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PYROCUMULONIMBUS FORECASTING

Needs and issues

K. J. Tory, M. Peace, W. Thurston
Bureau of Meteorology
Bushfire and Natural Hazards CRC





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Cover: Pyrocumulonimbus cloud formed above the Waroona fire in Western Australia, 7 January 2016. Image courtesy Tracy Vo, Channel 9 Perth.



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END USER STATEMENT

Paul Fox-Hughes, *Tasmanian Regional Forecast Office, Bureau of Meteorology.*

Pyrocumulonimbus events can substantially change the weather characteristics in the vicinity of fires, which may drastically affect fire behaviour. This is of very considerable concern for fire managers, and therefore for fire weather forecasters. In particular, the wind around a fire can become very erratic in the presence of pyroCb, with downburst winds a greater risk than at other times. Lightning from pyroCb can ignite additional fires, and in extreme cases pyroCb may generate tornadoes (such as occurred during the 2003 Canberra fire).

Forecasters and fire managers need to be aware of the possibility of pyroCb development to allow for the chance of such erratic fire behaviour. The environments that support pyroCb development, then, are an important topic of study for the Bushfire and Natural Hazards CRC, and the results of this research project will be of great interest to all involved in the planning for and management of dangerous wildfires.



BACKGROUND


A pyrocumulus cloud is a dense cumuliform cloud associated with fire or volcanic activity. It is produced by intense heating of air, which can lead to deep ascent and subsequent condensation and cloud formation when the rising air becomes saturated due to cooling from adiabatic expansion. The process is similar to conventional convective cloud formation, except the fire or volcano provides the primary lifting mechanism. If the heat source is sufficiently large and intense and the atmosphere sufficiently unstable the pyrocumulus cloud can develop into a deep convective column resembling a conventional thunderstorm (Cumulonimbus), which may be accompanied by strong inflow, dangerous downbursts and lightning strikes. When associated with fire, the inflow may enhance fire spread rates and fire intensity, the downbursts may cause sudden changes in fire spread rate and direction, and the lightning may ignite additional fires. It is these fire generated cumulonimbus (PyroCb) events that we focus on in this report. The reader is referred to a previous report titled “Pyrocumulonimbus: A literature review” (Tory and Thurston, 2015) for a more detailed summary of the PyroCb literature. In that report we defined PyroCb to be the subset of PyroCu that produces rain. However, it is perhaps more important to focus on PyroCu that has the potential to impact fire behaviour. In the remainder of this report we extend the PyroCb definition to include any non-raining PyroCu that may have a non-trivial impact on fire behaviour. The earlier report also discussed the following topics relevant to the present report: Environmental conditions that favour PyroCb development, heat and moisture contributions to PyroCb from the fire, and PyroCb triggers.

After finding no papers specific to the topic of PyroCb forecasting in fire and meteorology scientific literature, we surveyed a selection of fire weather forecasters and researchers from Australia and North America to tap into their experiential knowledge. We combine their knowledge with recent results from observational studies and our own idealised fire plume simulations, to construct a PyroCb conceptual model that best fits all these inputs. This conceptual model should be considered a work in progress. There are many knowledge gaps associated with the model, which will hopefully be filled in the next few years, allowing the development of an improved model. The conceptual model is used to: highlight aspects of PyroCb formation that are not well understood, and propose experiments and procedures that will improve understanding of PyroCb formation. We suggest a recently proposed objective technique for analysing PyroCb formation potential to be tested by forecasters and verified when possible.

PyroCb conceptual model

The PyroCb conceptual model includes a number of assumptions based on the similarity to conventional Cumulonimbus (Cb) systems, plus one well-established fact of plume behaviour. But first we define PyroCb as fire-induced cumuliform cloud that produces rain. Both PyroCb and Cb require:

- i. A conditionally unstable atmosphere, and
- ii. A lifting mechanism to release the instability.



It is clear to the forecasters we spoke to that if the atmosphere alone is conducive to Cb development, or at least marginally conducive, then the presence of a large, hot fire will highly likely produce pyroCb. Even the presence of large cumulus clouds in the vicinity of a large, hot fire is a good indicator of pyroCb potential. However, forecaster experience shows that PyroCb can develop when measures of conventional Cb potential are unfavourable, which suggests that the fire is more than just a lifting mechanism, i.e., the fire provides heat and moisture (from evaporation of fuel moisture and combustion chemistry) that enhances the conditional instability above that of non-fire affected air. Thus, at the core of the proposed PyroCb conceptual model:

1. *A PyroCb is a series of thermals or a plume of air made buoyant by heating from the fire, which rises to a level of condensation, where condensational heating further enhances the buoyancy contributing to deep ascent.*

In this report we define the term “fire plume” to mean the buoyant thermals or plume of smoke, combustion gases, and entrained air, emerging from the fire. We also use “the plume” to refer to the combined fire and moist convection plume of the PyroCb. How much heat and moisture the fire needs to contribute to the fire plume for PyroCb to be initiated is still under debate, since the fire plume gas composition is not well understood, and changes very rapidly with ascent, as significant quantities of environmental air are entrained into the plume. This brings us to the well-established fact of plume behaviour underpinning the PyroCb conceptual model,

- iii. Entrainment dilutes the plume.

The combustion gases and radiatively heated air in the immediate fire vicinity have considerable buoyancy that results in strong vertical acceleration and significant entrainment of environmental air. The continual entrainment of environmental air with height dilutes the plume buoyancy until eventually it becomes neutrally buoyant. Laboratory studies (e.g., Morton and Ibbetson 1996, Morton 1997a, 1997b), experimental fire studies (e.g., Finney and McAllister 2011), idealised modelling (e.g., Thurston et al. 2013), and fire plume observations (e.g., see PyroCb literature review, Tory and Thurston 2015) all show that the entrainment is significant and persistent, and that the entrained flow substantially dilutes the hot gases as they ascend. As a consequence any estimate of the relative fraction of fire heat and fire moisture to entrained environmental air in the plume decreases with height above the fire. It follows that our PyroCb conceptual model is:

2. *The PyroCb plume is a column or series of thermals initiated by heated air and hot combustion gases. As the plume rises, it entrains environmental air throughout its depth, so that by the time condensation occurs the plume typically consists of mainly cooler and usually drier environmental air.*

Two more assumptions underpinning our conceptual model are:

- iv. Entrainment rates are strongly affected by the fire plume nature and structure.
- v. The fire plume nature and structure is strongly influenced by fire size and intensity, and the atmospheric environment.



Idealised modelling demonstrates that upright convection column-like fire plumes experience lower entrainment rates than highly turbulent, puffing, bent-over fire plumes (e.g., Thurston et al. 2013). These studies suggest a range of intermediate fire plume structures are also likely, with convection-column-like plumes favoured by large, intense fires in weak background winds, or convergent boundary layers, and the bent-over plumes favoured by smaller, weaker fires in stronger background winds, or divergent boundary layers. Other environmental conditions are likely to impact fire plume structure, such as vertical wind shear, variable wind direction with height, atmospheric stability, and turbulence intensity and scale. Thus the final statement underpinning our PyroCb conceptual model is:

3. *The atmospheric environment and fire size and intensity largely determine whether a fire plume of sufficient scale can reach the condensation level and trigger deep convection.*

In the remainder of the document we seek to demonstrate the three statements, before introducing a semi-objective tool for assessing PyroCb potential, and discuss the need for further observations and modelling. Issues raised are discussed and summarised in the last section.



1. THE ROLE OF THE THERMODYNAMIC ENVIRONMENT

A PyroCb is a series of thermals or a plume of air made buoyant by heating from the fire, which rises to a level of condensation, where condensational heating further enhances the plume buoyancy contributing to deep ascent.

In the previous report (Tory and Thurston 2015) we noted that an inverted-V sounding has been postulated to be necessary for pyroCb development. A good example is presented in Fig. 1. It shows a deep well-mixed boundary layer (that favours intense fires), and a moist conditionally unstable middle-troposphere, which ensures entrainment above the condensation level doesn't overly dry out the moist convective plume. These conditions also favour high-based thunderstorms, and downburst development. Recent studies (Peterson et al. 2015, hereafter P15 and Lareau and Clements 2016, hereafter LC16) have documented PyroCb cases with distinctly drier thermodynamic profiles (introduced in Section 4), which suggest instead that the inverted-V profile may be *ideal* for PyroCb development rather than *necessary*. P15 note that PyroCb can develop in a thermodynamic environment that supports high-based dry thunderstorms, but suggest upper-level divergence is also *necessary* for PyroCb development. If this latter point is true an assessment of upper level divergence could be an important and useful PyroCb forecast procedure. However, the statement needs more rigorous testing, which could be achieved by investigating upper level divergence in reanalysis data for documented PyroCb cases.

It is worth reviewing the concept of Convective Available Potential Energy (CAPE) to better understand the PyroCb potential in Fig. 1, and to illustrate how fire heat and moisture can increase the thermodynamic instability (Fire-CAPE).

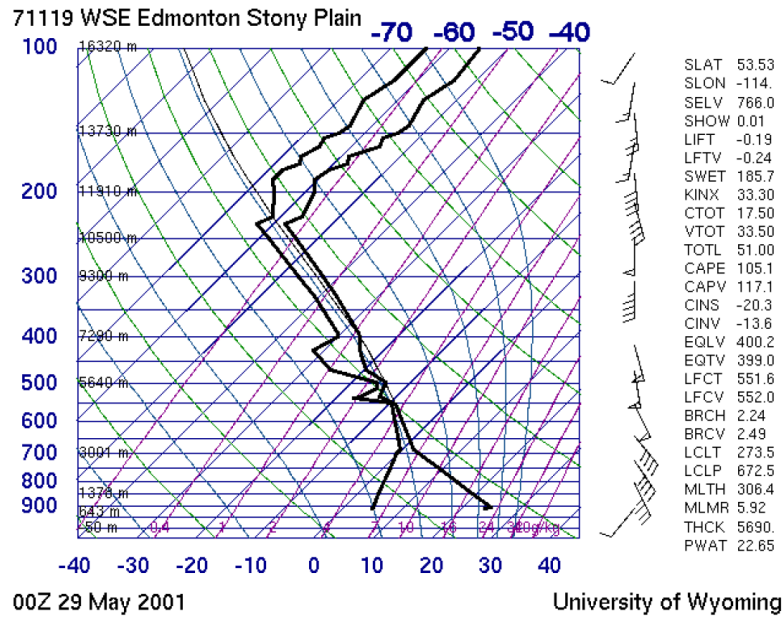


Figure 1: Edmonton thermodynamic sounding, 0000 UTC, 29 May 2001, during the development of PyroCb at the Chisolm fire, which was located about 150 km north of the sounding location. The right-most black line shows air temperature as a function of height above the surface. The left-most black line shows the corresponding dew-point temperature. Reproduced from Fig. 4 of Rosenfeld et al. (2007).

Fire-CAPE

To assess the atmospheric stability and the potential for pyroCb, forecasters have adapted conventional tools for identifying Cb potential, in particular convective available potential energy (CAPE). An example for assessing CAPE is given in Fig. 2. CAPE is calculated on a thermodynamic diagram by taking a hypothetical air parcel (which may be sourced from the surface or elsewhere in the lower troposphere, or it may be a parcel representing a mixed layer of air) and raising it adiabatically until it reaches the lifting condensation level (LCL) and then raising it moist adiabatically until it is no longer warmer than the environment (the equilibrium level, EL). The level of free convection (LFC) is the height at which the parcel first becomes warmer than the environment (positively buoyant). CAPE is represented by the area between the parcel path and the environmental trace in the layer between the LFC and EL. (Note, in the example presented in Fig. 2 the LCL and LFC are coincident, and the EL is at the tropopause.) CAPE provides an estimate of the buoyant energy of a convective air parcel. In reality convective parcels are turbulent and they entrain environmental air, which dilutes the parcel buoyancy by mixing colder environmental air into the convective cloud, and through evaporative cooling of cloud moisture by the drier entrained environmental air. This plume weakening from entrainment (see next section) is generally ignored for conventional Cb, which have horizontal scales of the order of a few to 50 kms, but it cannot be ignored for pyroCb, which might have horizontal scales one or two orders of magnitude smaller. All of the

following discussions of hypothetical parcel paths, CAPE, and condensation levels, are based on the conventional Cb conceptual models, and thus neglect entrainment, unless otherwise stated.

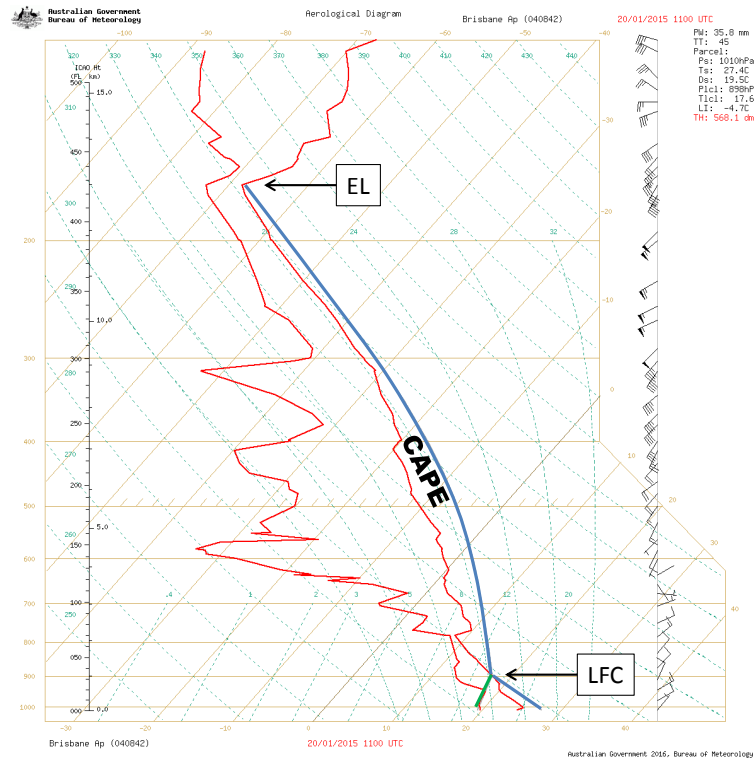



Figure 2: Thermodynamic diagram showing the environmental temperature (right red line) and dewpoint temperature (left red line), and a hypothetical parcel trace (blue line). The level of free convection (LFC) and equilibrium level (EL) are indicated by arrows. Convective available potential energy (CAPE) is represented by the area between the environmental temperature trace and the parcel trace, in the layer between the LFC and EL.

The fire adds additional heat and moisture to the environment, which may trigger pyroCb if the atmosphere is sufficiently unstable. Estimates of Fire-CAPE, such as that proposed by Potter (2005), can be visualised in Fig. 2 by shifting the green line slightly to the right to represent a contribution of fire moisture, and the straight section of the blue line to the right to represent the fire heat. The subsequent curved blue line would then be located further right indicating greater parcel buoyancy. This thought exercise also helps illustrate how moistening alone lowers the LCL, and heating alone raises the LCL, with both increments resulting in greater parcel buoyancy.

As mentioned earlier and discussed below, it is not clear what quantity of heat and moisture the fire provides, nor is it clear what the ratios of fire heat and moisture should be for each fire. It is equally unclear how a CAPE calculation should be modified to take into account the fire heat and moisture, due to the very significant fire plume dilution from entrainment (see Section 2). A range of



possible additional temperature and moisture perturbations have been considered (e.g., Potter 2005), with the amount based on a subjective assessment of the fire size and intensity, and some implied estimate of plume entrainment rate. These perturbations included varying ratios of heat and moisture as well as varying amounts, and the results provided an indication of the sensitivity of various atmospheric profiles to the perturbations. Potter's (2005) results demonstrated the point raised above that heating alone raised the LCL, and moisture perturbations lowered the LCL. This distinction might be important, since a lower LCL will generally be associated with greater CAPE, because the parcel path begins to deviate onto a warmer moist adiabat at lower levels (i.e., a warmer ascent). (Moist adiabats are marked by the dotted curved lines in Fig. 2 that are approximately parallel to the curved blue line.) Thus a lower LCL would be expected to be associated with more vigorous ascent above the LCL, not to mention the less lifting required for the LCL to be reached, and the reduced likelihood that the fire plume loses buoyancy (via entrainment) before the LCL is reached (see Section 2).

A subsequent study that considered the chemistry of combustion, evaporation of fuel moisture, and heat losses from the fire plume via radiation, identified a range of plausible heat to moisture contributions that suggested many of Potter's heat and moisture ratios were likely to be unrealistic (Luderer et al. 2009). Furthermore, the study concluded that for most fires, the fire moisture is likely to have minimal impact on pyroCb development. This conclusion has since been supported by two observational studies (P15, LC16) of large pyroCb that formed in deep, well-mixed boundary layers, with high condensation levels, in which any fire moisture would be expected to become highly diluted from plume entrainment by the time the condensation level was reached.

A modelling study of a pyroCb event that spawned a tornado (Cunningham and Reeder, 2009) arrived at the opposite conclusion: "the production of water by the fire has a huge effect on the development of pyro-cumulonimbus cells and the associated tornadogenesis". However, our calculations of their moisture to heat flux ratio, revealed a value three times higher than Luderer et al.'s moistest scenario, which according to Luderer et al. would be unrealistically moist.

The fire heat to moisture ratio debate is not yet settled. The remaining discussion in this paragraph is based on personal communication with Brian Potter. Until direct observations of heat and moisture near flame height are made it will not be clear whether the Luderer et al. (2009) proposed range of ratios is realistic. There are two arguments that might suggest the range of Luderer ratios should be extended further in favour of moisture. Firstly, incomplete combustion might be expected to release most or perhaps all the trapped fuel moisture, but not all the heat. Secondly, an investigation into water vapour release in biomass combustion concluded that some fuels contain significantly higher amounts of non-chemically-bound moisture than that measured using standard oven drying techniques (i.e., oven drying does not remove all the non-chemically-bound moisture, Parmar et al. 2008). In some fuels that Parmar et al. assesses the actual fuel moisture was double that measured by oven drying.

2. THE ROLE OF ENTRAINMENT

The PyroCb plume is a column or series of thermals initiated by heated air and hot combustion gases. As the plume rises, it entrains environmental air throughout its depth, so that by the time condensation occurs the plume typically consists of mainly cooler and usually drier environmental air.

This statement implies that before the condensation level is reached the fire plume has experienced significant dilution from entrainment such that it is composed mostly of entrained environmental air. This level of dilution can be demonstrated with a simple thought experiment. Assuming adiabatic expansion and cooling of the fire plume below the condensation level, a simple equation can be constructed that expresses the plume temperature at the condensation level, as a function of mixed environmental air (θ_{env}) and hot combustion gases and fire heated air (θ_{fire}),

$$\theta_{plume} = \theta_{env} + \Delta\theta_{CL} = \frac{\alpha\theta_{env} + \beta\theta_{fire}}{\alpha + \beta} \quad 1.$$

where θ is potential temperature (temperature after taking into account the effects of thermal expansion), α and β represent the fractional quantities of the environmental and fire air respectively, and $\Delta\theta_{CL}$ is a measure of how much warmer the fire plume is than the environment at the condensation level. For simplicity we have assumed the fire plume has uniform cross-sectional temperature and the environment potential temperature below the condensation level is constant. Equation 1 is rearranged to get a dilution ratio,

$$\frac{\alpha}{\beta} = \frac{\theta_{fire} - \theta_{env} - \Delta\theta_{CL}}{\Delta\theta_{CL}}. \quad 2.$$

We consider extreme examples of fire temperature ranging between 2 to 3 times the environment temperature (e.g., $\theta_{env} \sim 300 \text{ K}$ and $\theta_{fire} \sim 600 - 900 \text{ K}$), and a range of $\Delta\theta_{CL}$ from 2–7 K (matching the diagnosed “fire heat” range found in Section 4). This yields dilution amounts that range from about 40 to 300 times. The smaller (larger) dilution ratio results from the cooler (hotter) fire and warmer (cooler) fire plume.

An equivalent equation could be constructed for moisture that yields the same dilution rates, which has important implications for fire moisture. The dilution rates suggest that unless very large quantities of moisture are released by the fire, the fire moisture might be diluted to insignificance before the fire plume reaches the condensation level. Recent idealised modelling studies using a Large Eddy Model (LEM, Thurston et al. 2016) have demonstrated very significant fire moisture dilution in idealised fire plumes developing in deep day-time boundary layers using the range of heat to moisture flux ratios proposed by Luderer et al (2009). These fire heat to moisture ratios ranged from 6.6 K of heat per $g \text{ kg}^{-1}$ of moisture (wet) to 35 K of heat per $g \text{ kg}^{-1}$ of moisture (dry). Fig. 3 shows the time height moisture distribution for an idealised fire plume that produced pyroCb using the wettest of these fire heat to moisture ratios. The fire moisture is evident in the blue shades, with the background (environmental) moisture value of 4 g kg^{-1} apparent in yellow. The dilution of the fire moisture with height is apparent in the lightening shades of blue. This figure shows that for even the wettest Luderer et al. (2009) scenario the fire moisture has become so dilute at the condensation

level (about 4–4.5 km) that the moisture content only exceeded the environmental concentration for brief periods at about 40 and 65 minutes. Needless to say, in the drier fire scenarios fire moisture became insignificant at much lower elevations.

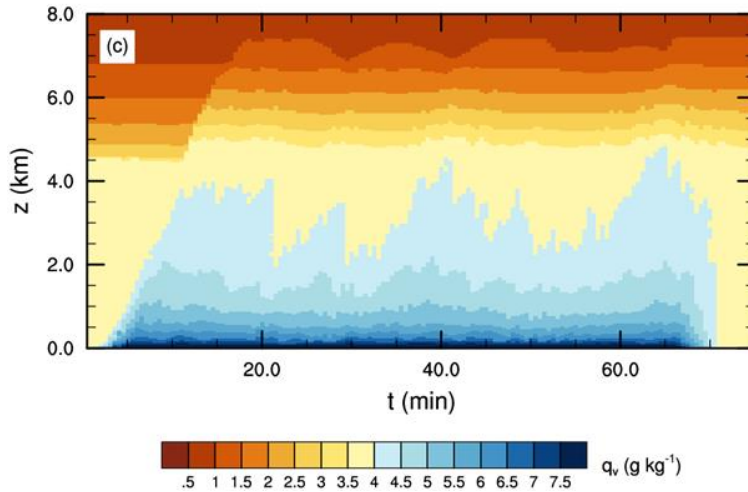


Figure 3: Time height profile of moisture content for a LEM simulation with a constant boundary layer moisture content of $4\ g\ kg^{-1}$, below 4 km, which decreases linearly above. A circular heat and moisture source of 250 m radius was added in the first few minutes with heat and moisture fluxes of 30 and $11.4\ kW\ m^{-2}$ respectively, corresponding to Luderer et al.'s (2009) “wetttest” fire scenario.



3. THE ROLE OF THE KINEMATIC ENVIRONMENT AND FIRE SIZE AND INTENSITY

The atmospheric environment and fire size and intensity largely determine whether a fire plume of sufficient scale can reach the condensation level and trigger deep convection.

The previous section illustrated that significant plume dilution from entrainment exists in fire plumes. Interestingly, the dilution might be expected to both hinder and be necessary for PyroCb to develop. Too much dilution and the fire plume loses buoyancy before the condensation level is reached, whereas insufficient dilution and the fire plume will ascend to very high levels before condensation occurs. These qualitative arguments are obviously sensitive to the plume moisture content. We speculate that most fires do not produce PyroCb because the entrainment causes the fire plumes to lose buoyancy either before, or soon after, the condensation level is reached. We base this speculation on comparisons of LEM simulations and observed fire plumes. Some idealised fire plumes are bent-over and puffy with only small puffs of plume air ascending to relatively high elevations (resembling wind-driven fires), whereas others have deep cores of rotating hot air that can penetrate deep into the middle troposphere (resembling convection column fires).

The ideal PyroCb scenario might be minimal entrainment in the drier, warmer, lower troposphere, in order to maximise transport of fire air to the cooler, more humid middle troposphere, where entrainment of moister, cooler air makes condensation more likely. It would follow that the convection column plume-type would be ideal for PyroCb development, since rotation reduces entrainment (e.g., Emmons and Ying 1967).

The LEM simulations mentioned above, and the various background environments responsible for the range of fire plume behaviour are discussed here. These simulations were performed with a surface heat source (representing a simple idealised fire) of constant size and intensity, but with varying background wind speed (Thurston et al. 2013). A realistic neutral turbulent atmospheric boundary layer was allowed to spin-up before the heat source was applied. For light background winds (5 m s^{-1}) the resulting fire plume was very intense and tall with counter-rotating gyres that penetrated deep into the stable layer above a deep (4 km) well-mixed boundary layer. This fire plume resembles the so-called “plume dominated fire”, often termed a convection column. For strong background winds (15 m s^{-1}) the fire plume was strongly bent-over with multiple turbulent puffs, which resembles a “wind dominated fire”. The maximum ascent in the strong wind case is about half that in the light wind case. For intermediate background wind cases the fire plume behaviour transitioned from one extreme to the other. This pattern of fire plume behaviour is illustrated in Fig. 4.

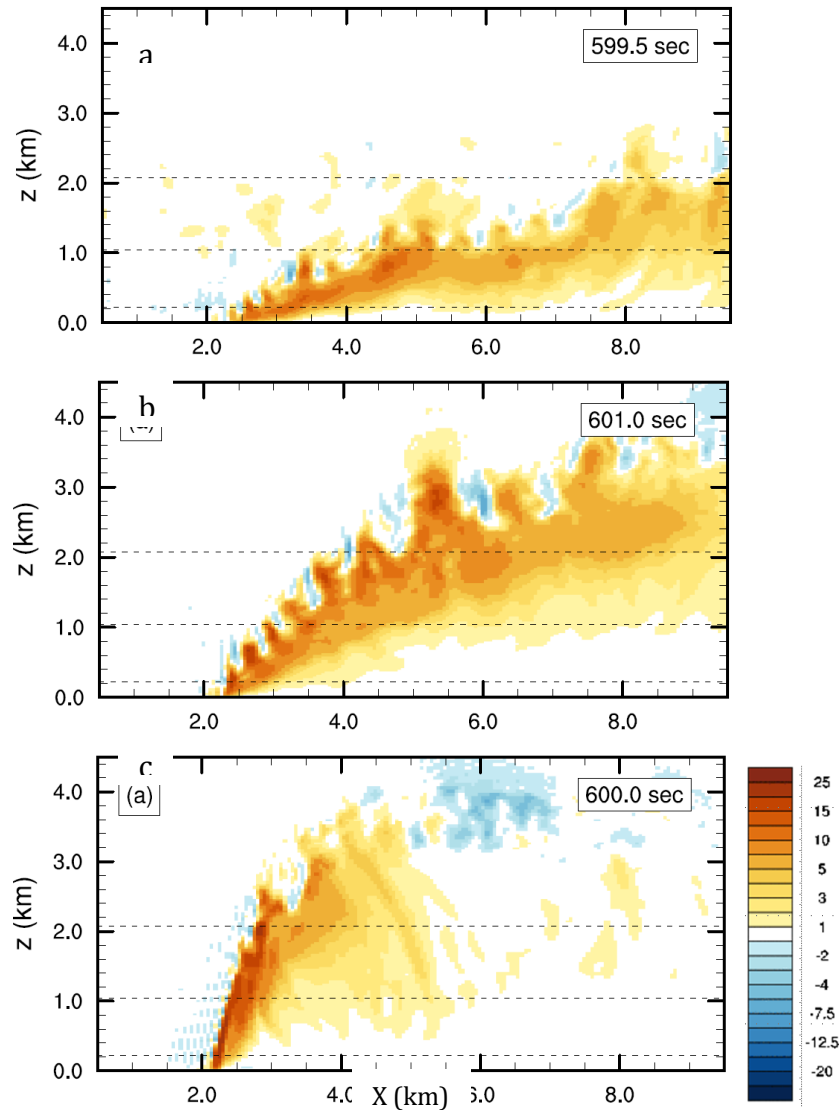


Figure 4: Large Eddy Simulations of instantaneous fire plume vertical motion in a downwind vs. height plane oriented along the plume axis for a surface heat source of 100 kWm^{-2} and radius 250 m , with background winds of (a) 15 , (b) 10 , (c) 5 m s^{-1} .

Additional experiments included reducing the surface heat source intensity for the same range of background wind speeds. The resulting fire plumes behaved like the higher intensity heat source fire plumes did in higher background wind speeds (i.e., weakening the heat source resulted in fire plumes being more highly dominated by the wind). This is illustrated in Fig. 5, which shows one-hour average fire plume vertical velocity rather than instantaneous values as in Fig. 4, for a range of heat sources and background wind speeds. The equivalent plots from Fig. 4 are in panels c, i and o. The left and middle panels have heat sources of 10 and 50% that of Fig. 4 (repeated in the right panel). In summary, simulations with weaker background winds showed increasingly taller and upright fire plumes, and simulations with lower intensity heat sources showed more bent over and puffing fire plumes. We expect less entrainment is required to dilute plumes

to a level of neutral buoyancy in weaker heating scenarios. Whereas entrainment rates are expected to be larger for the higher heating scenarios, when greater plume buoyancy enhances plume turbulence.

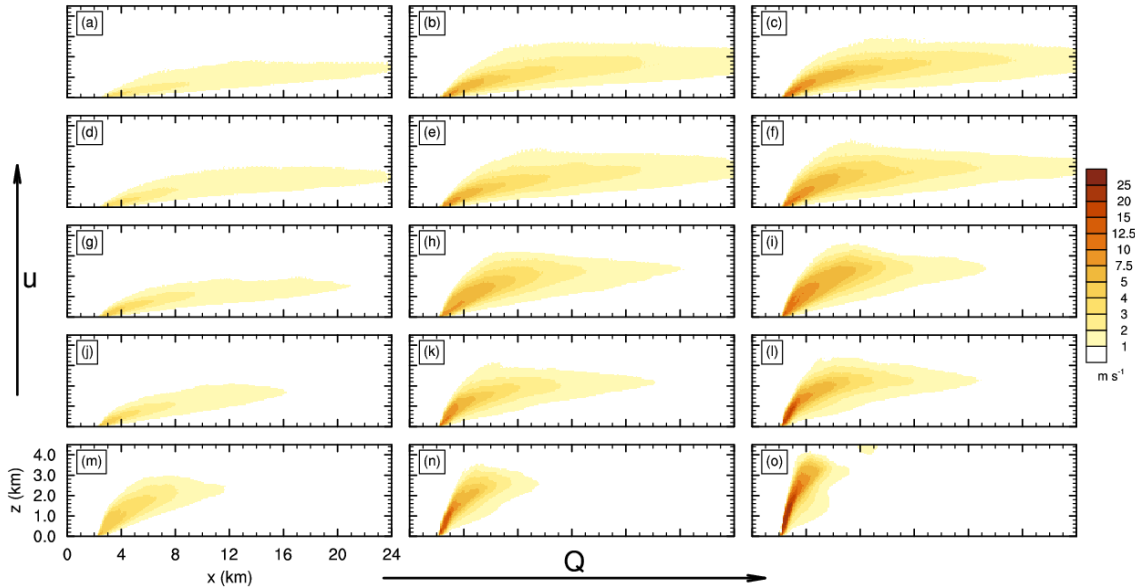


Figure 5: As in Fig. 4, but one hour mean fire plume vertical motion with variable heat source intensities and additional background wind speed cases of 7.5 and 12.5 $m s^{-1}$ (wind speeds increasing from 5 to 15 $m s^{-1}$ up the page). The left, centre and right panels have heat sources of 10 $kW m^{-2}$, 50 $kW m^{-2}$, and 100 $kW m^{-2}$ (as in Fig. 4), respectively.

While the lifting mechanism for pyroCb is the fire plume itself, forecasters also look for additional lifting enhancement, such as convergence lines (from sea breezes, or fronts), and topographically induced convergence and ascent. While the importance of lifting enhancement for pyroCb formation has not yet formally been demonstrated, there is abundant anecdotal evidence of pyroCb development when fires are impacted by convergence lines (Mills 2005, Engel et al. 2012, Peace et al. 2015a, 2015b), and the common occurrence of PyroCb in steep terrain may be related to topographically influenced ascent, combined with other factors such as higher fuel loads, upslope fire runs, and lee-slope vortices. It is even possible that boundary layer convergence is necessary for PyroCb formation. This hypothesis is backed up by Large Eddy Modelling (LEM) experiments (Thurston et al. 2014), which showed the transition of an idealised fire plume from a bent-over, puffing plume, to a more upright and more intense plume in just a few minutes, when the background boundary layer winds changed from being divergent to convergent. The vertical motion increased and the entrainment decreased in the latter fire plume configuration, allowing the less dilute plume to penetrate significantly deeper into the atmosphere. While in these simulations the transition occurred without any atmosphere-fire feedback (the simulated fire had a constant heat source), anecdotal evidence suggests the transition to an upright plume may increase burn rates, which further intensifies the fire-plume behaviour. Figure 6, reproduced from Thurston et al.



(2014, Fig. 3.18), shows three fire plume structures for convergent, neutral and divergent boundary layers, in an environment of strong background wind (15 m s^{-1}). The fire plume in the convergent boundary layer is stronger and deeper, and less dilute (not shown) than the other two fire plumes, which means it should lift warm moist air more rapidly towards the condensation level.

These results suggest that a wind-driven fire could transition to a convection column plume structure, if it encounters a lull in wind speeds, and/or an increase in fire intensity, and/or background boundary layer convergence. The results are also consistent with anecdotal descriptions of fire plumes transitioning between plume driven and wind driven modes. There may also be many other environmental influences that affect fire plume development and structure, some that we know of, such as wind shear, stability and topographically influenced flows, and others that we are not yet aware of. For brevity, we group all such influences together under the label of “atmospheric environment”. The convection column plume structure should be more favourable for PyroCb development as the deeper plume penetration increases the likelihood that the condensation level can be reached.

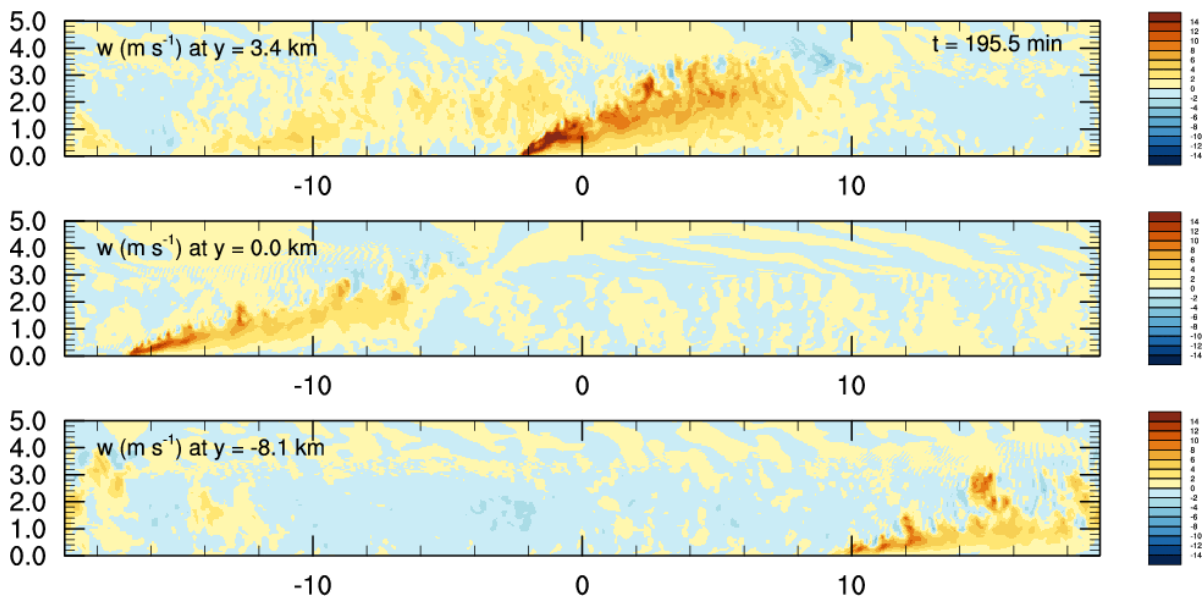


Figure 6: Vertical cross-sections through the fire plume centres 15 minutes after the heat source was added to an environment of strong background wind (15 m s^{-1}) with a 3 km deep well-mixed boundary layer, for (upper panel) a fire plume in the ascending branch of a boundary-layer roll, (middle panel) a fire plume in an environment with no boundary-layer rolls, and (lower panel) a fire plume in the descending branch of a boundary-layer roll. (Reproduced from Thurston et al. 2014.)



4. SEMI-OBJECTIVE FIRE-CAPE

The recent studies of P15 and LC16 consider alternative CAPE calculations for fire environments, without the ad-hoc addition of fire heat and moisture. P15 calculated CAPE for the most unstable layer (MU-CAPE), which is the maximum CAPE for any lifted parcel in the lowest few km. The method recognises that lifting of dry surface air is less likely to identify any positive CAPE, whereas lifting of an elevated moist layer might. It recognises that fire plumes entrain air from all layers. Examples are given in P15's Fig. 10, reproduced here in Fig. 7, which show weak or near neutral MU-CAPE for three time periods in which they observed PyroCb.

LC16 on the other hand were able to measure (observe) the condensation level, and by marking the condensation level on a thermodynamic diagram, compare it with theoretical condensation levels. They found the cloud base was much higher (more than 1000m) than predicted by both the MU-condensation level and the mixed-layer condensation level (calculated from the average moisture and potential temperature in the boundary layer), and significantly underestimated the associated CAPE values. (This result will not necessarily be true for all fires.) The condensation level under-estimation is illustrated in their Fig. 9, reproduced here in Fig. 8. They term the observed condensation level the convective condensation level (CCL) and the associated CAPE the CONV-CAPE. The CCL is simply the height at which a lifted surface parcel would condense assuming it was the same temperature as the environment. (To find the CCL in Fig. 8, lift the moistest parcel along a line of constant mixing ratio until it encounters the temperature trace.) A hypothetical surface parcel temperature is then estimated by following a dry adiabat (purple line) back down to the surface. This hypothetical parcel is about 7° C warmer than the maximum surface temperature on that day. The study suggests that the appropriate fire heat and moisture to be added to estimate the fire-CAPE appropriate for this fire is $0g\ kg^{-1}$ moisture and 7° C heat, which is consistent with Luderer et al.'s (2009) argument that fire moisture is not likely to be significant. Interestingly the heat contribution is more than double the largest value Potter (2005) considered. Importantly, this fire heat is the amount of excess heat the fire plume needs to have retained, after heat losses to radiation and dilution from plume entrainment, during the ascent from the fire to the condensation level.

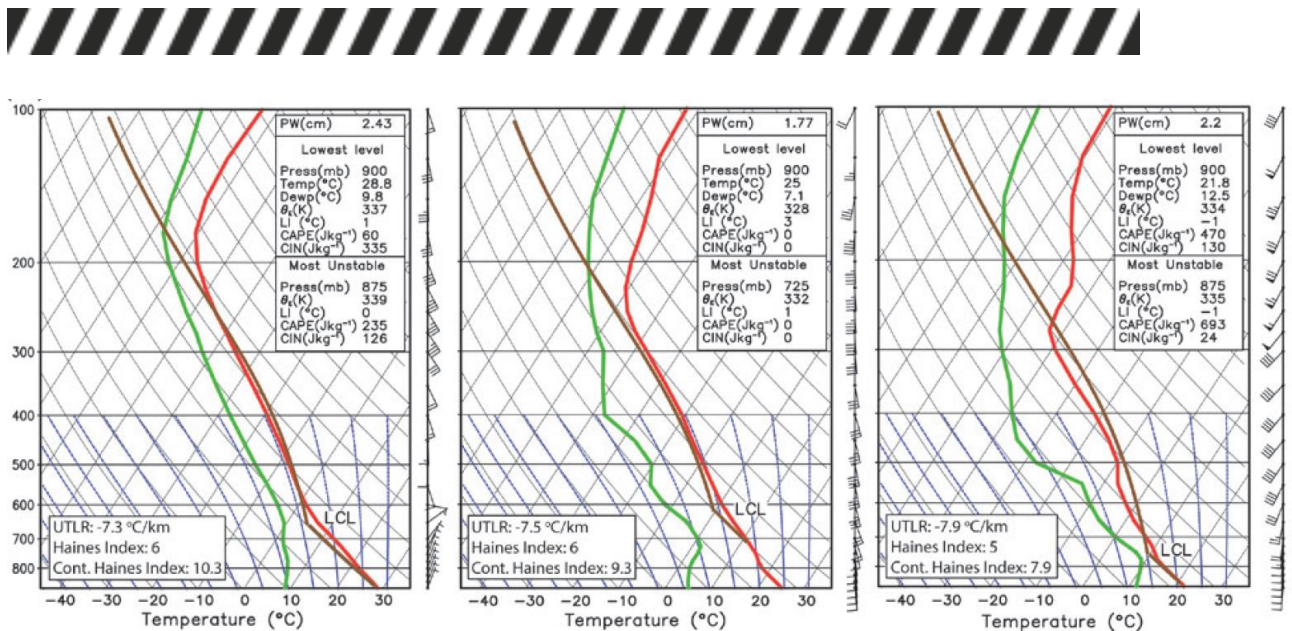


Figure 7: Soundings derived from the North American Regional Reanalysis grid box closest to a remote automatic weather station located at the Crane Flat Lookout, with red and green profiles indicating the environmental temperature and dewpoint, respectively, during the California Rim Fire of August 2013. (Left) 0000 UTC 20 August, (centre) 2100 UTC 21 August, (right) 0000 UTC 26 August. The brown parcel path corresponds to the most unstable layer (MU) parcel. (Reproduced from Fig. 10 of Peterson et al. 2015.)

This CCL and CONV-CAPE can be calculated from any sounding, and indeed when added to P15's three soundings (Fig. 9) reveals non-trivial CONV-CAPE on all three days (determined from the area between the blue and red curves, where the blue curve is to the right of the red curve). The CONV-CAPE is greater than the MU-CAPE (area between the brown and red curves, where the brown curve is to the right of the red curve). The estimated fire heat for the three soundings is between about 2 and 5° C. The CONV-CAPE analysis can provide useful information about any PyroCb that actually forms. It can also be used as a forecast tool, since the diagnosed fire heat and CCL can provide insight into relative fire size and intensity that might be required for PyroCb to form. For example, due to the diluting effect of entrainment one might expect that larger and/or more intense fires will be necessary to generate PyroCb for both large fire heat and high condensation levels, than weaker fire heat and lower condensation levels. We expect that CONV-CAPE is the most objective method currently available for estimating Fire-CAPE, although it is clear that estimating the potential for PyroCb development remains a highly subjective process. The CONV-CAPE technique is perhaps an incremental improvement on existing methods for estimating Fire-CAPE, but it still requires testing and verification to determine its applicability to a wide range of conditions.

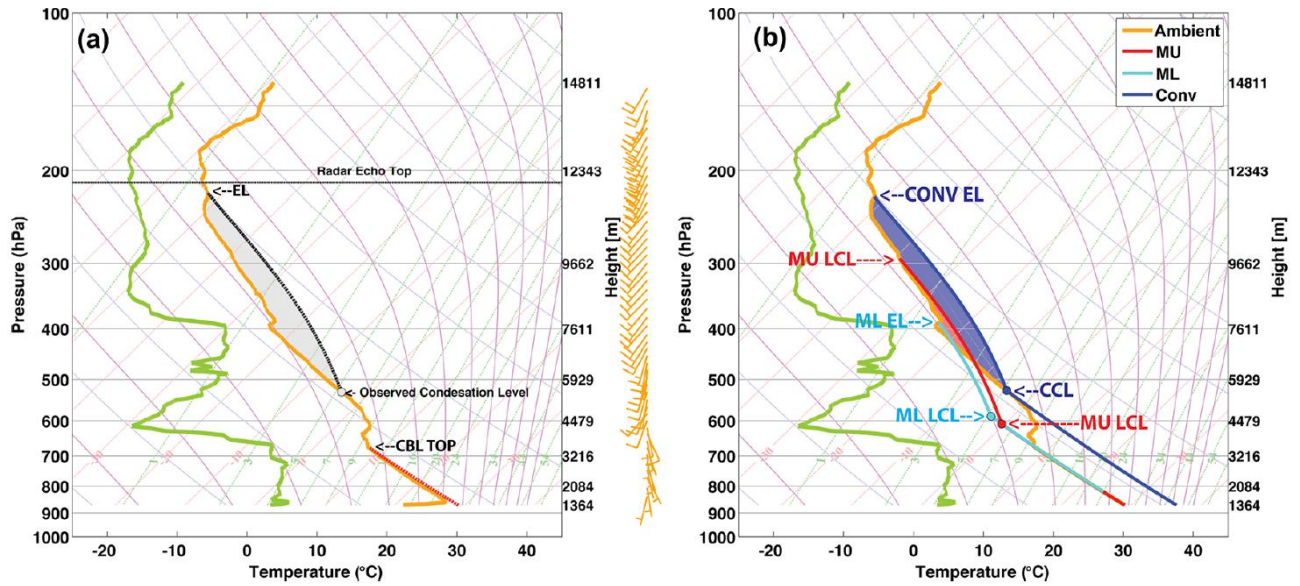


Figure 8: Thermodynamic analysis of the ambient environment and plume parcels. (a) Observed sounding from 2 August 2014, 2100 local time showing the adjusted boundary layer profile (dashed red line), the lidar-derived condensation level (grey circle), the moist adiabatic ascent from the condensation level, equilibrium level, and the radar derived echo tops. (b) Analysis of lifted parcels, showing the most unstable (MU), mixed-layer (ML), and convective (CONV) parcel trajectories. The condensation and equilibrium levels for each parcel are shown, and their CAPE is shaded. (Reproduced from Fig. 9 of Lareau and Clements 2016.)

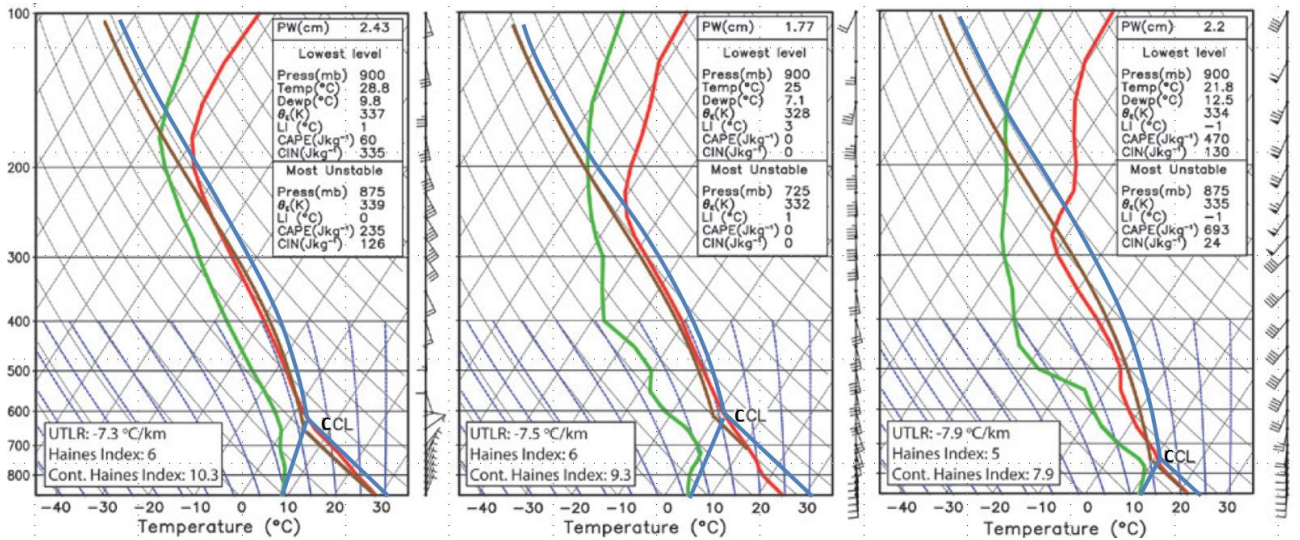


Figure 9: As in Fig. 7 but with Lareau and Clement's (2016) CONV parcel path added in blue, and the LCL labelled CCL.

5. NEED FOR OBSERVATIONS AND MODELLING

The preceding discussion highlights that many aspects of PyroCb that are not well understood, including: (i) the relative contributions of fire-moisture and atmospheric moisture to PyroCb formation, (ii) the sensitivity of formation to fire size and intensity, and (iii) the influence of the atmospheric environment on fire plume structure. Most recent studies have considered the fire/atmosphere moisture debate, with few focusing on the issues of fire size versus intensity, or fire plume structure and atmospheric environment. More fire plume observations and modelling studies are required to address these issues, including: plume composition observations from a variety of fires burning a variety of fuels; observations of the atmospheric profile in the vicinity of pyroCb; and fire plume structure and moisture content using radar and lidar (L16). From such observations, fire plume condensation levels can be determined and compared with expected condensation levels in the absence of fire. The difference can provide a quantitative assessment of fire heat and moisture ratios, since fire plumes with high (low) fire moisture to heat ratios are expected to produce lower (higher) condensation levels.

While it is not clear whether the height of the condensation level is important for influencing fire behaviour, it is possible that the additional buoyancy produced by condensational heating, and the level at which this occurs, may impact the plume behaviour, and perhaps the potential for fire-brand lofting. Furthermore, the fire heat/moisture ratio debate does not address broader issues influencing PyroCb development, e.g., the importance of fire size and intensity, background atmospheric environment, and fire plume structure. These questions can be addressed using large-eddy simulations, which have been shown to accurately represent boundary layer turbulence and generate realistic plume characteristics (e.g., Devenish & Edwards 2009, Devenish et al. 2010, Thurston et al. 2013). An additional advantage of large-eddy studies is that pseudo observations can be sampled at any desired point in space and time. Thus, a broad range of scientific questions can be addressed

Potential LEM experiments

Here we list a number of experiments that could be performed using the LEM documented in Thurston et al. (2013). Each experiment should provide very useful information on PyroCb development.

1. Fire-CAPE moisture/heat ratios: Investigate under what conditions fire moisture becomes important. Expand the moisture/heat ratio in favour of moisture. Try conditions with a shallower condensation level.
2. Fire size/intensity: Explore the parameter space. Choose a successful pyroCb simulation and reduce the fire size and intensity until a pyroCb no longer develops.
3. Fire plume structure: Add moisture to the boundary layer roll experiment. Does pyroCb develop more readily in the convergent boundary layer environment compared to the divergent environment?
4. Experiment with more complex background wind structures, including vertical wind shear and variable wind directions with height.



Investigate entrainment rates in a wide range of fire plume structures. How does entrainment rate vary with rotation or updraft speed? How does fire plume surface area to volume ratio affect entrainment rate?

6. SUMMARY AND DISCUSSION

A survey of fire weather forecasters and researchers from Australia and North America unearthed five assumptions that underpin a proposed conceptual model of PyroCb formation. This model should closely resemble PyroCb conceptual models forecasters have developed over preceding decades, but might differ slightly in detail due to the incorporation of recent idealised fire plume modelling results. The five assumptions are:

- i. PyroCb formation requires a conditionally unstable atmosphere, and
- ii. A lifting mechanism to release the instability.
- iii. Entrainment dilutes the plume.
- iv. Entrainment rates are strongly affected by the fire plume nature and structure, and
- v. The fire plume nature and structure is strongly influenced by fire size and intensity, and the atmospheric environment.

Here, the atmospheric environment loosely describes a potentially vast set of conditions that strongly impact plume behaviour, including background wind speed, wind shear, boundary-layer convergence or divergence, topographically influenced flows, dry and moist atmospheric stability, plus other factors we are not yet aware of.

These five assumptions gave rise to the following three-part conceptual model of PyroCb:

1. *A PyroCb is a series of thermals or a plume of air made buoyant by heating from the fire, which rises to a level of condensation, where condensational heating further enhances the buoyancy contributing to deep ascent.*
2. *The PyroCb plume is a column or series of thermals initiated by heated air and hot combustion gases. As the plume rises, it entrains environmental air throughout its depth, so that by the time condensation occurs the plume typically consists of mainly cooler and usually drier environmental air.*
3. *The atmospheric environment and fire size and intensity largely determine whether a fire plume of sufficient scale can reach the condensation level and trigger deep convection.*

Since this report is based largely on existing PyroCb forecaster experience, we do not expect the above PyroCb conceptual model to differ much from existing forecast conceptual models. Furthermore, the additional insight provided by the LEM simulations reported on here is likely to confirm forecaster experiential knowledge already incorporated in forecast conceptual models. Significant conceptual model changes will need to wait for results from future modelling and observational studies. Thus, we are not currently in a position to recommend any significant change to forecast procedures. Forecasters will continue to assess the potential for Cb formation without fire and then take into account how heat and moisture from the fire might alter this potential. The fire size and intensity needs to be considered, as well as the kinematic environment, which can impact significantly the fire plume structure (how deep the plume rises) and fire plume entrainment rates. Indeed, forecaster experience suggests that a



boundary-layer lifting mechanism is perhaps one of the most important predictors for PyroCb formation.

More specifically, PyroCb observational studies have identified atmospheric environments that favour pyroCb formation (the inverted-V sounding, Fig. 1), and offer important advice for forecasters and fire fighters of warning signs such as cumulus cloud development, as well as danger signs for people on the fire ground, such as virga in the lower troposphere, which demonstrate downbursts are likely (Rothermel 1991). The recent studies of P15 and LC16 offer useful information on plume structure and composition that could aid pyroCb forecasting, by proposing methods that incorporate the potential contribution of fire heat and moisture to pyroCb development. However, the debate on what constitutes realistic heat to moisture ratios, or how they vary from fire to fire, is not resolved. There is a clear need for observations within plumes, as well as additional observations of the immediate environment surrounding a wide range of fires to test the ideas proposed in P15 and LC16. The latter observations could be collected routinely if fire-fighting aircraft were instrumented with standard atmospheric observation instruments and data loggers. In addition, measurements of the condensation level could be made if pilots were to fly to the condensation level and record the height, or if ground-based mobile lidar or radar were made available.

In the absence of observations of fire plume gases, fire plume structure, and often no recent nearby atmospheric soundings, forecasters have only ad-hoc methods for estimating the important contribution of fire heat and moisture to potential pyroCb development. Existing techniques in which small heat and moisture perturbations are added to a conventional CAPE calculation (fire-CAPE) are likely to have aided forecasts of pyroCb, but recent observation studies (P15 and LC16), a theoretical study (Luderer et al. 2009), and an idealised fire plume study (Thurston et al. 2016) suggest fire moisture is insignificant, and consequently the added value might be for the wrong reason. Other studies suggest very moist fires are possible (Parmar et al. 2008), in which case the addition of fire moisture to fire CAPE calculations should not be discarded out of hand. However, for dry fuels in deep atmospheric boundary layers, similar to the conditions reported in P15 and LC16, it is likely that the best method for estimating Fire-CAPE is the CONV-CAPE of LC16 (Figs 8 and 9), then MU-CAPE of P15 (Fig. 7). Both assume the fire moisture has been diluted to insignificance by the time the fire plume reaches its condensation level. Both offer a method for diagnosing the condensation level, and the former provides a method for diagnosing a potential fire-heat contribution. However, assessing PyroCb formation potential remains a highly subjective process, due to its great sensitivity to the many factors that influence fire plume characteristics (e.g., fire size, fuels, winds, atmospheric stability), and the non-linear response of the plume to these conditions. Consequently, an ensemble approach to the development of any forecast guidance tools would be advised. For example, Fire-CAPE estimations could be made for a range of fire-heat values, and the sensitivity to these values could be tested by assessing the relative spread of the Fire-CAPE results. Forecast guidance tools based on other methods would similarly benefit from an ensemble approach.



The methods for diagnosing the condensation level, fire-heat and Fire-CAPE are based on traditional Cb forecasting techniques that ignore the potential plume dilution from entrainment of environmental air. The much smaller scales of fire plumes compared to typical convective clouds, means that entrainment cannot be ignored. Indeed, the fire size and intensity will play a large role in determining whether or not a fire plume will retain sufficient fire-heat to reach the condensation level. The greater the fire heat required and the higher the condensation level, the larger and more intense the fire is likely to need to be. Fire plume structure is also likely to be important in this regard, since bent-over puffing plumes experience more entrainment than upright convection columns. Anecdotal observational evidence (e.g., Mills 2005, Engel et al. 2012, Peace et al. 2015a, 2015b) and idealised LEM simulations (Fig. 6) suggest that fire plumes in convergent boundary layer flow are more likely to develop convection column characteristics with relatively low entrainment rates. LEM simulations also suggest that intense fires in lower background wind environments are also more likely to develop convection columns. This does not rule out the formation of convection columns in high wind conditions, such as the Victorian fires on Black Saturday (7 February 2009). Instead it suggests the fire needs to be larger or more intense in such conditions, or perhaps form in a period of enhanced boundary layer convergence and/or reduced wind speed, such as the arrival of a sea-breeze or cold front.

In closing, we reiterate the great need for more observations of fire plume gases and the immediate plume environment, with the latter potentially provided by instrumenting fire-fighting aircraft. The idealised LEM experiments show great promise too, with the existing studies providing only a hint of what can be achieved using cloud resolving models to study pyroCb. For pyroCb forecasting we suggest the LC16 technique for diagnosing Fire-CAPE, condensation levels and fire-heat, could be very useful, but will require testing and verification for a range of fire conditions. Any recommendations on how to account for the impact of fire plume dilution from entrainment will have to wait for the next generation of observations and LEM experiments.

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REFERENCES

- Cunningham, P., and M. J. Reeder, 2009: Severe convective storms initiated by intense wildfires: Numerical simulations of pyro-convection and pyro-tornadogenesis. *Geophys. Res. Lett.*, **36**, L12812, doi:10.1029/2009GL039262
- Devenish, B. J. and J. M. Edwards, 2009: Large-eddy simulation of the plume generated by the fire at the Buncefield oil depot in December 2005. *Proc. Roy. Soc. A*, **465**, 397—419.
- Devenish, B. J., G. G. Rooney and D. J. Thomson, 2010: Large-eddy simulation of a buoyant plume in uniform and stably stratified environments. *J. Fluid Mech.*, **652**, 75—103.
- Emmons, H. W. and S. J. Ying, 1967: The fire Whirl. In *Proceedings of the 11th International Symposium on Combustion*, pp.475—488, Combustion Institute, Pittsburgh, PA, USA, 1967.
- Engel, C. B., T. P. Lane, M. J. Reeder and M. Rezny, 2012: The meteorology of Black Saturday. *Q. J. R. Meteorol. Soc.*, **139**, 585—599.
- Finney, M. A. and S. S. McAllister, 2011: A review of fire interactions and mass fires. *J. Combustion*, Article ID 548328, 14 pages. doi:10.1155/548328.
- Lareau, N. P. and C. B. Clements, 2016: Environmental controls on pyrocumulus and pyrocumulonimbus initiation and development. *Atmos. Chem. Phys.*, **16**, 4005—4022. doi:10.5194/acp-16-4005-2016.
- Luderer, G., J. Trentmann and M. O. Andreae, 2009: A new look at the role of fire released moisture on the dynamics of atmospheric pyro-convection. *Int. J. Wild. Fire*, **18**, 554—562.
- Mills, G. A., 2005: A re-examination of the synoptic and mesoscale meteorology of Ash Wednesday 1983. *Aus. Met. Mag.*, **54**, 35—55.
- Morton, B. R. and A. Ibbetson, 1996: Jets deflected in a crossflow. *Experimental Thermal and Fluid Science*, **12**, 112—113.
- Morton, B. R., 1997a: Discrete dry convective entities: I Review. *The physics and parameterization of moist atmospheric convection*, 143—173.
- Morton, B. R., 1997b: Discrete dry convective entities: II Thermals and deflected jets. *The physics and parameterization of moist atmospheric convection*, 175—210.
- Parmar, R. S., M. Welling, M. O. Andreae and G. Helas, 2008: Water vapor release from biomass combustion. *Atmos. Chem. Phys.*, **8**, 6147—6153.
- Peace, M., Mattner, T., Mills, G. A., Kepert, J. D., and McCaw, L., 2015: Fire-Modified Meteorology in a Coupled Fire-Atmosphere Model. *Journal of Applied Meteorology and Climatology*, **54**, 704—720, doi:10.1175/JAMC-D-14-0063.1
- Peace, M., McCaw, L. W., Kepert, J. D., Mills, G. A., Mattner, T., 2015: WRF and SFIRE simulations of the Layman fuel reduction burn. *Australian Meteorological and Oceanographic Journal*, **65**: 3-4,302-317
- Peace, M., Mattner, T., Mills, G. A., Kepert, J. D., and McCaw, L., 2016: Coupled Fire-Atmosphere Simulations of the Rocky River Fire using WRF-SFIRE, *Journal of Applied Meteorology and Climatology*, **55**, 1151—1168
- Peterson, D. A., E. J. Hyer, J. R. Campbell, M. D. Fromm, J. W. Hair, C. F. Butler and M. A. Fenn, 2015: The 2013 Rim Fire: Implications for predicting extreme fire spread, pyroconvection, and smoke emissions. *Bull. Amer. Met. Soc.*, 229—247. doi:10.1175/BAMS-D-14-00060.1.
- Potter, B. E., 2005: The role of released moisture in the atmospheric dynamics associated with wildland fires. *Int. J. Wild. Fire*, **14**, 77—84.
- Rosenfeld, D., M. D. Fromm, J. Trentmann, G. Luderer, M. O. Andreae and R. Servanckx, 2007: The Chisolm firestorm: observed microstructure, precipitation and lightning activity of a pyro-cumulonimbus. *Atmos. Chem. Phys.*, **7**, 645—659.
- Thurston, W., K. J. Tory, R. J. B. Fawcett and J. D. Kepert, 2013: Large-eddy simulations of bushfire plumes in the turbulent atmospheric boundary layer. In: *MODSIM2013, 20th International Congress on Modelling and Simulation*, J. Piantadosi, R. S. Anderssen, and J. Boland (eds.), Modelling and Simulation Society of Australia and New Zealand, 284—289, ISBN: 978-0-9872143-3-1.



- Thurston, W., R. J. B. Fawcett, K. J. Tory and J. D. Kepert, 2014: Bushfire CRC Final Report for Project titled "Understanding Complex Fire Behaviour: Modelling investigation of lofting phenomena and wind variability", ISBN 978-0-9875218-8-0.
- Thurston, W., K. J. Tory, R. J. B. Fawcett and J. D. Kepert, 2016: Large-eddy simulations of pyro-convection and its sensitivity to moisture. *5th International Fire Behaviour and Fuels Conference proceedings*. 6pp
- Tory, K. J. and W. Thurston, 2015: Pyrocumulonimbus: A literature review. *Bushfire and Natural Hazards CRC Report*, NO. 2015.067.