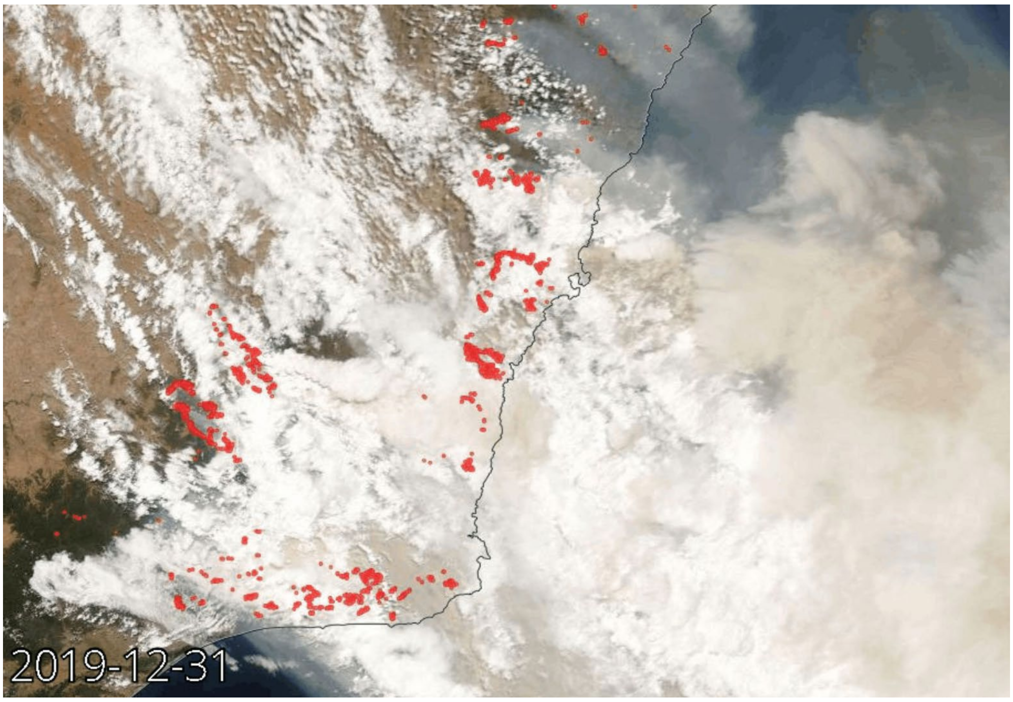
A CLASSIFICATION OF VIOLENT PYRO-CONVECTION



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PREAMBLE

When a fire forms deep flaming, it can rapidly change its behaviour, and become dangerous to fire crews and the community. When such a Blow-Up Fire Event (BUFE) occurs, it typically lasts up to three hours and defies all attempts at suppression. Containment efforts often make matters worse. The only certain incident objective then must be to save lives. It is therefore essential that we do everything that we can to understand these events.

For decades there has been a global scientific collaboration looking at the most obvious manifestation of BUFEs, the fire thunderstorm, or pyroCb. These are readily seen in satellite imagery and have been logged for many years. Increasingly, fire services are paying attention to pyroCbs.

There are a number of forms of pyroCb that can be distinguished. Being able to distinguish these using remote sensing can allow a better discrimination of events on the fire ground that caused them – and, critically, the potential for more events in the near future. This is a valuable lesson-learning process, which at times requires significant changes in the existing thinking of fire services.

Significantly, there are also other forms of BUFE that are not readily resolved in satellite imagery. For these, there is a need to routinely use radiosonde profiles, weather radar, and any other sources of information that may be to hand – including observations from the fireground. The distribution of critical elements over the landscape and over time may be needed to fully resolve fire dynamics and the resulting Violent Pyro-Convection (VPC). The classification scheme below uses that data.

A new BUFE forecasting tool for south-east Australia is available: **https://www.highfirerisk.com.au/hpf/**

DEFINITION: VIOLENT PYRO-CONVECTION (VPC)

A fire's local shape and intensity determines the local behaviour of the smoke plume above it. Very low intensity produces sluggish, white, wispy smoke that rapidly mixes out with the surrounding air. As intensity increases, the smoke gains in density and persists longer, while rising, before mixing out. As defined by Brian Potter, there are a series of stages as a plume builds. Here we will look at two end stages. Both correspond to BUFEs and deep flaming.

VPC Scenario 1. At very high intensities, the plume resists mixing out as it rises, and punches out of the mixed layer. The plume rises well above the top of that layer (the Lifted Condensation Level, LCL, or cloud base), above which there will be a pyrocloud within the plume. This is often termed a plume-dominated fire. The atmospheric profile is unstable.

VPC Scenario 2. At very high intensities, the plume is trapped below a low-level inversion and moves downwind under that cap. Typically the only pyrocloud that forms is localised pyroCu or towering pyroCu. The atmospheric profile is stable.

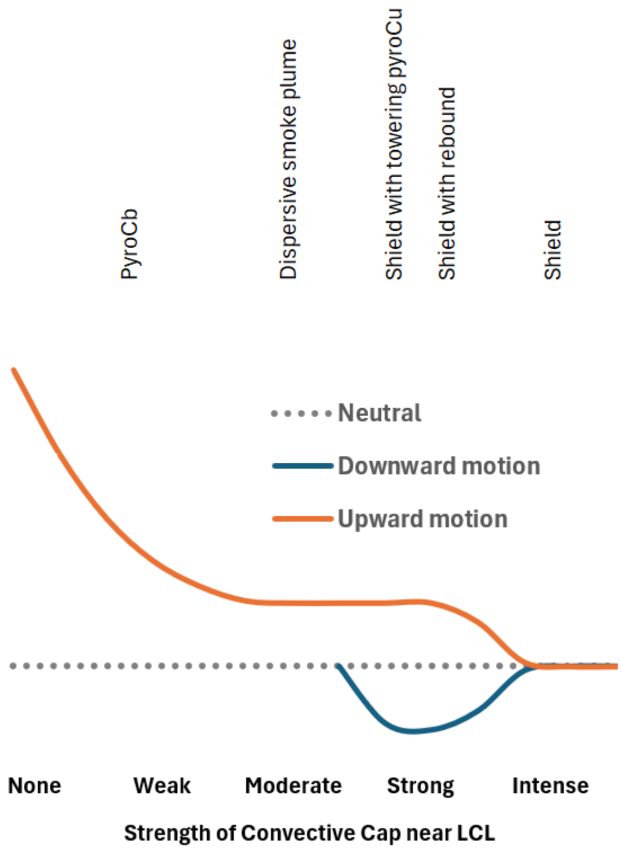
The following types of violent pyro-convection are covered here:

Unstable (Scenario 1)	PyroCbs	Type U1. PyroCb (no context) Type U1a. PyroCb event Type U1b. PyroCb cluster Type U1c. PyroCb Pulse Type U1d. PyroCb outbreak Type U1e. PyroCb super outbreak
	Non-pyroCb events	Type U2. Sub-UTLS event Type U3. Pyro-puff (isolated towering pyro-Cu) Type U4. Fire-enhanced ambient Cb
Stable (Scenario 2)	Type S1. Smoke shield Type S2. Smoke shield with rebound Type S3. Smoke shield with towering pyroCu	

STABLE VS UNSTABLE

Events described here are given an initial letter:

- **S** for events under stable profile (strong or intense caps), and
- **U** for events under an unstable profile (weak or absent caps).



Assumed relationship between convective cap and formation of VPC. Downwards motion results from a rebound after overshooting under a strong cap. Intense caps prevent the overshoot.

GLOSSARY

BT: Brightness Temperature, referring to the emitting object's thermodynamically derived temperature, based on its properties in specific infra-red bands. Here, this refers to data derived from satellite imagery of fires, clouds, and plumes. This data should be managed by technical specialists.

BTD: The difference in the derived BT for two infra-red bands. This can provide valuable intelligence about smoke and aerosol load of plume-tops. This data should be managed by technical specialists.

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

Complex: When multiple large fires are burning in close proximity it may be necessary to manage them as one event. Fires in a such a complex may share the potential for BUFEs to form.

Deep flaming: Deep flaming is a switch from line-fire propagation of the fire to a large area flaming at the one time. This alters the base of the fire plume and alters the air flow around the fire ground.

Division: In large fires, Sectors may need to be grouped in Divisions to avoid exceeding span-of-control limits and to avoid issues with communications and logistics.

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. The fire ground risk profile radically alters when this transition occurs.

Flashy fuels: Flashy fuels, especially low grasses, burn quickly and their plumes mix out readily.

Glaciation: Glaciation refers to the freezing of water droplets within a cooling cloud or plume. As a pyrocloud has many condensation nuclei, this is generally considered to occur when it cools below -40°. At this stage pyrogenic lightning is considered to be possible.

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

Megafire: A mega fire is one that spreads over a large landscape over a protracted time, defying intensive containment efforts. They are best considered to be quasi-steady-state fires.

Plume-dominated fire behaviour: Plume-dominated fire behaviour occurs when the air flow upwards, in the plume, and the required vertical or horizontal inflows, alter the behaviour of the fire. This can be both a cause of the key feedback loop or part of it.

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.

Sector: An operational sub-division of a fire's perimeter that allows optimised tactics, planning, and logistics.

UTLS: the Upper Troposphere-Lower Stratosphere, the height at which the atmosphere's dynamic changes from cooling with height to warming, preventing or impeding further convective rise.

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.

Footnote: Terms like "pyro" and "pyro-convection" are being used operationally for VPC in some areas, but have little value, as both can be correctly applied to a candle flame.

Note: where distances are specified, these should be considered to be indicative and not necessarily aligned with the direction of fire dynamics. It is more likely that they are linked to weather system dynamics. Duration times given are also indicative.

This version: No 1c, 26 January 2025.

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REQUIRED OBSERVATIONS TO UNDERSTAND VPC

VPC occurs on a large scale. Normal fireground observation systems may fail to pick up what is required to understand what is happening. The following can be used:

- Low earth orbit satellites, especially those with VIIRS sensors.
- Geostationary satellites, such as the Himawari series.
- Weather radar. If available data from a range of scan angles. Doppler data is very useful.
- Weather observations and forecasts.
- Reliable Drought Factor data. Detection of the onset of dry fine fuels requires DF to be correct, a challenge for modelled or remotely-sensed data (especially where satellite data are cloud-affected). Field validation should be used.
- Atmospheric profile data: radiosonde observations are preferable to modelled data due to better resolution of convective caps and dew point depression events. Care needs to be taken to account for any nocturnal inversion, especially for nocturnal BUFEs.
- Photography from a distance – over a hundred kilometres distance is preferable.
- Lightning detection data.
- Terrain data, especially with regards to VLS and eruptive growth.

INITIATION OF VIOLENT PYRO-CONVECTION

Violent pyro-convection (VPC) is the visible manifestation of a fire that has coupled with the atmosphere above, producing dynamic fire behaviour in a BUFE.

That coupling typically requires deep flaming to form with low fine fuel moisture. Easy spot fire occurrence is typically considered to occur below 5% by weight.

Deep flaming is a switch from line-fire propagation of the fire to a large area flaming at the one time. This alters the base of the fire plume and alters the air flow around the fire ground.

All of these require non-flashy fuels to allow the plume time to develop fully.

There are seven known causes of deep flaming:

- **Strong winds**, which extend the flaming zone over the duration of the burn-out time. This is a well-known safety hazard for fire crews.
- A **wind change**, which makes an existing flank into one or more new headfires, which may interact with the old headfire. This is a well-known safety hazard for fire crews.
- **Eruptive growth**, where a fire can continue accelerating upslope in a steep, trench-like landform. This may happen in multiple trenches at once. This is not a well-known hazard but has produced a number of serious burn-over events.
- **Vorticity-driven Lateral Spread**, where a fire enters a lee-slope eddy wind, and simultaneously spreads sideways (at up to 5 km/hr) while spotting downwind (up to 6 km). It requires prevailing wind speeds over 25 km/hr. This is the most likely cause of damaging fire events in rugged terrain. This is not generally a well-known hazard.
- **Dense spotting**, where a field of interacting spotfires, whose intensities increase in convergence zones, emulate deep flaming. This is not a well-known hazard.
- **Inappropriate use of accelerant** – often under the auspices of the Incident Action Plan. Certain ignition patterns can emulate deep flaming, while any ignition in a VLS-prone landform will produce deep flaming. This is not a well-known hazard.
- **Interior Ignition**, where, in Boreal Forests, the fire's initial passage only burns some vegetation types. The ignition of unburnt islands at later times can cause interaction with the main fire able to emulate deep flaming. This hazard has patchy understanding.

In all of these cases the local fire rate of spread or intensity may exceed, by a considerable margin, estimates produced by established fire behaviour prediction systems.

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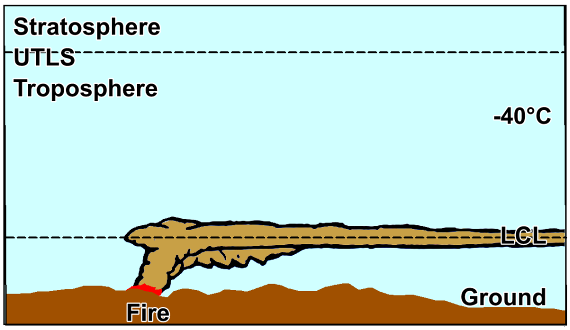
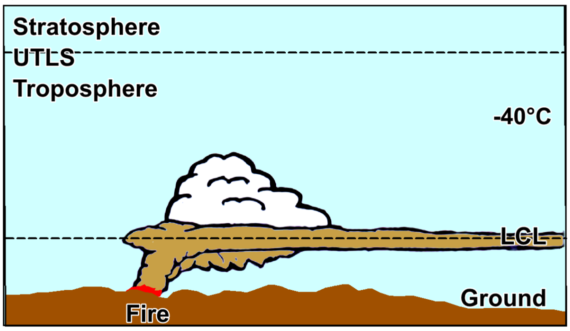


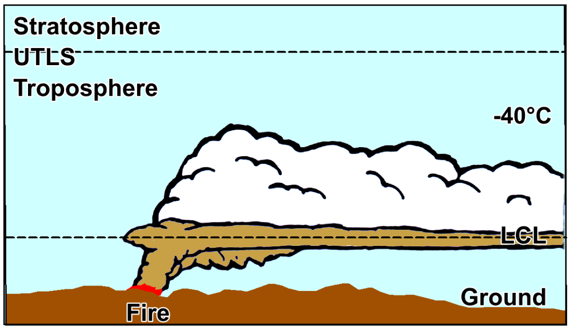
Type S1: Smoke shield

b)



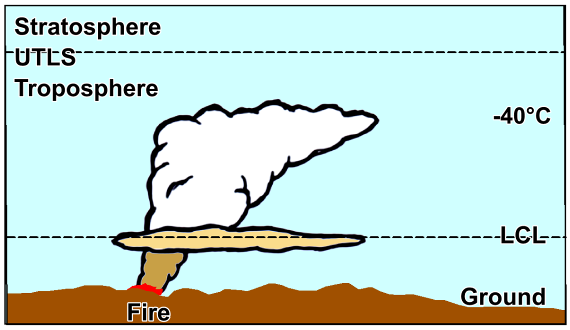
Type S2: Smoke shield with rebound

c)



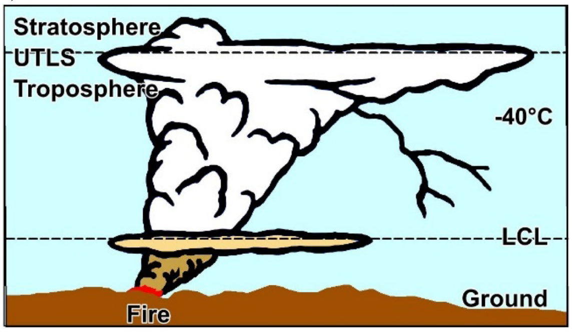
Type S3: Smoke shield with towering pyroCu

d)



Type U1: Sub_UTLS event

e)



Type U2: PyroCb

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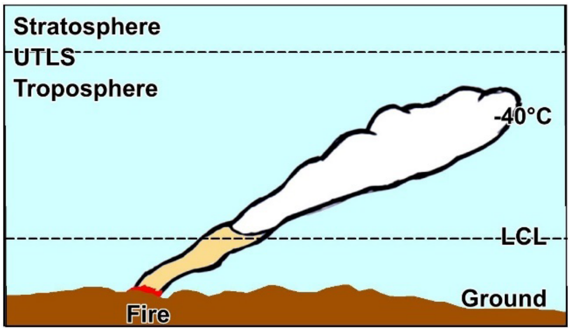

Type U3: Pyro-puff (towering pyroCu)

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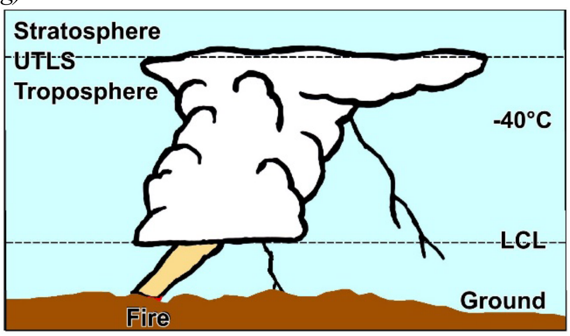
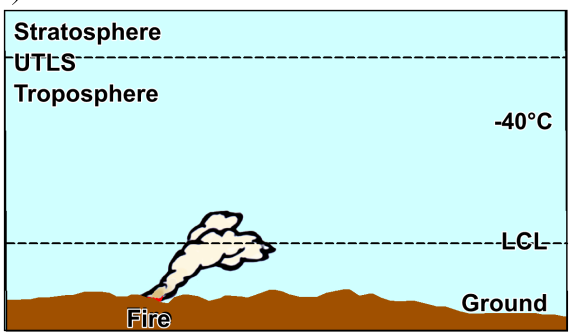


Type U4: Fire enhanced ambient Cb event

h)



Non-VPC fire.

Idealised depictions of types of violent pyro-convective events. Wind is blowing from left to right.

BOUNDARY CONDITIONS FOR USE

In the context of a large uncontained wildfire: VPC is observed, predicted or could occur given forecast conditions; or VPC occurred in the past and is being analysed retrospectively.

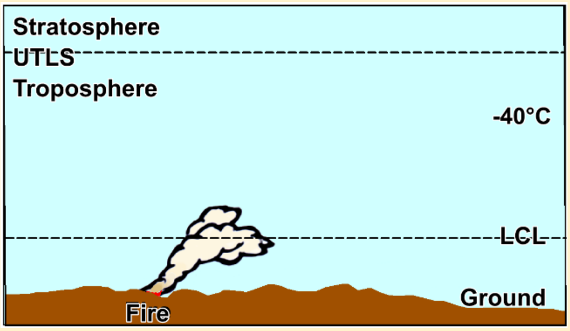
The goal is to identify events, and in so doing (a) have a name of facilitate clear and unambiguous communication; (b) identify associated specific risks to guide risk mitigation; and (c) allow proper use of the event in analyses to help in future fire situations.

This report in no way serves to predict VPC.

MODERATELY STABLE PROFILE

Normal fire (No VPC)

If the convective cap is moderate – broadly between 4°C and 6°C – the plumes of these fires mix out rapidly as they rise, do not couple with the air above, and do not form VPC. Cu clouds are often present but have no impact on fire dynamics.



VERY STABLE PROFILE

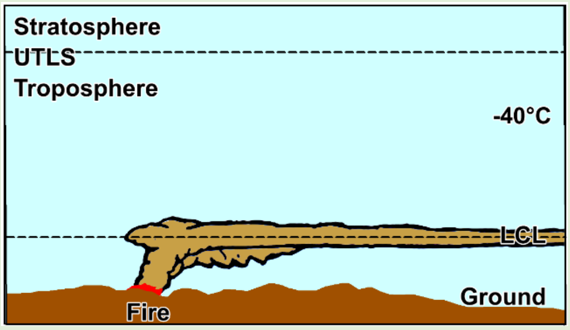
With a strong convective cap a kilometre or so above the fire ground (typically below the LCL), convection is limited while advection dominates. Such caps are commonly from subsidence around large high pressure cells. Subsidence inversions often bring dry air close to the surface, able to be mixed down during hot uphill fire runs. Deep flaming is involved, but radiative forcing has not been observed. Most events are in the lee of high country, and many feature downslope laminar flow. There may also be a hydraulic jump, perhaps 20 km to 100 km downwind, which is rarely above the source on the fireground, but could produce dangerously unpredictable fire behaviour elsewhere. Events could involve isentropic drawdown.
VLS, if not other causes, can create a BUFE in these profiles. More data on this are required.
These events have long been common in, for example, California and the Mediterranean basin. They recently became newsworthy in Hawaii. They were not recognised in Australia prior to 2010, and yet were behind c. half of major fire events during Black Summer.

All such fires spread by dense short and medium range spotting, and are thus poorly held (if at all) by most containment options (even with no fuel ahead of the fire for 1.5 km). They present significant safety risks for fire crews, especially if the occurrence of dense spotting is not anticipated. Enhanced situation monitoring is essential.

Under this condition, fires are able to generate a form of VPC, which rises above (to a limited extent) and moves away from the fire. Nevertheless, it's intensity can alter fire ground weather and fire behaviour, creating a range of safety hazards. With all of the plume's energy constrained below the LCL there may be significant safety issues for fireground aviation.

Type S1. Smoke shield

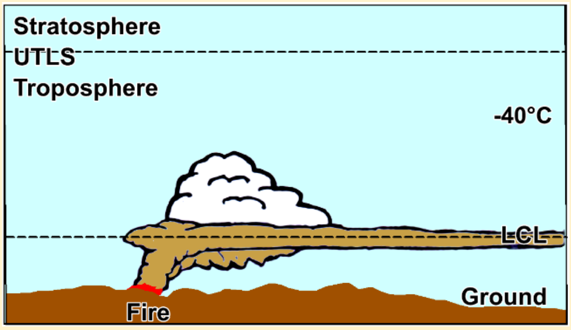
If the profile is very stable, with an intense convective cap (over 10°C), there is likely to be no pyrocloud. This is because the plume cannot pass the cap, and spreads out sideways as it advects away from the fire. There can be some immediate gravity-driven downwash of large aerosol and perhaps firebrands in the immediate lee of the main plume.



Type S2. Smoke shield with rebound

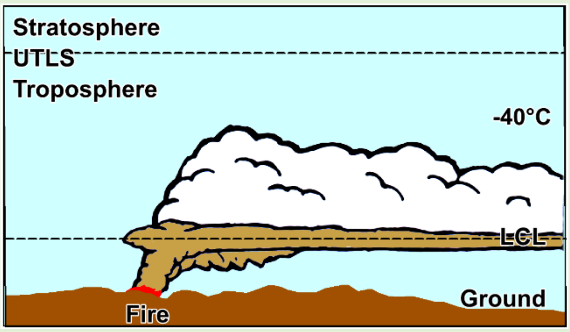
If the profile has a very strong convective cap, between roughly 8° to 10°C, short-lived towering pyroCu are likely to be present. Overall, the plume cannot pass the cap, but its core does initially push past, forming a towering pyroCu. Once initial upward momentum and the effect of latent heat of condensation dissipates this subsides back to the smoke shield, with the cloud evaporating. After that, the plume spreads out sideways as it advects away from the fire. There are indications of the potential for a downburst, not necessarily aligned with the prevailing winds (rather reflecting the balance between the wind vectors and outwards plume spread vectors). There can be some immediate downwash of large aerosol.

A key safety concern arises if the fire is on high ground, closer to the LCL, as the downburst can rapidly push fire downslope, with the potential to cross containment efforts.



Type S3. Smoke shield with towering pyroCu

Q4 b) If the profile has a strong convective cap, between roughly 6° to 8°C, then persistent towering pyroCu are likely to be present. The plume cannot pass the cap, except in its core which pushes past, forming a towering pyroCu. Once initial upward momentum and the effects of latent heat of condensation dissipate this persists for some time. The rest of the plume also spreads out sideways as it advects away from the fire. There can be some immediate downwash of large aerosol.



UNSTABLE PROFILE, BUFEs EXPECTED

Unstable profile (convective cap weak, less than 4°C).
Prior to initiation of VPC, there may be a “bow wave” cloud – a horse-shoe shaped lenticularis – wrapped around the upwind edge of the plume. The bow wave may also be detectable in satellite water vapour imagery.

Such fires require conditions for BUFEs be observed/forecast/expected, thus able to produce coupling of the fire with the atmosphere above and produce VPC.

PYROCB description:
A pyroCb is a cloud that forms in a rising fire plume (convection column) and has all of the following properties: (1) reaching the UTLS; (2) Cb morphology, including an anvil, sometimes an overshooting top; (3) often a cauliform texture to the basal parts; (4) glaciation (and perhaps subsequent lightning generation) when average cloud-top BT falls below -40°C; and (5) an unambiguous linkage to convection immediately above the fire. The duration of the source BUFE exceeds the time taken to reach the UTLS, so the anvil is clearly linked to the fire.
The fire needs to form deep flaming under an unstable profile.

These fires often spread by dense short and medium range spotting, and are thus poorly held (if at all) by most containment options (even with no fuel for 1.5 km ahead of the fire). They present significant safety risks for fire crews, especially if the occurrence of dense spotting is neither forecast nor detected.
The pyroCb event may emerge from only a localised part of the fire’s extent – the rest must not be overlooked.
PyroCbs reach the UTLS, and the resulting plume cloud has an anomalous Brightness Temperature Difference (BTD) (i.e., 3.0 µm BT – 10.3 µm BT exceeding 50°C) due to the aerosol within it.
Reaching the UTLS guarantees glaciation and lightning. Strong convection creates indraft winds that dominate fire behaviour. On reaching the LCL, the condensation of water vapour (from indrafts and from combustion) releases latent heat of condensation, which may be up to three times the heat from the fire. This enhances convection. For a large range of altitudes the plume will be thermally expanding, and thus resisting mixing out. This often gives the plume a cauliform appearance. The radiant heat from the fire causes radiative forcing of the aerosol-filled plume. Airborne infrared imagery above the BUFE shows reflection, scattering and re-radiation underway for up to 2 km above the fire. This aids thermal expansion within the plume.
PyroCbs can often occur nocturnally, if the fire’s energy release can negate the nocturnal inversion. Mixing down of dry air aloft or nocturnal low-level jets can be involved, as can burn-out ignition patterns. PyroCbs or Cbs appear to be able to be initiated when a passing atmospheric disturbance such as a soliton or a derecho disrupts the convective cap. These are uncommon and not well known, and future instances need to be studied.
A fire that creates a pyroCb: radically changes winds around the fire edge; impedes situational awareness; creates major vorticity events; causes low oxygen combustion; and, as a result, creates ember storms. All of these are dangerous for fire crews.
Pyrogenic lightning may cause new ignitions downwind (based on upper steering winds, not surface winds).

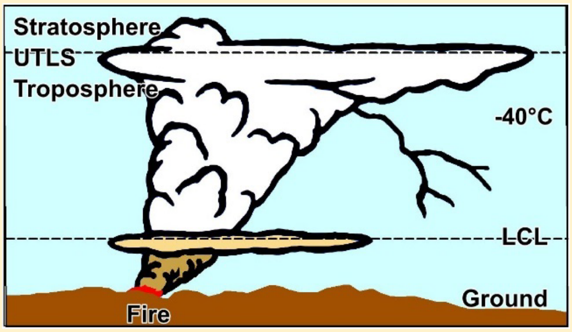
It is important to note that pyroCbs involve very small water droplets, due to smoke provide many nucleation particles. As a result downburst events are not expected. It is feasible that a fire-enhanced Cb (U4) could produce a downburst – covered by normal fire ground safety alerts for Cbs.

Type U1. PyroCb

There is a need for a range of terms to describe pyroCbs.

If it is a poorly understood event lacking contextual details, for instance if a pyroCb is reported with no extra information, it is called a pyroCb. However, due to the varying impacts on fire behaviour and fire crew safety that such events signify, it is desirable to, if possible, further classify pyroCbs, below. Sometimes there will be insufficient information to do so (especially with forecasts or with retrospective analyses) or the Incident Management Team lacks the capability or resources to further classify the event.

If in near real-time, the affected Division should be treated as dangerous for fire crews for, nominally, three hours, with continuing re-assessment of the fire-ground risk profile.



Type U1a. PyroCb event

A pyroCb can occur when VPC production originates from a limited area, typically less than 50km, linked to a single or multiple overlapping BUFEs.

This is likely to be from a single fire or fire complex, and likely from a single Division. After initiation, the BUFE typically lasts for up to three hours.

The affected Division should be treated as dangerous for fire crews for, nominally, three hours, with continuing re-assessment of the fire-ground risk profile.

Type U1b. PyroCb cluster

Here VPC initiation spans a broader area, typically involving multiple fires in a limited area, a fire complex, or more than, indicatively, 50km across a fire-affected area. VPC production does not exceed the lifetime of the underlying BUFE event, typically 2 to 3 hours.

On a landscape with multiple fires, or fire complexes, conditions amenable to BUFEs may occur nearly simultaneously on more than one fire. This reflects the spacing of fires across the landscape, and often shows passage of a trough, wind change event, or the sudden removal of a convective cap (such as by the removal of dense smoke by a wind change).

All sectors and divisions of all fires involved should be treated as dangerous for fire crews for a minimum of three hours, with continuing re-assessment of the fire-ground risk profile. Affected and nearby Incident Management Teams need to coordinate their assessments.

Type U1c. PyroCb Pulse

Here VPC production originates from a limited area, typically a single fire, part of a fire complex or a span of less than, indicatively, 50km in a fire-affected area. VPC production exceeds the lifetime of a typical BUFE event, typically 2 to 3 hours. (This does not apply if the underlying fire significantly abates.)
A dangerous fire can produce a series of pyroCbs from a common source area, the extent of which reflects the rate of expansion of the fire. The cause of this “cycling” has proven difficult to ascertain, but may be due to terrain patterns or to unstable feedback loops between the fire

and its environment. Some or all pulses are pyroCbs, some may be Sub-UTLS events.
Pulses act to extend the window of dangerous conditions beyond those of single pyroCb events – perhaps for an entire shift – requiring continuing re-assessment of the fire-ground risk profile.

Type U1d. PyroCb outbreak

Here VPC initiation spans between, indicatively, 50 km to 200km typically involving multiple fires in a limited area (often a fire complex) or less than 24 hours. An outbreak of pyroCbs involves a series of pulses from a cluster (i.e. spanning more than the duration of a typical BUFE, 2 to 3 hours, and more than 50km). General fire intensity does not abate for that duration. Not all events in a cluster need to pulse.

All sectors and divisions of all fires involved should be continually re-assessed for danger to fire crews, with changes to incident objectives implemented as and when required.

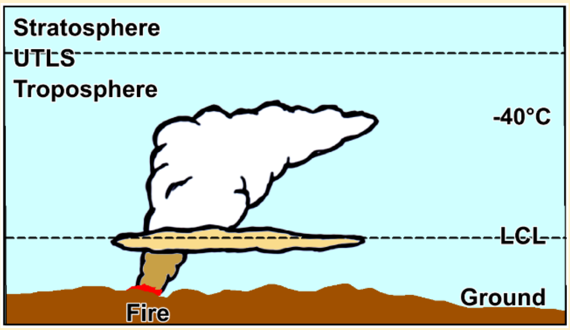
Type U1e. PyroCb super outbreak

Here VPC initiation spans more than, indicatively, 200km and one day.
This somewhat arbitrary term has been applied to a single event (in southeast Australia between 28 December 2019 and 4 January 2020) when regional conditions amenable to large numbers of BUFEs occurred over a number of days. This was associated with branched inshore troughs ahead of a stalled cold front. A long-lived low-pressure recirculation formed, keeping fire behaviour elevated.
All sectors and divisions of all fires involved should be continually re-assessed for danger to fire crews, with changes to incident objectives implemented as and when required. This need carries over between shift cycles. The conditions involved mandate specialist meteorology advice, a specialist intelligence cell, and a dedicated remote sensing group. It is expected that future events (under the influence of climate change) could radically alter this definition.

Type U2. Sub-UTLS event

Within this group, there is one outlier: if there is an inversion between LCL and UTLS, significant towering pyroCu may occur. While outwardly resembling a pyroCb, these do not reach the altitudes required to qualify as a pyroCb – the cloudtop temperatures may not fall below -40°C, inhibiting in-cloud glaciation and lightning. The stronger the upper-level cap, the more the plume-top can visually resemble a pyroCb's anvil.

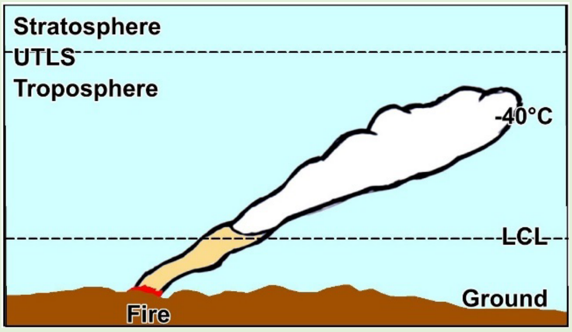
There can be interaction between fire weather and the plume, especially if the plume top is at high altitude, allowing strong *convective dynamics near the fireground.*



UNSTABLE PROFILE, BUFEs NOT EXPECTED

Type U3. Pyro-puff (isolated towering pyro-Cu)

If one of more fire Sectors make hot uphill runs, causing mixing down of dry air aloft, increasing fire intensity during the run, a short-lived form of VPC may occur. The resulting feedback does not persist when the uphill run ends. Potentially, burn-out ignition patterns could be involved, via a high isoperimetric ratio (the ratio of a fire's basal perimeter to its area). If this is possible, then such ignitions should be halted immediately.
Short-lived (under 30 minutes generation time above fire) towering pyroCu, minimum average cloud-top temperature typically above -40°C.



The duration of core plume generation is less than the time taken for the plume to reach maximum altitude.

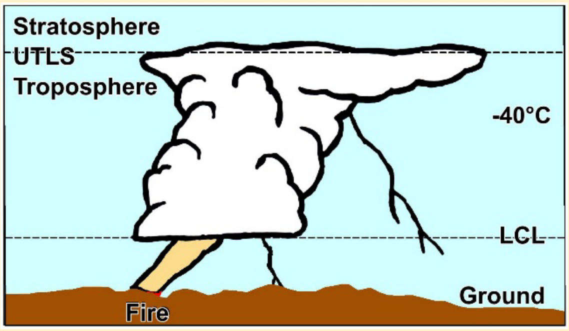
Normal fire ground safety protocols should apply during such hot uphill runs, with monitoring for enhanced feedback developing.

Type U4. Fire-enhanced ambient Cb

If Cbs occur, or are about to occur within (typically) 50km of the fire ground, the smoke plume can then be entrained into a Cb's inflow.

BUFEs are commonly linked to trough lines, as are Cbs – so it is not unexpected that in some cases there is an ambiguity between a Cb or pyroCb label. Evidence suggests that North American pyroCbs occur preferentially in conditions conducive to Cbs, whereas there is no evidence for this in Australia.

Ambient Cbs lack the abundant condensation nuclei that make pyroCbs so distinctive. Satellite imagery can help distinguish them – if the anvil has a cloud-top infrared Brightness Temperature (BT) anomaly, or is discoloured by aerosol, then it is part of a pyroCb (see above).



Beyond the normal fire-ground safety issues from Cbs, there is some evidence that extra care is needed on the fireground as fire behaviour may be directly affected by these events.

Some final points…

There are correlations between data or indices often used to predict dangerous fire behaviour.

As an example, if VPC is possible, the LCL be will at a lower pressure level (i.e. higher altitude) than those used to generate the Continuous Haines Index (CH), Mid-level Haines Index or Mid-Level LASI. These indices are widely stated as including a measure of stability. Yet here "stability" primarily refers to conditions above the LCL. There may, however, be a strong correlation between conditions above and below the LCL if there is a dangerous wildfire burning, requiring verification for incident-critical intelligence products.

Such fires are often seen as being more likely the higher the fire danger is. Outside the tropics, every fire danger index uses both temperature (T) and relative humidity (RH). This is described as a measure of the weather and its ability to dry outside fine surface fuel. T &RH also define the LCL - a cloud property - on a day when a dangerous fire can burn. In this report, which deals with the atmospheric profile, reference to the LCL is preferred to the use of Fire Danger Indices.

It is for this reason that the usual fire weather concepts are not used in this report.

Fuel load is also a common input to predictions of fire behaviour.

If a BUFE forms, the result does not obviously reflect fuel load or fuel arrangement. The plume dynamics considered by atmospheric scientists using satellite data seem remarkably similar, whatever the forests type involved. The only role for fuel is the presence of an uncontrolled QSS wildfire as a precursor. It should be noted that the often-observed the lack of significant effect of prior fuel reduction burning (beyond, say, two years age) is consistent with this.

This leads to two outcomes: (1) there is no use of fuel type in this report, and (2) there is a clear need for further study to see if there is any role for fuel metrics in BUFEs.

This report may be updated from time-to-time as new lessons are learned from future fire events.

The author thanks the global on-line Pyro-Cb group, and especially Mike Fromm and Dave Peterson from the US Naval Research Laboratory, for their work in developing our understanding of these challenging fire events.

MF is also thanked for valuable comments on early drafts of this report. I also thank Edward Hyer (USNRL) for comments on the previous draft, sent to the pyroCb group for comment.