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PYROCUMULONIMBUS: A LITERATURE REVIEW

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Cover: A pyrocumulonimbus plume appears during the Tostaree fire in Victoria in February 2011.

Photo by Gail Wright, Department of Environment, Land, Water and Planning, Victoria.

TABLE OF CONTENTS

1. BACKGROUND

A pyrocumulus cloud is a dense cumuliform cloud associated with fire or volcanic activity (although here we report only on fire pyrocumulus). It is produced by intense heating of air, which leads to deep ascent and subsequent condensation when the rising air becomes saturated due to cooling from adiabatic expansion. The condensation is evident in cloud formation. The process is similar to conventional convective cloud formation, when a lifting mechanism (e.g., orographic lifting, intersection of two air masses) raises air beyond where the cloud forms (the lifting condensation level) to where the additional condensational heating makes the air positively buoyant (the level of free convection). Turbulent entrainment of cooler and drier air from outside the rising airmass dilutes the cloud buoyancy, which can limit the size and growth of the cloud (e.g., fair weather cumulus). At the opposite extreme, larger and more intense lifted regions can accelerate to the tropopause. As they cross the tropopause into the much more stable air in the stratosphere, they become cooler than the ambient air, and hence negatively buoyant. However, they may possess enough momentum that they overshoot the level of neutral buoyancy Outflowing air at the tropopause gives these cumulonimbus clouds their classic anvil shape (a nimbus cloud is a cloud that produces precipitation). Evaporation of moisture by entrained dry air in these clouds leads to cooling and descent and the release of previously suspended precipitation, which can result in heavy downpours and intense downburst winds.

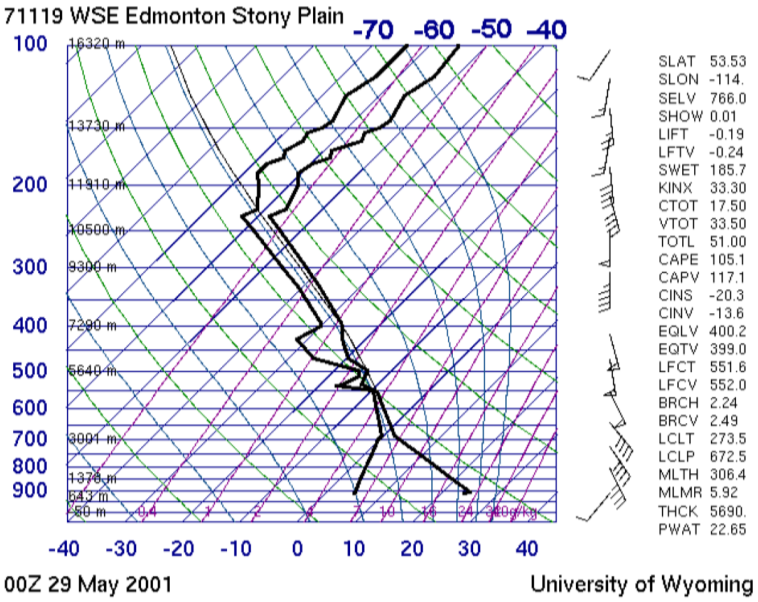
The main difference between conventional cumulus and pyrocumulus clouds is that the lifting in the latter cloud type is provided by the buoyancy from the heat and perhaps moisture released by the fire. Pyrocumulus is quite common and can form as small clouds above small fire plumes, or individual fire plume puffs. Alternatively, in large fires with an intense convection column the cloud may resemble towering cumulonimbus with updrafts that penetrate into the stratosphere (e.g., Fromm and Servranckx 2003, Mitchell et al. 2006, Fromm et al. 2006, see also the review paper by Fromm et al. 2010). Hereafter we refer to these pyro-clouds as pyrocumulonimbus, regardless of whether rain associated with the cloud has been observed.

There is abundant anecdotal evidence to suggest that the presence of pyrocumulus activity can have a significant impact on fire behaviour, including: (i) the amplification of burn- and spread-rates (Fromm et al. 2006, Trentmann et al. 2006, Rosenfeld et al. 2007, Fromm et al. 2012), (ii) enhanced spotting due to larger and more intense plumes (e.g., Koo et al. 2010), and (iii) ignition of new fires by pyrocumulonimbus lightning strikes due to pyrocumulonimbus conditions favouring hotter and longer-lived lightning strikes (e.g., Rudlosky and Fuelberg 2011). The intense updrafts in pyrocumulonimbus clouds can carry significant quantities of smoke and aerosols into the stratosphere that can have important climate impacts (large fires can produce hemisphere-scale stratospheric smoke distribution, Fromm et al. 2000). However, the focus of this review is on the potential impact of pyrocumulus on fire behaviour and will not cover smoke and aerosol distribution.

It is worth making the distinction here between wind-driven and buoyancy-dominated plumes or convection columns. Fires associated with wind-driven plumes are dominated by strong winds that drive the flames forward. Such fires tend to be reasonably predictable (e.g., Banta et al. 1992). Buoyancy-dominated plumes tend to occur in lighter wind conditions and are associated with strong convection columns that tower above the fire (e.g., Rothermel 1991).

2. CONDITIONS FAVOURABLE FOR PYROCUMULONIMBUS DEVELOPMENT

The cloud dynamics of pyrocumulonimbus (PyroCb) clouds are very similar to conventional thunderstorms, since PyroCb clouds are essentially cumulonimbus clouds in which the lifting mechanism is heating from the fire. It follows that conditions that favour thunderstorm development will also favour PyroCb development, except that warm moist low-level air, ideal for thunderstorms, does not favour fire spread. Ideal PyroCb conditions are thus similar to ideal thunderstorm conditions but with a dry rather than moist lower troposphere (e.g., Goens and Andrews 1998, Trentmann et al. 2006, Rosenfeld et al. 2007, Cunningham and Reeder 2009, Fromm et al. 2012, Johnson et al. 2014). Meteorologists assess the potential of the atmosphere to generate thunderstorms in terms of its thermodynamic profile, specifically the vertical profile of air temperature and moisture . An adjustment from a thunderstorm-friendly thermodynamic profile to a fire-friendly thermodynamic profile yields the classic inverted-V profile on a thermodynamic diagram, which is widely recognised to favour severe weather (e.g., Beebe 1955, Wakimoto 1985). An example of the inverted-V sounding is illustrated in Fig. 1 (reproduced from Fig. 4 of Rosenfeld et al. 2007). It represents a dry well-mixed lower layer over-laid by a moist middle troposphere. It is present in all PyroCb studies that we are aware of (e.g., Goens and Andrews 1998, Trentmann et al. 2006, Rosenfeld et al. 2007, Cunningham and Reeder 2009, Fromm et al. 2012, Johnson et al. 2014), which suggests it may be a necessary condition for PyroCb. Here the dry adiabatic temperature trace forms the right side of the inverted-V, while the moisture profile, relatively dry at the surface with decreasing dew-point depression to near-saturation in the middle troposphere, makes up the left side. The inverted-V profile also favours downburst development, when precipitation from the moist middle-troposphere evaporates as it falls through the dry layer below. If precipitation does develop in PyroCb clouds, downbursts should be expected (e.g., Rothermel 1991). These downbursts can be very hazardous to fire crews as the winds can be gusty and intense and come from a completely different direction to the ambient flow, and in complex terrain may further accelerate down valleys causing highly unpredictable changes in fire intensity and spread (e.g., the Dude River (Arizona, USA) fire in which six fire fighters perished, Goens and Andrews 1998). Moreover, the downburst winds are much more difficult to predict than other common causes of wind change, increasing the danger to fire crews.



SLAT	53.53
SLON	-114.
SELV	766.0
SHOW	0.01
LIFT	-0.19
LFTV	-0.24
SWET	185.7
KINX	33.30
CTOT	17.50
VTOT	33.50
TOTL	51.00
CAPE	105.1
CAPV	117.1
CINS	-20.3
CINV	-13.6
EQLV	400.2
EQTV	399.0
LFCT	551.6
LFCV	552.0
BRCH	2.24
BRCV	2.49
LCLT	273.5
LCLP	672.5
MLTH	306.4
MLMR	5.92
THCK	5690.
PWAT	22.65

Figure 1: The Edmonton thermodynamic sounding, 0000 UTC, 29 May 2001. 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. 2003.

While thunderstorms are less likely[1] to form in the low-level dry environments typical of bad fire days, the presence of PyroCb (or an inverted-V thermodynamic profile) suggests that sufficient lifting from *any* mechanism could potentially produce thunderstorms with the threat of downbursts and lightning ignitions (see below). Such lifting can be provided by flow over significant topographic features, as was observed near the Waldo Canyon fires (Johnson et al. 2014). Downbursts initiated in these thunderstorms impacted the fire, leading to accelerated burn rates, the onset of PyroCb and lightning activity.

3. PRECIPITATION IN PYROCUMULONIMBUS

The high aerosol concentration in smoke plumes has been reported to enhance deep convection (relative to clean convection) by delaying the formation of precipitation and suppressing downdrafts and warm rain (e.g., Reutter et al. 2014, and references therein). This allows more liquid condensate to freeze, and thus providing more latent heat release at higher levels that further invigorates the deep convection. (Latent heat is released in the condensation of moisture vapour to liquid water, and further in the freezing of liquid water to ice crystals.) In a cloud microphysics modelling study with realistic aerosols, Reutter et al. (2014) found that in strongly polluted plumes the formation of rain, graupel and hail is delayed, which resulted in significantly higher amounts of snow and ice in the upper cloud regions, much less hail and graupel in the middle-level cloud and significantly less rainfall. This study suggests pyro-convection is less

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[1] The dry air that favours fire activity reduces but does not eliminate the chance of deep convection. For example, the meteorological situation that lead to a major fire run in the Coonabarabran fire in NSW on 13 January 2013, also featured a significant level of thunderstorm activity.

favourable for precipitation than non pyro-convection. However, the abundance of anecdotal evidence of the occurrence of pyro-convective downbursts suggests that evaporation of the precipitation that does occur can still have significant consequences (e.g., Rothermel 1991). Intense outflow from evaporative downbursts might be sustained for tens of minutes, and can potentially push the fire in any direction (e.g., Rothermel 1991, Goens and Andrews 1998). Rothermel warns that precipitation or even virga (precipitation which evaporates before it reaches the ground) below a cell could provide a short-term warning of the arrival of potentially dangerous downburst winds.

4. AMPLIFICATION OF BURN AND SPREAD RATES

The presence of PyroCb clouds is potentially very serious, as they are often associated with highly unpredictable fire behaviour. However, many papers imply or suggest that the unpredictable fire behaviour occurs when the fire is associated with a buoyancy-dominated plume (e.g., Rothermel 1991, Banta et al. 1992), which is easily distinguishable from the bent-over plumes of a wind-driven fire. Much of the evidence for the unpredictable behaviour is descriptive and based on human observation and speculation. There is considerable scope for research to investigate these observations and speculation. According to Banta et al. (1992) the buoyancy-dominated plume creates strong, turbulent indrafts that feed fresh air to the fire, allowing it to rapidly intensify. Rothermel (1991) suggests: “The process feeds on itself and accelerates as the convection column grows”, which appears to imply a positive feedback between the plume and fire, which could potentially lead to very high intensity fires. While this potential positive feedback process is not dependent on the presence of pyrocumulus it may be amplified by or perhaps be more likely to occur, with the additional buoyancy and deeper upright plume that could develop in a PyroCb cloud. Strong buoyant accelerations close to the ground surface was found by Smith et al. (1975) to generate a “fire wind”, which is driven by the dynamic pressure field associated with the near-ground acceleration.

5. ENHANCED SPOTTING POTENTIAL IN PYROCUMULONIMBUS

Spot fires develop when burning embers or firebrands are lofted in the plume and are carried by winds aloft into unburned fuel (e.g., see the review article by Koo et al. 2010). Firebrand lofting occurs when updraft velocities in the fire plume exceed the terminal velocity of burning embers. Thus the stronger, deeper and more sustained the upward velocity, the higher firebrands can be lofted and the larger (denser) the firebrands that can be lofted. If there are strong ambient winds, then there is great potential for significant horizontal ember transport. A conventional fire plume (without pyrocumulus assistance) tends to be contained within the surface atmospheric mixed layer, which in extreme conditions can exceed 5 km in depth (e.g., the Black Saturday fires of southeastern Australia in February 2009, Engel et al. 2012, Fawcett et al. 2013). An exception is a rotating plume, with associated reduced entrainment, which may contain strong updrafts that penetrate some distance into the stable layer above (Thurston et al. 2013). However, this penetration depth is small compared to the updrafts in a PyroCb that have been documented penetrating deep into the stratosphere, up to 16 km (e.g., Fromm et al. 2006). It follows that the development of PyroCb can potentially increase firebrand lofting heights by three to five times, which greatly increases the potential firebrand transport distances. For example, a spot fire was reported to have formed more than 30 km downwind of the Kilmore East fire during Black Saturday (Cruz et al. 2012) when PyroCb clouds were present.

6. ROTATION IN PLUMES

The presence of rotation in plumes can affect fire behaviour (e.g., Forthofer and Goodrick 2011). The inertial stability of a rotating plume opposes radial flow, such that entrainment into the plume may be reduced by an order of magnitude compared with a non-rotating plume (e.g., Emmons and Ying 1967). This is important because entrainment of cooler environmental air dilutes the plume buoyancy and vertical momentum, which reduces potential firebrand lofting heights, and would presumably reduce the likelihood of a buoyancy-dominated plume. The surface pressure at the base of rotating plumes can be very low, resulting in strong inward turbulent flow, which causes increased mixing in the fire area that results in higher gas temperatures and reaction rates (Snegirev et al. 2004).

Plume rotation can be caused by a variety of processes. The mechanism in common to all is the stretching of vertical vorticity near the plume base from vertically accelerating flow, which leads to an exponential increase in vertical vorticity magnitude. The various processes for generating vertical vorticity at the plume base (e.g., Forthofer and Goodrick 2011) include: (i) tilting of horizontal vorticity (typically associated with the frictional vertical shear of the horizontal wind), which results in the development of two counter-rotating gyres; (ii) the production of lee vortices from flow around topographic or structural features, or even complex fire patterns; and (iii) vertical shear vorticity associated with meteorological features such as cold fronts.

7. LIGHTNING IGNITIONS IN PYROCUMULONIMBUS

PyroCb clouds can produce cloud to ground (CG) lightning with the potential to ignite additional fires. CG lightning transfers positive (+CG) or negative (–CG) charges from the cloud to the ground. While –CG are most common, +CG are the most dangerous as they contain long periods of continuous current (> 40 ms), exhibit the greatest peak current, and carry the largest charge transfer to the ground (Rudlosky and Fuelberg 2011, and references therein). The following discussion borrows heavily from Rudlosky and Fuelberg (2011). +CG tend to cause more damage to power and electricity infrastructure and ignite more forest fires than –CG. –CG are most common because they occur frequently in thunderstorms that develop in moist environments. Drier environments with higher cloud bases (Carey and Buffalo 2007) have high concentrations of +CG flashes, as do thunderstorms that ingest smoke (Williams et al. 2005, Lang and Rutledge). It follows that the dry environments in which PyroCb develop and the abundant smoke in these clouds are ideal for +CG development. Thus, one might expect any observed CG lightning from PyroCb, and nearby thunderstorms that have ingested smoke, to have an elevated risk of igniting additional fires.

8. HEAT AND MOISTURE CONTRIBUTION TO PYROCUMULONIMBUS FROM THE FIRE

It was noted above that the heat from the fire provides the lifting mechanism to initiate cumulus convection in PyroCb. The other important ingredient is moisture, which when condensed produces latent heating that enhances the plume buoyancy. Moisture in the plume is sourced from the air drawn into the fire and air entrained into the plume, from moisture in the fuels evaporated by the intense heat of the fire, and from the moisture released as the by-product of cellulose combustion (e.g., Potter 2005). Since convective available potential energy (CAPE) calculated on a thermodynamic diagram is used routinely by forecasters to identify the potential for thunderstorm development, the use of a "fire-CAPE" (CAPE, modified by the additional heat and moisture produced by the fire) could be of use for identifying the potential for PyroCb development. However, it is not clear how much heat and moisture needs to be added to the atmospheric temperature/moisture trace (i.e., the thermodynamic profile mentioned previously) to provide a realistic estimate of the PyroCb potential, which will obviously depend on the size and intensity of the fire, and the plume entrainment rate.

Potter (2005) estimated the level of free convection (LCL) in a number of pyrocumulus fires, and compared the estimate with the theoretical atmosphere-only LCL from nearby radiosonde observations, and was able to estimate the additional moisture that would be needed to lower the atmosphere-only LCL to the estimated pyro-LCL. These estimates ranged from 1 to 4 g kg^{-1}. Estimates of the plume levels of neutral buoyancy at the plume top were also made, and used to estimate the combined heat and moisture from the fire necessary for the plumes to reach that level. Potter then recalculated the CAPE and other thermodynamic properties with six combinations of additional heat and moisture amounts to get a feel for the sensitivity of CAPE to his estimates of realistic heat and moisture production in large fires. The values he used are as follows, with the first and second numbers referring to the heat in °C and moisture in g kg^{-1} respectively: (2,0), (0,2), (2,2), (3,0), (0,3), (3,3).

Luderer et al. (2009) considered the relative ratios of heat to moisture production one might expect in combustion. Their results should reduce one of the degrees of freedom when considering how much heat and moisture should be added to the environmental thermodynamic profile to produce fire-CAPE estimates. They calculated the heat and water vapour directly released from combustion. Then they considered the additional plume moisture source from a wide range of possible fuel moisture fractions (0 to 80%), and the heat loss in evaporating that fuel moisture, plus a wide range of possible radiative heat loss fractions (0 to 50%). The net result yielded sensible heat to moisture release ratios that ranged between 6.6 K g^{-1} kg for the very moist and high radiative heat losses, to 35 K g^{-1} kg for completely dry fuel and zero radiative heat losses. While this study does not provide estimates of how much heat and moisture should be added to estimate fire-CAPE, it does provide a realistic range of heat to moisture ratios that could be investigated. It also suggests that of the hypothetical ratios Potter considered, his dry fires would be the most realistic.

Interestingly, Luderer et al. (1990) also investigated how the addition of heat and moisture in the above ratio range, might affect the height of the LCL. While Potter assumed the fire should reduce the height of the LCL due to the increased moisture, Luderer et al. showed that this is probably only likely for very moist fuels burning in very dry air. Indeed for most of the range of heat/moisture release ratios and environmental humidity they considered, the tendency for the additional heat to raise the LCL far outweighed the tendency of the additional moisture to lower it. The authors did not consider the possible effects of entrainment of environmental air on this balance. We expect that such entrainment would most likely tend to reduce the change in LCL.

9. PYROCUMULONIMBUS TRIGGERS

From the preceding discussion it is clear that a significant volume of fire heated air must be lifted to the level of free convection before PyroCb can develop. A source of moisture from the environment, fuel and/or combustion is obviously necessary. The plume needs to remain relatively undiluted in order for the warm moist air to remain buoyant all the way to the LFC. To achieve this, the heat source needs to be relatively large and intense, and the wind not too strong, as smaller, weaker fires in higher winds develop turbulent, puffy plumes with comparatively low heights of ascent (i.e., wind-driven fires, Thurston et al. 2013). Anecdotal evidence suggests buoyancy-dominated plumes, and especially rotating plumes, allow deeper penetration of the plume gases and thus make it more likely that the LFC may be reached. Above the LFC, a moist mid-level troposphere will favour PyroCb development by minimising evaporative cooling of cloud water by dry air entrained into the plume.

Anecdotal evidence suggests that near-surface wind surges associated with nearby thunderstorm outflows (e.g., Rosenfeld et al. 2007, Johnson et al. 2014), the arrival of cold fronts (Engel et al. 2012, Mills 2005) or sea breezes (Peace et al. 2014a,b,c, Peace 2014), and boundary-layer rolls (Sun et al. 2009) can trigger the transition from a wind-driven fire to a more upright plume and PyroCb. It seems likely that the wind surges themselves can provide a period of increased fire intensity, and the arrival of cold fronts and sea breezes may lead to a period of reduced deep-layer wind speed, and a deep layer of increased humidity. The increased fire intensity and reduced deep-layer wind speed favour the transition to a buoyancy-dominated plume, and the increased atmospheric moisture will favour cloud formation and condensational heating. Even if the surface humidity increases, there is a time-lag of hours before the fine-fuel dryness is affected (Bureau of Meteorology Report, 1963[2].)

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[2] Chapter 2, paragraph 6: "Even for finely divided fuels Wright found the lag to be of the order of two hours." The Wright paper mentioned is probably: Wright, J. G., 1930: The influence of weather on the inflammability of forest fire fuels. *The Forestry Chronicle*, **6**(1), 40-55, 10.5558/tfc6040-1.

10. QUESTIONS TO BE ADDRESSED

1. Under what circumstances are the fire-induced winds, which affect the fire behaviour, different once a pyroCb forms?
2. Does the existence of PyroCb (or indeed any buoyancy-dominated plume) impact the fire behaviour (i.e., the implied positive feedback between plume and fire of Rothermel 1991, and Banta et al. 1992)?
3. What is the relative importance of environmental factors, fire-induced heating, and fire-induced moisture to the development of PyroCb?
4. How can the relationship between rotation and entrainment rate be quantified?
5. Can existing thunderstorm prediction tools be modified to forecast the potential for formation, and the likely strength, of pyroCu and pyroCb?

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