QUALITATIVE FOREST FIRE DANGER

NEW TOOLS TO ANTICIPATE BLOW-UP FIRE EVENTS

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UNSW CANBERRA

UNSW Bushfire

This report is one of a series designed to provide access to operational tools derived from new thinking about the worst kinds of bushfire in the modern context.

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For access to the BUFO2 model, see Level 3 at: https://highfirerisk.com.au/hpf/

This material is for guidance only. In mission-critical situations always seek corroborating intelligence sources. This work and fires discussed are not included in the AFDRS.

It is critical that users of the Continuous Haines Index, used as a watch-out in AFDRS, carefully consider what is in this report.

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INTRODUCTION

Australia is famed for its bushfires. Its fire services are among the most skilful in the world in their ability to mitigate the risks to their communities and the things of value to those communities. Every couple of decades there were major fire catastrophes that defied all suppression attempts, with 1939 and 1983 being good instances.

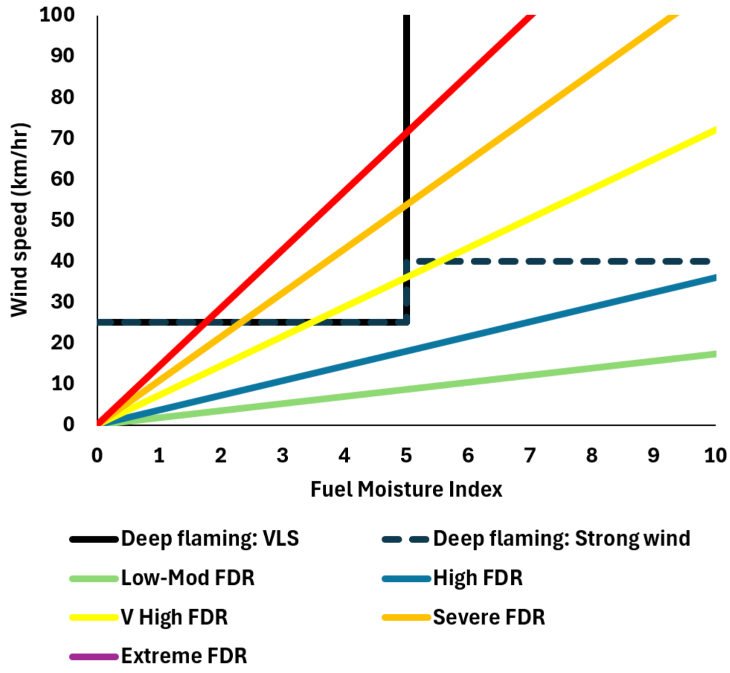
Since the turn of the century, these events have become increasingly common in southern forested areas, so much so that in some regions they are the dominant form of bushfire and the dominant source of risk.

This change has led to detailed scientific studies of these fires and their drivers. It has become clear that we face a second “species” of fire, which has to be managed alongside the first.

Normal fires – Quasi-Steady State Fire Behaviour: you can predict fire spread if you know the terrain, the weather and the fuel. Fire danger varies as a “weather” dial is turned up or down – it is a **quantitative** concept. Many will remember the circular FDR slide-rules.

New fires – Dynamic Fire Behaviour: the fire responds to terrain, atmospheric stability and the fire itself (creating a feedback loop). Fire danger is based on, metaphorically, flicking switches, not turning dials – it is a **qualitative** concept.

The graph below shows the distinction. The graph compares values of FMI and of wind speed. The colour diagonal lines show the upper bounds of the standard fire danger ratings (prior to the AFDRS). The black line shows the bounds for the onset of VLS, which requires low FMI and raised winds. VLS can occur even in Very High FDR, and is unlikely in Catastrophic FDR under strong winds if the fuels are moist (although other sources of deep flaming may kick-in, such as strong wind – above the black dashed line).



The first section of this report explores this in more detail. Predicting the transition to dynamic fire behaviour requires an understanding of that transition.

Clearly new predictive tools are needed, as is rapid adaptation in the face of climate change.

Work on this to date includes:

- The Bureau of Meteorology developed a predictive tool for fire thunderstorms that is predicated on the fire's plume being of a specific type (like from an industrial smoke stack), which is rarely the case.
- The Continuous Haines Index, an upgrade of the mid-level Haines Index, which looks for instability of dry air in the mixing layer. When a BUFE is possible then CH does not measure stability above the mixing layer, and functions as a fuel dryness index, with some indication that dry air aloft could be mixed down during a hot fire run.
- BUFO2, a predictive model based on the requirement for deep flaming, which in turn requires dry fuel. This is part of a framework designed to give long-range forecasts of when BUFO2 techniques are required.

This report firstly describes a new simple phase diagram that seeks to provide guidance on whether a BUFE is likely through weather creating deep flaming. It does not seek to forecast pyroCbs or foehn events. By providing a simple tool that does not require high skill levels, it becomes possible to anticipate the need for an FBAN with suitable skills.

By requiring only data on temperature and relative humidity it uses what is typically on hand in a fire control centre or even in the field. The tool is a guide only, and requires frequent re-use and verification from other sources if it becomes mission-critical.

This report then describes the BUFO2 model.

UNDERSTANDING THE TRANSITION FROM NORMAL TO DYNAMIC FIRE BEHAVIOUR

The relationship between normal fire behaviour and dynamic fire behaviour can be explored using a tiered phase diagram.

T = Temperature (°C); RH = Relative Humidity (%); U = Wind Speed (km/hr); FL = Fine Fuel Load (t/ha); FMI = Fuel Moisture Index; FDI = Fire Danger Index; ROS = Rate-of-Spread (km/hr)

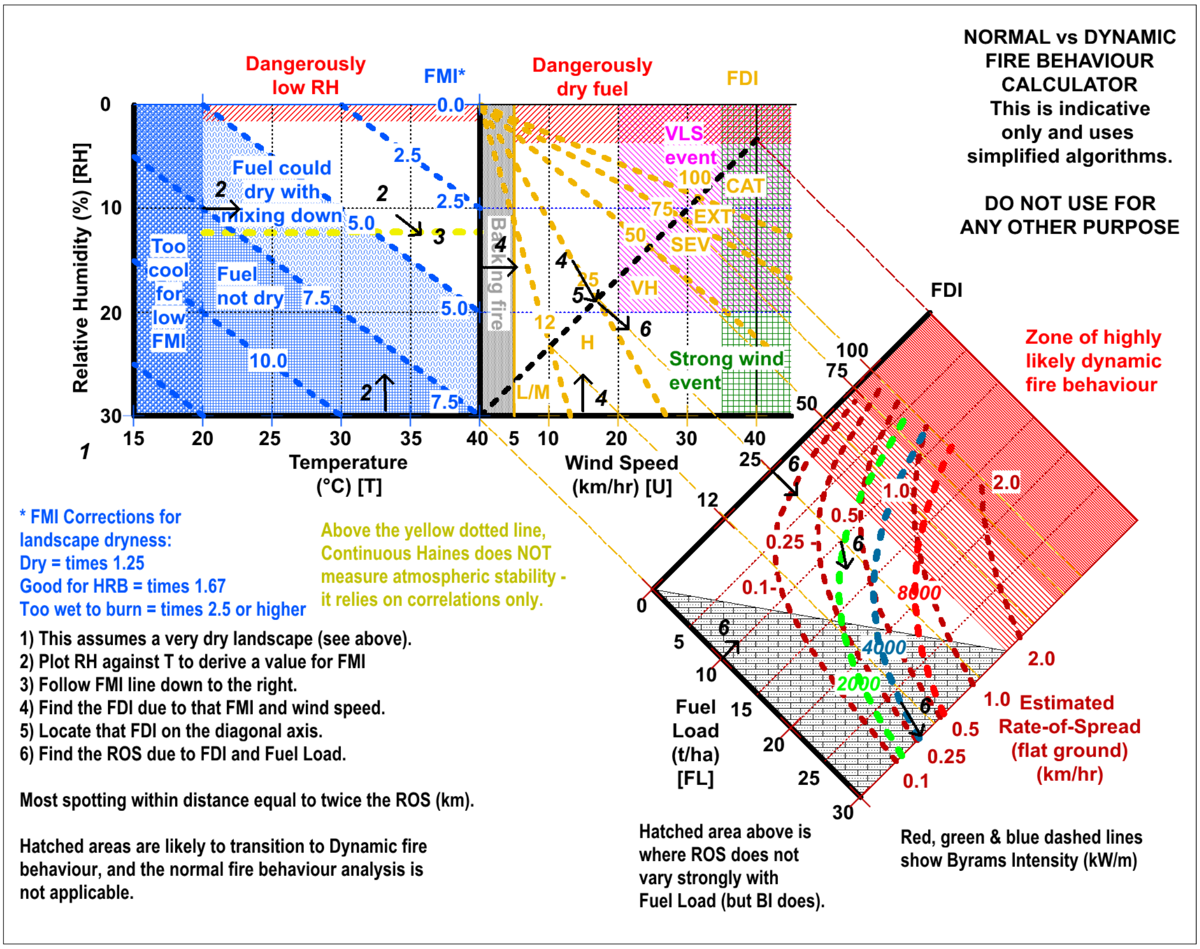
This uses the following simplified algorithms:

FMI = 10-(T-RH)/4

FDI = 7*U/FMI

ROS = FDI*FL/800

Due to this, the following should not be used for safety-critical purposes.



For a bad fire day, with elevated drought, a lot of the "space" used by the FDR model indicates that instead dynamic fire behaviour should be expected in hilly, forested country.

PREDICTING THE POTENTIAL FOR A BUFE

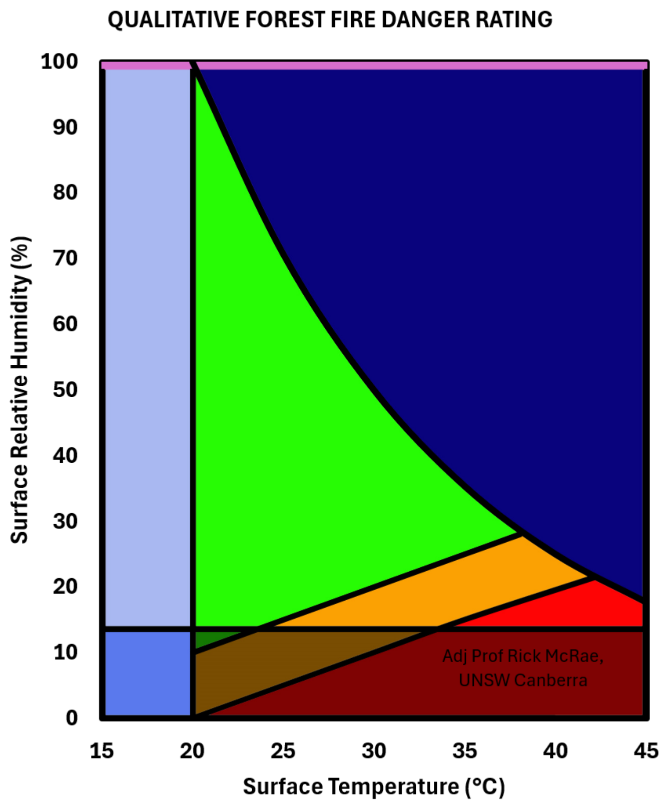
The tool uses a space defined by the full range of RH values, and a temperature range of 15°C to 45°C, the typical thinking space for bad fire behaviour. It seeks to partition that into a series of spaces that suggest different things about potential fire behaviour. It also makes specific reference to how CH performs.

The following ideas are used:

1. Fine forest fuel's FMI is 10-0.25*(T-RH). This simple index matches almost all FMC indices, typically in a curved form. Fine fuel is dry enough to support easy spotting at 5%. FMI has good agreement with other indices at the 5% mark.
2. If the DP exceeds 20°C, the air is too wet to allow dry fine fuel. Rain or storms are likely. This threshold is turned into a RH variable that depends on DP and T.
3. When T is below 20°C, FMI cannot go below 5%.
4. When the difference between surface T and DP in an aerological diagram is too large, the LCL is above where CH measures the atmosphere's properties. It therefore cannot measure stability above the LCL. There may be correlations between conditions above and below the LCL, however direct measurements, such as from an aerological diagram are better.
5. As T changes, a value for RH can be set that shows when FMI reaches 5% (i.e. T-RH=20). It is only with lower values of RH that a BUFE can be expected.
6. However, a hot "normal fire" run can cause mixing down of dry air aloft if there is some present (noticeable in an aerological diagram). It has been assumed that the threshold for this is at T-RH=10. This is a working assumption needing future field verification.
7. If a BUFE is possible, then the Drought Factor is 10. This is incorporated into the diagram. If DF was lower, then for any T, RH would need to be lower. T-RH would need to be replaced in previous dot points above by:
   (T-RH)*10/DF.

A VLS-driven BUFE underway in September 2024 in California, This is a detailed view of a VLS core moving right-to-left, igniting the landscape for kilometres downwind (away from the camera) as it progresses.
The front cover image is the next day showing the view from downwind of a similar event, moving left to right and spotting towards the camera.
(Images: HPWREN)

THE PHASE DIAGRAM



*	1	Low FMI, BUFE possible	Stability not measured by CH
*	2	Low FMI, BUFE possible	Stability measured by CH
*	3	Low FMI with mixing down	Stability not measured by CH
*	4	Low FMI with mixing down	Stability measured by CH
	5	Unable to achieve low FMI	Stability not measured by CH
	6	Unable to achieve low FMI	Stability measured by CH
	7	Too cool for low FMI	Stability not measured by CH
	8	Too cool for low FMI	Stability measured by CH
	9	Too damp for a large fire	Stability measured by CH
	10	Saturation - Fog threshold	Stability measured by CH

White dots are from balloon flights during Black Summer
* = able to form a Blow-Up Fire Event if drought and wind raised
APPROXIMATE ONLY - FOR GENERAL GUIDANCE

You will need observations of the surface temperature and relative humidity, and modelled value of C-Haines (CH).
Plot T & RH, and note the coloured area on which they fall.

STABILITY
If it is a dark colour at the bottom of the graph, then CH is measured entirely below the LCL, and can say nothing explicitly about stability in the free atmosphere above - e.g. no insight into pyroCb formation.
Otherwise there may be some insight into the stability of initial levels above the LCL, but low FMI is less likely.
CH may indicate a subsidence inversion near or below the LCL, which could block all plume rise but also put drier air close to the surface. CHaines may also indicate general mixing down of dry air aloft, and able to be mixed down, if the DP falls faster with height than indicated by dry adiabatic processes.

BLOW-UP FIRE EVENTS
BUFEs require fine fuel to be dry enough to support ready spotting. Using the rule of thumb of 5% for the threshold, this happens in the red areas (1 or 2).
A hot uphill run in a valley can cause mixing down of dry air aloft if it is present - orange areas (3 or 4).
If data falls within areas 1 to 4 then advise IMT that steps are needed to avoid deep flaming or hot runs.

FOLLOW-UP DATA
If the observations fall on or near areas 1 to 4, then analyse any relevant radiosonde or modelled data.
Look for:
- low level and high level inversions.
- lower than expected dew points in the mixing layer (above ground & under LCL).
Otherwise only Quasi-Steady State fire behaviour is to be expected, requiring data on drought and wind.
Re-assess frequently.

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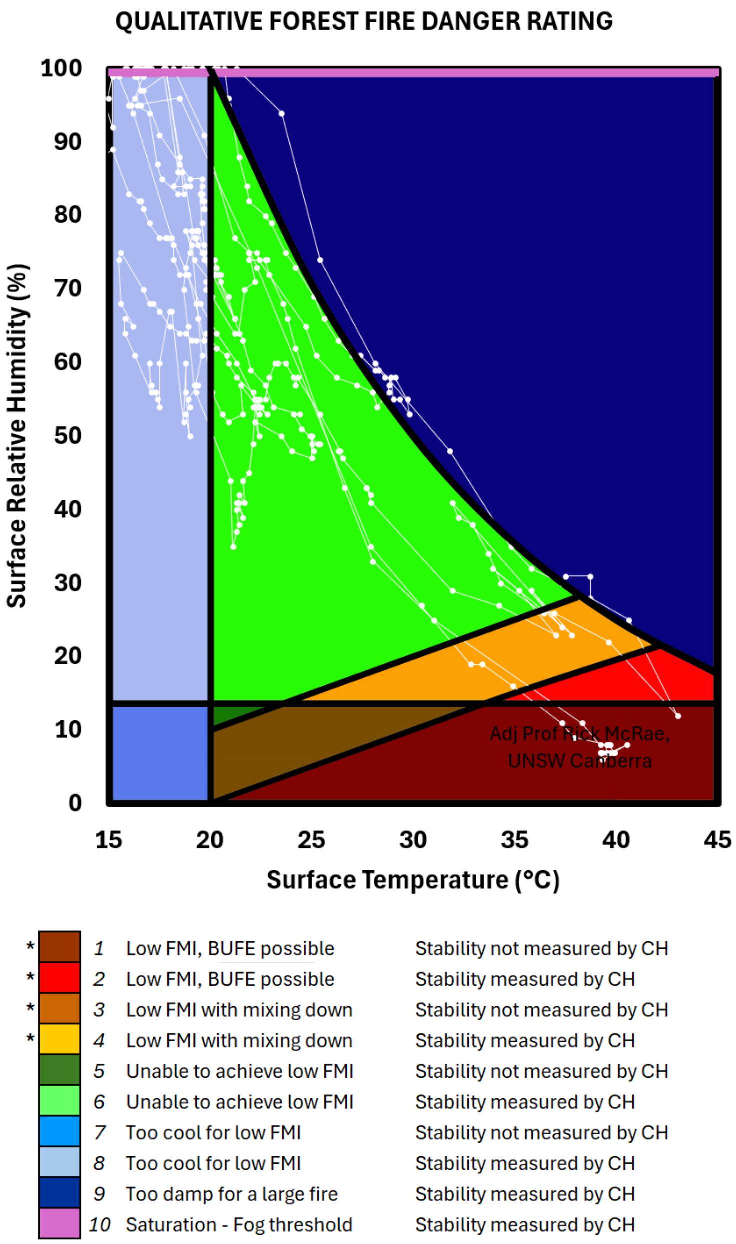
WORKED EXAMPLE

This graph shows three days of weather data from the Nowra area, spanning 31/12/2019 to 04/01/2020. Some of the nocturnal data are off the plot.



It entered zones 1 and 2 twice, where a BUFE was possible. The first time produced a pyroCb. Five days later it did again (events 2019ar and 2020b in the Australian PyroCb Register).

2019ar	2019 (31 Dec) NSW: Nowra	2019	31/12/2019	NSW	Nowra	150.5	-35	Very high
2020b	2020 (04 Jan) NSW: Nowra	2020	04/01/2020	NSW	Nowra	150.4	-34.8	Very high

This was predicted by BUFO2, however this diagram makes clear not just when it enters the “danger zones” but when it is heading towards them.

PREDICTING THE OCCURRENCE OF A BUFE

If the seasonal conditions are such that landscape dryness permits low FMI and high flammability for 100 hour dead-and-down fuels (see: https://highfirerisk.com.au/hpf/) then it is important to be able to precisely anticipate the onset of a BUFE.

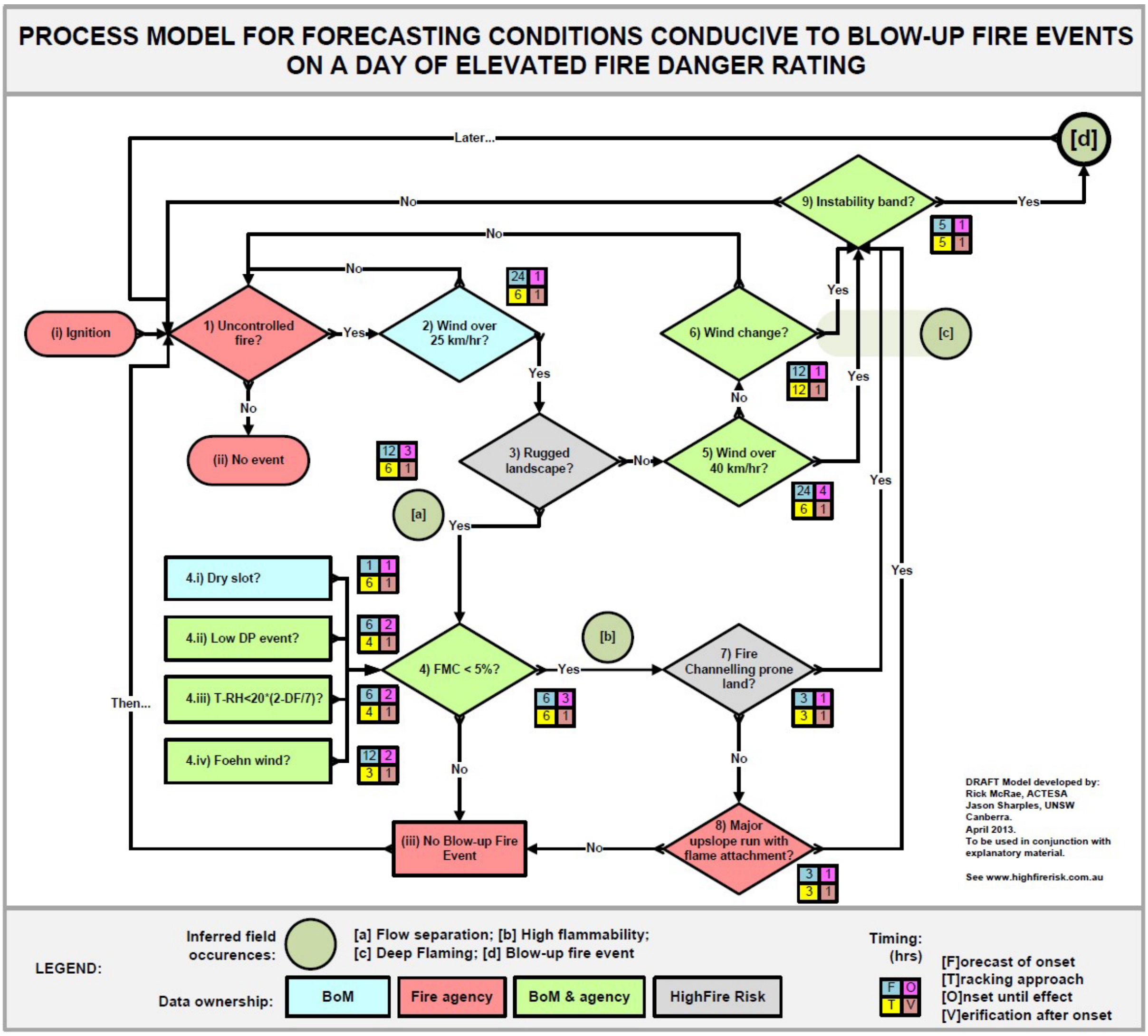
The BUFO2 model is designed to do that.

It takes inputs on the atmospheric profile, and the presence of the drivers of any of the seven known causes of deep flaming.

The worksheet is presented below. The second page provides quick descriptions of the key terms used.

The original BUFO[1] model used a flow diagram – see below.

Neither version of BUFO use C-Haines.



BUFO2

Blow-Up Fire Outlook model. V2 14/09/2021
Rick McRae & Jason Sharples, UNSW Canberra.
A model for prepdicting Blow-Up Fire Events (BUFEs) & pyroCbs
Used if (a) elevated fire danger & (b) uncontained fire, or potential for one.

DATE: (dd/mm/yyyy)		**FIRE:**	
TIME: (hh:mm)		**SITE:**	

Fill-in or cross-out all white boxes.
Complete sections (2) to (6).

(1) DEFAULT = no BUFE & no pyroCb **#1**

(2) AMBIENT STATE

		Synoptic		#2
		A	N	D
Cap	L	AL	NL	DL
	M	AM	NM	DM
#3	H	AH	NH	DH

State is the 2-letter code in the table.

ASSESSMENT:

ABBREVIATIONS
A: Ascending, unstable
B: BUFE
D: Descending (isentropic drawdown)
DPD: Dew Pt Depression near LCL
E: Eruption
FDI: Fire Danger Index
FMI: Fuel Moisture Index (% ODW)
H: Conv cap High, > 8°C
II: Interior Ignition
L: Conv cap Low, < 4°C
M: Conv cap Moderate
N: Neutral stability
O: Outflow wind, downburst **#25**
P: pyroCb
U: wind speed (horizontal, surface)
VLS: Vorticity-driven Lateral Spread

(3) OBSERVATIONS or FORECASTS
Tick boxes if observed or predicted.

(4) DRIVERS

(5) ASSESSMENT QUALIFIERS
If any drivers are present, then...
start with B, vary as directed. Ref [2] and [4]

#4	#5	#6	#7	#8	#9	#10	#11	#12								
Trench / gully?	VLS-prone landform?	Dew Pt depression?	Fire nearby?	Low FMI?	Varying FMI?	U > 25km/hr?	U > 40km/hr?	Wind change?		Tick if all requirements (3) in place.	AL?	AM?	NH? Or DH?	NH?	DH?	
									E		Add P	Add P				#18
									VLS		Add P	Add P				#19
									U fresh		Add P					#20
									Wind change		Add P		None			#21
									II		Add P			Add O	None	#22
									Burnout		Add P			Add O	None	#23
									DPD		Add P			Add O	None	#24
Terrain (HFR)		Skw -T	IMT etc	Fuel state		Fire Wx										
#13		#14	#15	#16		#17										

(6) RESULT

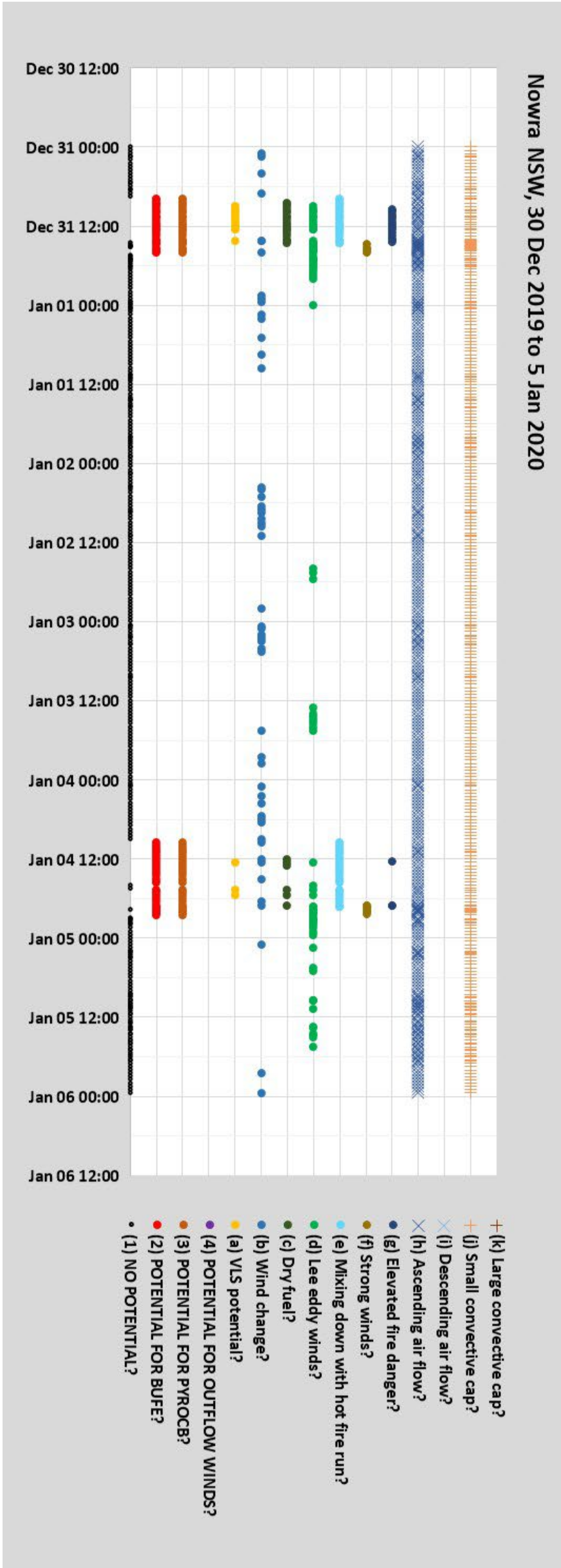
None?		(Y o rN)
(B) BUFE?		
(P) PYROCB?		
(O) OUTFLOW?		

Notes:

NOTES FOR BUFO2 MODEL

#1	The starting point is that boundary conditions exist, but there is no indication of a BUFE. The goal is to change that.
#2	Synoptic patterns affect the vertical air flow. Ascending air flow is most common ahead of troughs or fronts. Neutral is common with subsidence inversions under high pressure cells. Descending air flows are common zonal set-ups in the lee of high country.
#3	The scale of the Convective Cap is gained from the most appropriate radiosonde trace. Modeled profiles are often inaccurate on this matter.
#4	The literature on eruptive fire spread makes clear that it is dependent on a trench-shaped feature inclined above about 26°. (#18)
#5	VLS requires a break in slope aligned roughly at right-angles to the prevalling wind. See www.highfirerisk.com.au (HFR) for details. It also requires dry fuel to support dense spotting (#8)
#6	Dry air within 100hPa of the LCL can be mixed down to replace air made to rise in a vigorous convective column. This can increase fire behaviour, leading to a BUFE.
#7	In forecast mode, BUFO considers what a fire might do in the future, especially in terms of terrain (e.g. will it be on VLS-prone terrain when the wind exceeds 25km/hr? #10)
#8	Low fuel moisture is a requirement for dense spotting. A value below 5% of oven-dried weight is the cut-off.
#9	For a campaign fire, fuel moisture can vary with time, making previously unburnt patches flammable, allowing deep flaming to form.
#10	Lee-slope eddy winds tend to start when the prevailling winds exceed 25 km/hr. This is a requirement for VLS.
#11	Winds above 40km/hr may create deep flaming due solely to high headfire rate of spread.
#12	Wind changes have been known to creat deep flaming.
#13	Terrain data includes more than slope, aspect and elevation. The VLS model should be used.
#14	This is extracted from Skew-T Log-P aerological diagrams.
#15	This requires fire spread predictions. It can include uncertainty (success of suppression, chance of spotting, etc). Data from IMTs, fire services, web sites, etc.
#16	Fuel state involves assessment of fuel availability - Drought Factor and fuel loads for forests fuels, or curing and fuel load for grasslands.
#17	Fire weather refers to the standard forecast products.
#18	Eruptions, or eruptive fire growth, is rapid accelleration due to fire entrainment in trench-like landforms. It includes ember storms at the top of that feature.
#19	VLS is the most efficent known process for forming deep flaming and the coupling of a fire with the atmosphere.
#20	Fresh winds can produce deep flaming, especially associated with uphill runs.
#21	Wind changes make a flank into a new headfire. Mostly this produces separate fingers of fire, but at times deep flaming can result.
#22	Interior Ignitions occurs wher eunburnt islands within previously burnt areas later acquire flammability and ignite. This can add up to deep flaming.
#23	Inappropriate use of incendiaries (under the auspicies of an IAP) is an increasingly significant cause of BUFEs. It is especialy important not to light into VLS prone landforms, and not light in a deep flaming pattern.
#24	Dew Point Depression events can cause rapid spikes in fire danger on the fire ground. The mixing down required often occurs after intense uphill runs.
#25	A fire on high ground can be quite close to the LCL. A hot uphill run can produce a plume that pushes hard against the cap. A rebound can produce an outflow wind, pushing the fire dangerously downslope.

There is a spreadsheet version of the model that uses forecast or observed weather timeseries and automates the process for each observation timestamp. Here is a worked example:



It is seen in this example that BUFE potential emerged around noon on the 31st December and the afternoon of 4th January. These created pyroCbs 2019ar and 2020b (see above for details of these).

Overall this reflects a potential for hot fire runs to mix down dry air aloft [e], especially in the complex cliff-lined sandstone canyons in the area. In the core times there is dry fuel [c] and sufficient winds [d] to generate VLS [a]. Both can produce pyroCbs [3] through creating enough heat to push through the small convective caps present [j].

GLOSSARY

AFDRS: The Australian Fire Danger Rating System is a combination of FDR and stylised gridded fuel loads. It indicates potential fire behaviour in the event of an ignition, and is purely aligned with QSS fire behaviour.

BUFE: A Blow-Up Fire Event (BUFE) occurs when part of a fire forms deep flaming.

CH: The Continuous Haines Index (CH) is measure of two critical elements of the atmospheric profile above: (1) how dry the air is c.1.5km up, and (2) how quickly it cools between 1.5km and 3km up. Care must be taken not assume that the second element refers to the whole profile's stability, as when FMI is low, the LCL may be more than 3km up.

Convective cap: A part of the vertical profile of the atmosphere where temperature warms as it rises (or cools less than expected). This forms an inversion, which my block the rise of a fire plume.

Deep flaming: While fires normally spread by means of a headfire, which is line of fire, in BUFEs they spread with large areas of ground alight at the one time. This changes the nature of the convective plume above, allowing it to rise to considerable heights without mixing out.

Dynamic fire behaviour: Dynamic fire behaviour is when the fire stops responding to the typical set of drivers (terrain, surface weather and fuel) and instead reflects the terrain, the atmospheric profile and the fire itself.

FDR: Fire Danger Rating is a categorised index indicating potential fire severity in the event of an ignition. It ignores terrain and excludes fuel. It is a fire weather index, and is purely aligned with QSS fire behaviour.

FMI: The Fuel Moisture Index is a parsimonious, unitless rule-of-thumb for the moisture content of dead fine fuel, equivalent to Fuel Moisture Content.

LCL: Lifted Condensation Level, where air lifted above the ground reaches 100% relative humidity, and possibly clouds start to form. It is important to note that air inside a fire's plume will have different properties to the surrounding air.

PyroCb: When there is no convective cap above deep flaming, the plume may be able to rise to the top of the Troposphere. A thunderstorm forms within the plume, but it is atypical due to the dense smoke inside it. Freezing and lightning form when its temperature falls below -40°C. Pyrogenic lightning is common.

Quasi-Steady-State fire behaviour: This is the "normal" form of fire behaviour, where (with some exceptions) terrain, fuel, and weather determine the behaviour of fire.

VLS: Vorticity-driven Lateral Spread is an effective source of deep flaming in rugged landscapes. I fire enters lee-slope eddy winds it gets entrained and can spread sideways while producing many spotfires downwind.

VPC: Violent Pyro-Convection, a broad term for the visible manifestation of a fire that has coupled with the atmosphere above, producing dynamic fire behaviour.