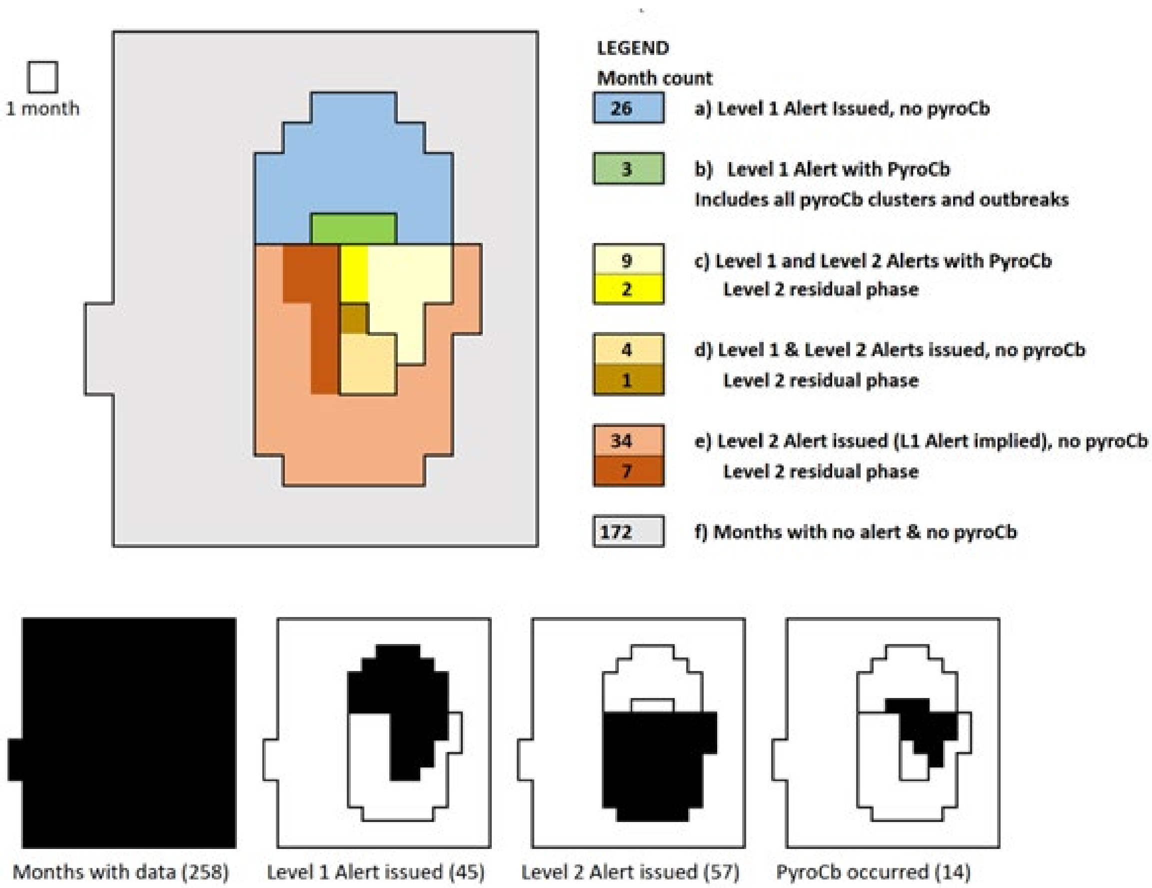


Figure 9: Breakdown of months with usable data (n=258) showing the performance of the HPF Levels 1 and 2 in terms of anticipating pyroCb occurrence. Areas in the plot are proportional to the number of months included. A Level 2 residual phase is after river dryings stop accumulating, and accounts for the delay in restoration of deep drainage when rainfall resumes.

5 early in the season were unsuccessful, largely due to underestimation of the role of the foehn effect in areas north of Sydney. After updating, the model yielded 7 alerts that covered fire activity that produced 7 BUFEs and 3 pyroCbs.

The full study uses the Australian PyroCb Register data only because the historical records for BUFEs are not complete. During the summer bushfires in 2019–20 in areas south of the Shoalhaven River including the ANYSO pyroCb super outbreak (Peterson *et al.* 2021), BUFEs and pyroCbs were recorded with a 5:1 frequency ratio suggesting a crude upper estimate of 600 BUFEs over the 20 years covered by this study. Thus, inclusion of BUFEs would be expected to reduce the size of groups (a) and (e) in Figure 9.

Discussion

It is important to remember that the HPF applies only to BUFEs. It is not intended to replace existing systems that work on steady-state fires. The HPF is intended to augment those systems by providing useful intelligence products to incident management teams on fireground elements not previously and explicitly covered.

Fire services agencies using this model would need to develop protocols to cover training, systems and operational processes ahead of the next alerts. This includes discussion, current sea surface temperature anomalies from the National Oceanic and Atmospheric Administration, riverflow data from the Bureau of Meteorology and access to the BUFO2 workbook. At the time of writing, the alert status was 'No Level 1 Alert', but an alert is possible in the months ahead requiring careful monitoring (Figure 10).

There is a need for the collection of data on the performance of the model during the trial. It is essential that future BUFEs are well documented, allowing an essential shift of operational focus away from pyroCbs. It is expected that future events will allow improvements to models and a reduction in false alarm rates in levels 1 and 2. Every major bushfire leads to new insights that cannot be anticipated. Also needed are insights into if the HPF can be reconfigured to apply to southwest Western Australia, which experiences significant numbers of pyroCbs.

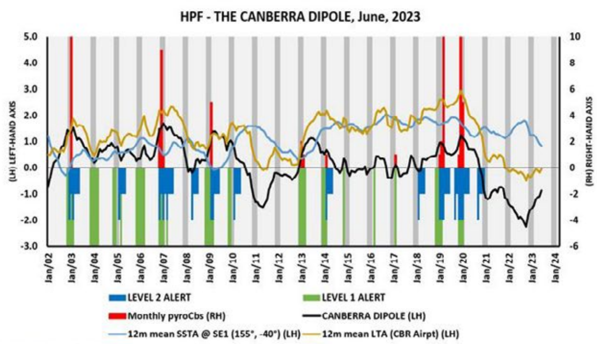
LEVEL 1 CANBERRA DIPOLE

This reflects interactions between land and sea that influence synoptic patterns conducive to wildfires (or rain). Note there has been a reformatting to make Level 2 Alerts explicit.

Data:

- Sea Surface Temperature Anomalies (SSTAs) - NOAA Coral Reef Watch;
- Land Temperature Anomalies (LTAs) & River flows - Bureau of Meteorology;
- PyroCbs - Australian pyroCb Register.

NO ALERTS, BUT MONITORING REQUIRED.



[Click on image to enlarge.]

ANALYSIS: While the current value is negative, indicating continued rain events across some of Eastern Australia, this is changing rapidly. There is no BUFE potential likely until positive values return and other critieria are met. This is not likely until, at least, late next summer. This could cause an alert for March 2024 at the earliest, otherwise no earlier than the following summer.
NOTE: The land TA ran at record values during Black Summer, and its recent minimum was at levels once considered quite warm. The key factor is the remarkable warm SSTA run of ten years. Recently a cool SSTA area has formed offshore from Sydney, which may have broken that run. The cool pool needs to become persistent for positive dipole values to form - remembering that the Dipole uses 12-month averaged TA values.

Figure 10: A screenshot of a HPF Level 1 analysis as at 30 June 2023.

Conclusion

The HPF is presented as a model that works well using 20 years of data. It is currently in a trial phase and is waiting the next onset of potential extreme bushfire development, either in the summer of 2023–24 or the following year. This depends on how rapidly the landscape and vegetation rebounds from recent wet years. Australia must do more to achieve rapid adaptation to climate change. Fromm *et al.* (2022) found no global trend in pyroCb counts over the last decade. Therefore, Australia's rapidly increasing trend raises questions about how the situation will evolve in the coming decade. Will the climb continue, or will it plateau out in line with the trend in the boreal forests? It is only through an ongoing dialogue between researchers and fire services operations that we can optimise the ability to anticipate what is the most worrying and dangerous type of bushfire.

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About the author

Adjunct Professor Rick McRae retired from a career in bushfires and emergency management spanning 3 decades. He is a visiting fellow at the University of New South Wales in Canberra. He specialised in fire behaviour and served on major fires in the ACT, Tasmania and Canada. He has served on national committees on bushfire matters and has run national emergency management workshops. He has specialised in the use of satellites, and on extreme wildfires.

