Government of Western Australia

DFES Department of Fire & Emergency Services

Bushfire Centre of Excellence
TRAINING / KNOWLEDGE / ENGAGEMENT

# The Influence of Pyrocumulonimbus Events on Fire Behaviour

## How pyrocumulonimbus events influence fire behaviour

Pyrocumulonimbus (PyroCb) events can influence fire behaviour by creating extreme and erratic fire conditions that reduce the accuracy of fire behaviour predictions. This factsheet helps fire managers recognise signs of potential PyroCb development and prepare for erratic fire behaviour.

PyroCb development is more likely in unstable atmospheric conditions. It can be further influenced by local topography and sea-breeze convergence lines. An unstable atmosphere increases convection, promoting fire plume development that can lead to PyroCb formation. During these periods, fireground conditions become particularly dangerous. Fire behaviour can be highly erratic, including rapid, unpredictable changes in wind direction and strength. There is also the potential for PyroCb-related lightning to ignite new fires.

Some indicators of instability, such as fire plume and cloud formation, can be visually assessed. However, upper atmospheric instability and wind patterns are unable to be detected without technical data. Tools like the Continuous Haines (C-Haines) Index and mixing height data offer useful guidance on the likelihood of PyroCb formation, but fire managers should also consult meteorologists to gain a full understanding of the risk.

***Figure 1*** *Example of a PyroCb cloud formed by an intense bushfire. A deep convective column rises from the fire plume and spreads into an anvil-shaped thunderstorm cloud. This can drive erratic and extreme fire behaviour.*

## What is pyrocumulonimbus?

Pyrocumulonimbus (PyroCb) clouds are thunderstorm clouds formed by the intense heating of air above a bushfire. They are tall, dense and convective, with a flat base and a spreading, anvil-shaped top (Figure 2).

The development of a PyroCb is preceded by a pyrocumulus (PyroCu) cloud. This forms when rising air from a fire begins to condense. PyroCu clouds are smaller and do not produce lightning. However, they are important because they can indicate that atmospheric conditions may support further vertical cloud growth.

If the atmosphere is unstable, a PyroCu may rapidly deepen and transition into a PyroCb. Not all PyroCu develop into PyroCb, but their presence should increase awareness of atmospheric instability and the potential for fire behaviour to escalate.

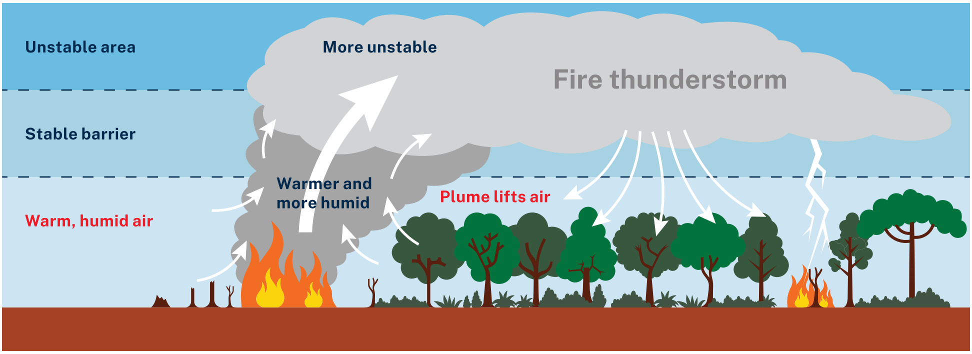


***Figure 2*** *Pyrocumulonimbus development and its impacts on the fireground, including lightning-ignited spot fires.*

## Atmospheric stability

**Stable atmosphere**
Fire plume development is less vertical, and smoke spreads beneath an inversion layer. A strong convection column is unable to form, limiting vertical cloud growth and preventing the development of PyroCu into deeper convective clouds (Figure 3). Stable atmospheres usually limit significant fire intensification, although intense fire behaviour may still occur where strong winds or heavy fuel loads drive the fire.

**Unstable atmosphere**
Fire behaviour is more intense because a strong convection column forms. Smoke rises higher and may form PyroCu above the plume. This can deepen and transition to PyroCb if instability extends into the middle and upper atmosphere.

## Temperature inversion

Normally, air temperature decreases with height. When an inversion is present, rising air is trapped beneath warmer air above. Inversions cap vertical motion, which strongly affects plume development and cloud formation. When a pronounced inversion is present, PyroCu growth is limited, and convective clouds are unable to develop high enough to form thunderstorms. Without an inversion, or where the inversion is weak, the atmosphere is unstable. This allows the PyroCu to deepen and potentially transition to a PyroCb event.

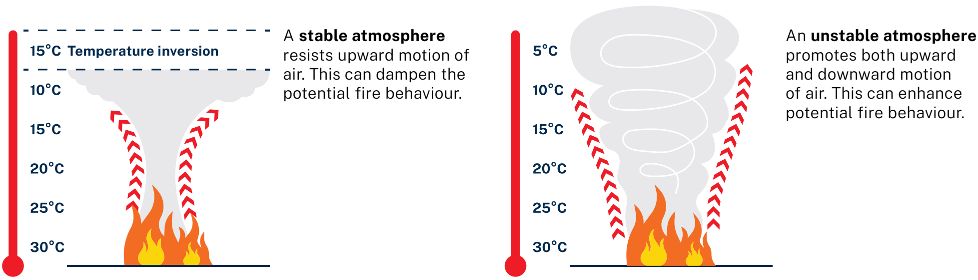


***Figure 3*** *The effect of inversion layer and atmospheric stability on fire development.*

# When do pyrocumulonimbus develop?

PyroCb form when heated air from a fire rises quickly and cools in the middle-to-upper atmosphere, creating clouds. In a deeply unstable atmosphere, these clouds can become thunderstorms, especially when a bushfire is large and intense (Figure 4). This increases instability and the likelihood of a PyroCb event (Tory et al. 2016). These thunderstorms can bring strong inflow winds, downbursts and lightning strikes (Figure 2).

Cumulus clouds indicate atmospheric instability and should prompt consideration of PyroCb development.

However, an inversion layer can block the transition from PyroCu to PyroCb.

For PyroCb to form, the atmosphere must be unstable or marginally unstable. This allows the fire plume to rise high enough to form thunderstorm clouds instead of being trapped below an inversion (Figure 2). Even plumes from planned burns can form PyroCb where supporting atmospheric conditions occur. Extra lifting sources, such as sea-breeze convergence lines, fronts, troughs and topography, can boost rising air and increase the chance of PyroCb development.

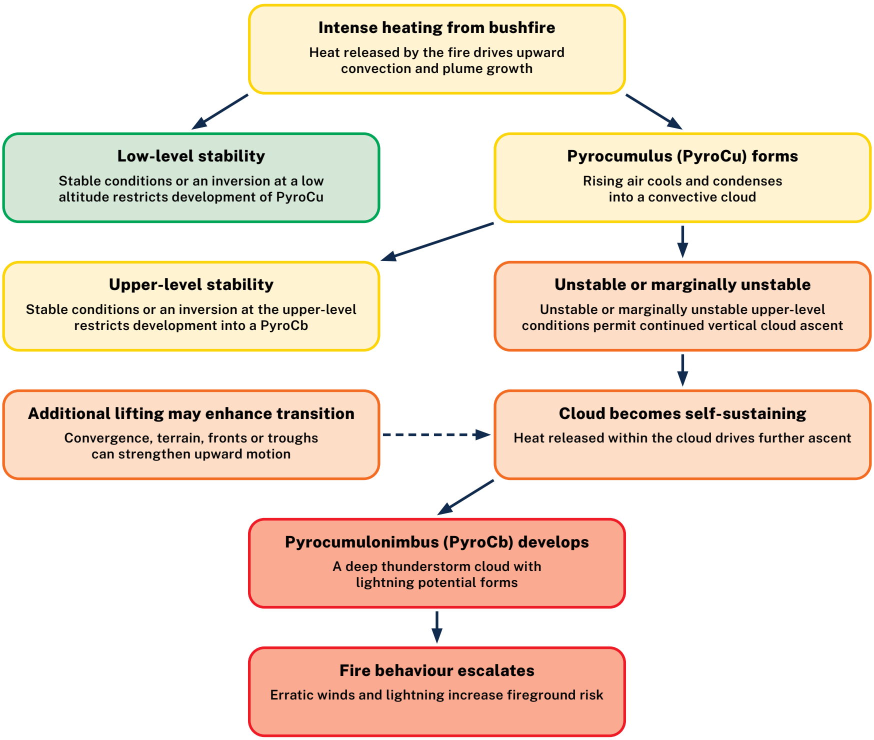


***Figure 4*** *Flow diagram showing how intense fire heating, atmospheric instability and additional lifting can enable the transition from pyrocumulus (PyroCu) to pyrocumulonimbus (PyroCb), leading to escalated fire behaviour.*

## Visual signs of PyroCb formation

Atmospheric instability can sometimes be assessed by observing smoke and cloud behaviour. This includes the development of cumulus clouds above or near a fire that may indicate a transition from PyroCu to PyroCb.

Firefighters should watch for:

- Smoke rising to high elevations and forming tall columns
- Natural thunderstorms developing near or downwind of the fire
- PyroCu or cumulus clouds with strong vertical growth above the fire
- Dust swirls or dust devils (willy-willies).

Visual indicators are useful, but if there is no smoke, cloud or dust, it is almost impossible to assess atmospheric stability without technical data or analysis.

**Rising smoke**

**Cumulus cloud or thunderstorm**

**Dust swirls or dust devils**

## How does pyrocumulonimbus affect fire behaviour?

Before a PyroCb forms, atmospheric conditions that support its development include strong winds and low relative humidity, which can accelerate fuel drying at the surface. Vertical mixing may also bring strong winds and drier air from higher in the atmosphere down to the surface, further worsening bushfire conditions. These conditions can produce elevated fire behaviour even before PyroCb development.

As a PyroCb forms over a fire, inflow winds intensify and may converge into the plume from multiple directions. Downdrafts often develop beneath the thunderstorm cloud, but their location relative to the fire is unpredictable (Fromm et al. 2022). Strong updrafts and downdrafts may occur over the fire or several kilometres away, creating highly variable and unpredictable winds across the fireground. These winds can drive dynamic fire behaviour, increase intensity and make spread less predictable. Fire intensity, flame height, rate of spread and ember spotting can all escalate. Wind surges may rapidly change the direction of fire spread and spotting. PyroCb events may also produce cloud-to-ground lightning from any part of the thunderstorm cloud, often beyond the fireground itself. Lightning poses a direct risk to ground crews and may ignite new fires in multiple directions, adding complexity to incident management. This creates ongoing risk, even after conditions appear to be moderate.

After the PyroCb has dissipated, fuels may remain very dry. Fuel-moisture recovery can lag by a few hours after increases in relative humidity, allowing elevated fire behaviour to persist while fuel moisture recovers. Lightning poses a direct risk to ground crews and may ignite new fires in multiple directions, adding complexity to incident management. This creates ongoing risk, even after conditions appear to be moderate.

# Predicting PyroCb development

Fire managers can use technical indicators to assess the likelihood of PyroCb development. This helps trigger further investigation and actions during large bushfires or large planned burns. The following 3 steps help guide operational decision making:

## Step 1

Check site weather conditions using the Bureau of Meteorology (BOM) website and products (such as Incident Weather Forecasts) or by consulting on-call meteorologists. Key indicators of atmospheric stability include:

- **Continuous Haines (C-Haines) Index:** Assesses dryness and instability in the middle atmospheric layer (1,500 to 3,000m). Values range from 0 to 13. Higher values indicate greater PyroCb potential (Figure 5).
- **Mixing height:** Indicates the depth from the surface to where warm air stops rising or condenses into cloud. This is the height a fire plume can reach.
- **Thunderstorm Activity Level (TAL):** Indicates the likelihood of natural thunderstorms.

## Step 2

Compare C-Haines, mixing height and TAL against the assessment guide (Figure 5) to classify conditions as **Unlikely, Marginal, Possible** or **Likely.**

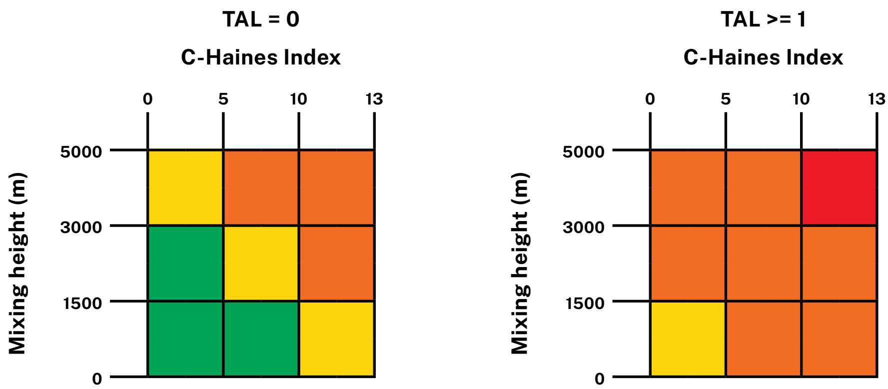


***Figure 5*** *Assessment guide linking C-Haines, mixing height and TAL to classify conditions for PyroCb development as Unlikely (green), Marginal (Yellow), Possible (orange) or Likely (red).*

## Step 3

Determine the development likelihood and use it to make a risk-informed decision (Figure 6).

| Development likelihood | Interpretation for decision makers |
|---|---|
| **Likely** | **Refer to operational considerations in Step 4** |
| **Possible** | **Consult with fire weather forecasters** If consultation suggests likely or possible assume PyroCB will occur. |
| **Marginal** | |
| **Unlikely** | **Exhibit a normal degree of caution** |

***Figure 6*** *Decision-making guide showing how development likelihood translates into operational responses, including consultation requirements and key safety messages.*

## Key safety messages for incident controllers and fire ground personnel

If development is **Likely** or **Possible**, apply heightened caution.

Conditions that can trigger erratic and extreme fire behaviour:

- The fire spreads rapidly and unpredictably, with flanks or tail turning into head fires.
- Sudden wind downbursts intensify activity and spotting.
- Lightning from the storm may ignite new fires.
- Elevated fire behaviour may persist after PyroCb activity, even if surface weather conditions are moderate.

Operational considerations in these conditions:

- Communicate the increased risks of erratic fire behaviour.
- Prioritise defensive over offensive strategies.
- Postpone large, planned burns and backburning when conditions support PyroCb development.
- Avoid direct attack.
- Avoid deadman zone.
- Maintain heightened awareness beyond the fire edge and following apparent weather moderation.
- Continuously monitor conditions and ensure actions follow operational guidelines.
- Consider a Red Flag Warning.

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Published by Bushfire Centre of Excellence, Department of Fire and Emergency Services.

Produced by Bushfire Technical Services, Department of Fire and Emergency Services.
March 2026



## Further Information

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