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# THE REAL-TIME TRIAL OF THE PYROCUMULONIMBUS FIREPOWER THRESHOLD

## Southern Australian 2019-20 fire season


**Kevin Tory**
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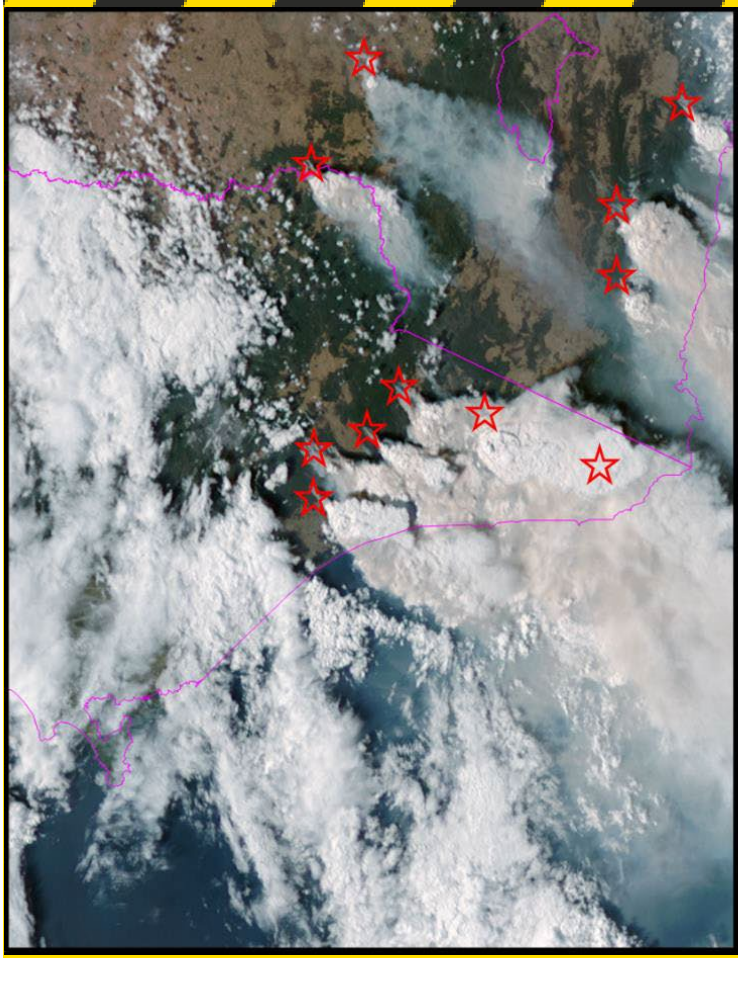

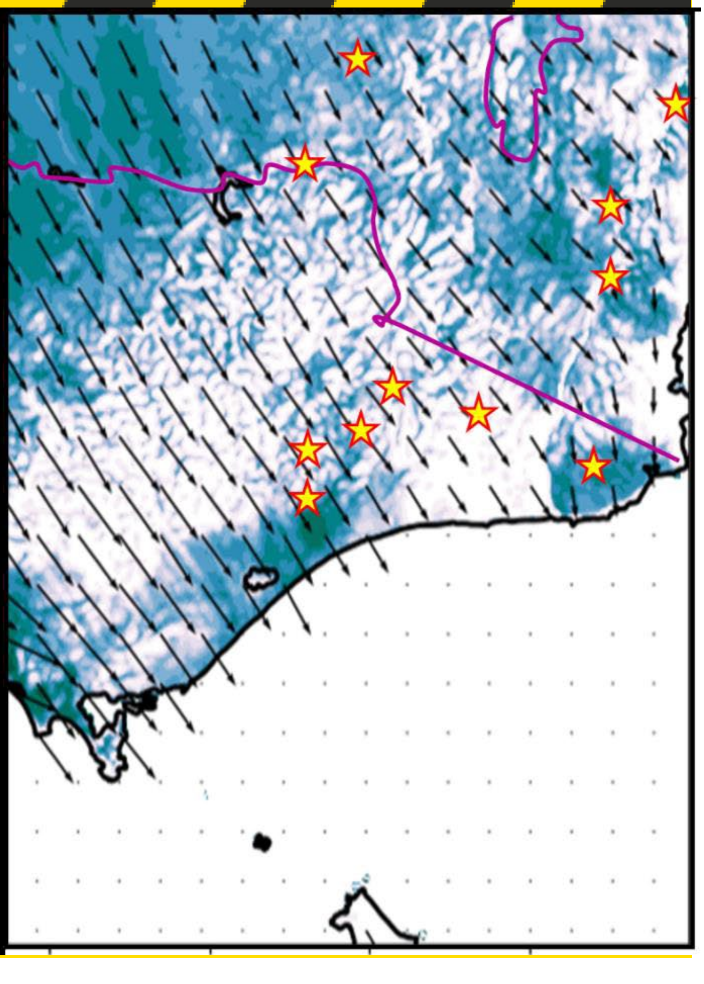

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Cover: Himawari satellite image (left) during the afternoon of the most active moist pyro-convective day of the 2019/2020 season, 30 December 2019. The corresponding PFT flag forecast (right) shows the potential threat was well forecast. The fire locations are indicated by stars.

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# ACKNOWLEDGMENTS

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# FOREWORD

This document reviews the real-time trial of the Pyrocumulonimbus Firepower Threshold (PFT) diagnostic during the 2019/2020 southern Australian fire season. The PFT was developed with support from the Bushfire and Natural Hazards Cooperative Research Centre, through the "Improved prediction of severe weather to reduce community impact" project. While this report was primarily prepared to meet project requirements, it contains useful information and insight into the PFT and deep moist pyro-convection prediction more generally, that should be of value to fire-weather forecasters, fire-behaviour analysts and their parent agencies.

The report introduces the PFT in Section 1 and shows examples of the forecast products from the 2019/2020 season in Section 2. Throughout the trial users provided feedback that ranged from technical issues to broader forecasting challenges. This feedback identified confusion surrounding the definition of pyroCb (Section 3), and difficulties in forecasting this not-well-defined and not-well-understood phenomenon (Section 4). Many examples are presented in Section 5 to illustrate some of the more pertinent issues that arose throughout the trial. These include the limitations of using parcel theory to predict moist- plume growth, and the need to include more factors in lightning prediction. Examples are also provided that illustrate the limitations of various PFT products. The application of the PFT to climate studies is discussed in Section 6, where the minimising of false positives is of higher importance than for forecasting applications where expert users can separate real from false threats. Methods to address two of the issues raised in the report were developed with support from the Earth System and Climate Change Hub of the Australian Government's National Environmental Science Programme. These are the reduction of false positives caused by unstable conditions during cold- outbreaks, and a procedure to bypass the parcel-theory assumption (Section 7). The report is summarized in Section 8, which includes a set of dot points that highlight areas for future investigation and lessons learned.

# 1 INTRODUCTION

When intense smoke plumes develop on wildfires, the so-called plume-dominated fires, fire behaviour can become erratic, unpredictable and the fire ground can become highly dangerous for fire fighters. Strong updrafts can transport burning embers downwind, amplifying firespread through the ignition of spotfires ahead of the fire front. The formation of deep, cumulus clouds with strong vertical motion in these plumes may amplify the dangerous fire behaviour, and introduce additional hazards separate to the fire such as extreme winds from evaporative downbursts, tornadoes and other intense vortices. When conditions are favourable the fire-induced deep, moist convection can produce lightning with the potential to ignite more fires. These fire-generated thunderstorms (FGT) are arguably a subset of events known as pyrocumulonimbus (pyroCb). The term pyroCb was introduced by researchers studying aerosols in the upper troposphere and lower stratosphere (UTLS). The cumulonimbus (Cb) component was understood to take the broader meaning of a towering vertical cloud with strong updrafts. In contrast meteorologists often use cumulonimbus as synonymous with thunderstorms, which has led to some confusion surrounding the term pyroCb, discussed in Section 3.

Recently, a procedure for identifying atmospheric conditions that favour deep, moist plume growth in wildfire smoke plumes was proposed, which estimates a theoretical minimum heat flux (or firepower) required for such plume growth, termed the Pyrocumulonimbus Firepower Threshold (PFT, e.g., Tory 2019). A real-time trial of forecast maps of a relatively simple PFT (hereafter PFT1) was performed over the southern Australian fire season of 2019-2020. PFT1 takes into consideration the magnitude of any inversion or stable layer the smoke plume must penetrate, the height the smoke plume must rise before sufficiently buoyant cumulus clouds form in the smoke plume, and incorporates the impact of background wind on plume rise via the Briggs plume-rise model (e.g., Briggs 1984). The highly complex process of moist plume development is reduced to a single analytic equation at the core of PFT1. Many simplifications and assumptions are required. However, the success of PFT1 during this trial, together with the extensive prior history of the Briggs model, suggests that the assumptions are reasonable. Below the condensation height it is assumed that the smoke plume can be described by a Briggs plume rising through a neutrally stable layer of constant background wind. Above the condensation height, it is assumed the rising moist plume can be described by simple parcel theory (as applied to common thunderstorm forecast products). One of the closure requirements for PFT1 is the specification of a moist, plume-top height. Pressure levels corresponding to typical tropopause heights were initially considered, but a desire to include potentially intense, shallower convection (including shallow FGT), led to the choice of a temperature dependent height corresponding to a level where cloud electrification is likely (-20 °C). It was recognised that this limit would over-predict lightning producing storms, but have the benefit of identifying the potential for development of other types of potentially-dangerous moist pyro-convection.

A PFT1 approximation was introduced in Tory and Kepert (2020) to facilitate a simple process for estimating and visualising PFT1 on a thermodynamic diagram,

$$PFT1 \sim 0.3 \times (Z_{fc})^2 \times U \times \Delta\theta_{fc} \quad \textbf{(1)}$$

where $zfc$ is the free-convection height in units of $km$ (the minimum height the plume must rise to initiate deep moist pyro-convection), $U$ is the average velocity magnitude of the mixed layer horizontal wind, units $ms^{-1}$, and $\Delta\theta fc$ represents how much warmer the plume needs to be than the mixed-layer potential temperature, units ℃ (or $K$). These units yield PFT1 values with units of $GW$.

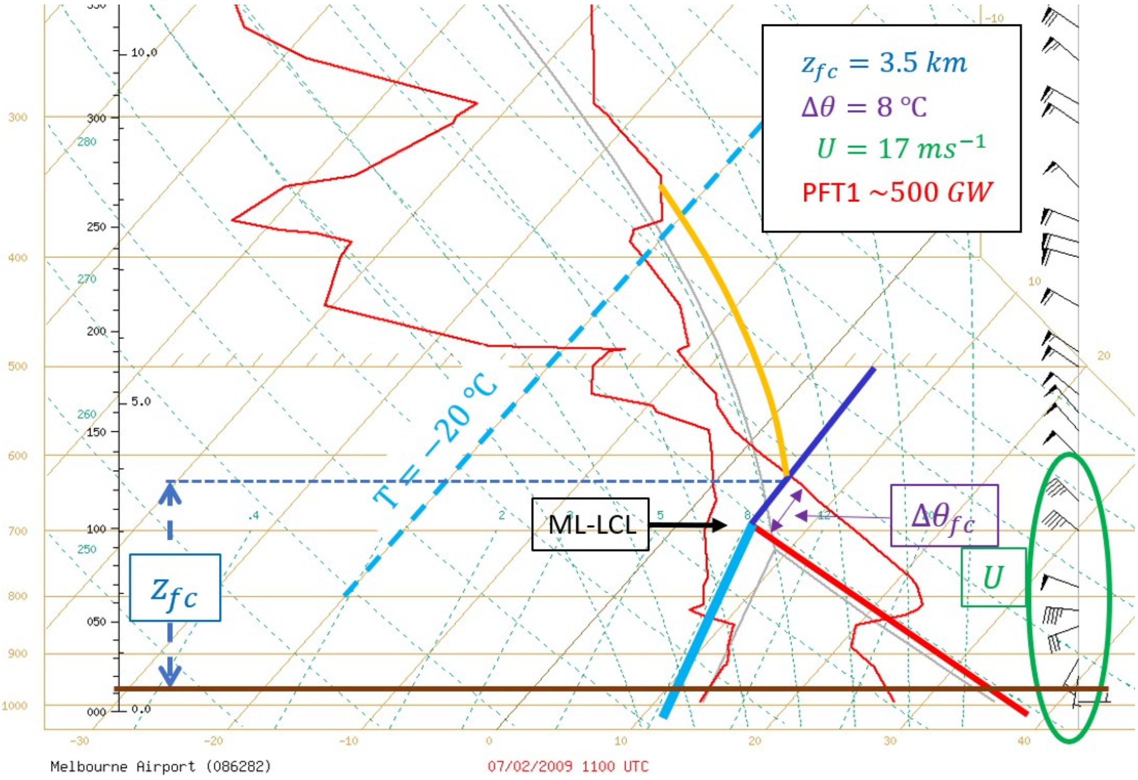


**FIGURE 1:** MELBOURNE AIRPORT SOUNDING 1100 UTC, 7 FEBRUARY 2009 (10 PM LOCAL TIME), WITH MARKERS USED IN THE MANUAL PFT CALCULATION (EQ. 1). THICK RED AND CYAN LINES REPRESENT THE MIXED-LAYER POTENTIAL TEMPERATURE AND SPECIFIC HUMIDITY RESPECTIVELY, WITH THE MIXED-LAYER LIFTING CONDENSATION LEVEL (LCL) MARKED AT THE APEX OF THESE TWO LINES. THE SATURATION POINT (SP) CURVE (APPROXIMATED BY THE BLUE LINE) IDENTIFIES THE POTENTIAL PLUME CONDENSATION POSITIONS. THE MINIMUM-BUOYANCY PLUME-PATH IS INDICATED BY THE GOLD CURVE. THE FREE- CONVECTION HEIGHT ($zfc$) IS THE HEIGHT AT THE BASE OF THE GOLD CURVE. THE PLUME MUST BE AT LEAST $\Delta\theta fc$ WARMER THAN THE MIXED-LAYER POTENTIAL TEMPERATURE (THICK RED LINE), AND THE AVERAGE MIXED-LAYER WIND TERM, $U$, CAN BE ESTIMATED FROM THE WIND BARBS HIGHLIGHTED IN GREEN.

An example is shown in Fig. 1 during the evening of the disastrous Black Saturday fires (e.g., Cruz et al. 2012). The mixed-layer potential temperature (thick red line) and specific humidity (thick cyan line) represent the average thermodynamic properties of air entrained into the plume. The saturation point curve is approximated by a straight line representing a 15:1 ratio[1] of plume temperature increment to plume moisture increment (units $K/g\ kg^{-1}$, blue line). It represents a range of possible positions where the plume can reach saturation (Luderer et al. 2009, Tory et al. 2018). The minimum-buoyancy plume- path that freely convects to a level cooler than -20 ℃ is indicated by the gold curve. The free-convection height ($zfc$) is the height at the base of the gold curve. Here the plume must be at least $\Delta\theta fc$ warmer than the mixed-layer potential temperature (thick red line), and the average mixed-layer wind term, $U$, can be estimated from the wind barbs highlighted in green.

[1] Note, in some of the earlier training material this ratio was incorrectly recorded as 10:1 temperature to moisture increment.

The three terms on the RHS of Eq. 1 give important insight into expected plume behaviour in their own right, and were included in the PFT1 forecast-product suite. For example, when $\Delta\theta fc$ is small the plume on a fire producing just enough firepower to exceed the PFT will be highly bent-over when it reaches $zfc$, whereas for large $\Delta\theta fc$ the plume needs to be much more buoyant to penetrate the inversion, and will be more upright as a consequence (Tory and Kepert 2018, 2020). Small $\Delta\theta fc$ is also an indicator that the environment is more likely to be favourable for conventional thunderstorms as well as deep, moist pyro-convection.

Early testing of PFT1 highlighted the fact that atmospheric conditions that favour the development of large and intense fires with deep flaming (hot, dry and windy) do not favour moist plume development (cool, moist and calm), and vice versa. Deep, moist pyro-convection only develops when there is some overlap in these opposing sets of conditions. For example, mega-fires might produce enormous firepower, sufficient to overcome the unfavourable conditions for moist-plume development, in which case moist pyro-convection (hereafter MPC) could perceivably develop regardless of how hot, dry and windy it is. On the other hand, a much smaller and less intense fire, producing a fraction of the firepower of a mega-fire, could generate MPC in a cool, moist and/or relatively calm environment, such as might occur when a wind change arrives at an already established large fire. Testing on a variety of historical case-studies revealed almost two orders of magnitude difference in PFT1 values diagnosed for confirmed FGT events (e.g., Tory 2019). It became clear that a useful forecast tool based on PFT1 would need to incorporate conditions that relate to potential fire size and intensity, either built into the diagnostic or separate to it. A PFT1 flag was trialled designed to flag forecaster attention whenever a favourable combination of moist plume formation and large intense fire formation conditions were present (Tory 2019). The PFT1 flag is essentially a ratio of PFT1 to a modified Vesta fire-danger index (Cheney et al. 2012). Forecast plots of the PFT1 flag and the modified fire-danger index were added to the suite of PFT1 forecast products (hereafter PFT1 forecasts).

Examples of PFT1 products are shown in Figs 2 and 3 on 30 December 2019 and 4 January 2020, respectively. The first was the most active day of the season with seven confirmed FGTs and a number of other deep MPC bursts (featured in the cover photo), and the second was also very active with four notable deep MPC events, two of which were confirmed FGT. See Section 2 for more detail.

A real-time trial of PFT1 forecasts took place during the 2019/2020 southern Australian fire season. Forecast maps at 6-hourly intervals were automatically generated from ACCESS-R data (the Bureau of Meteorology's numerical weather prediction model) for five regions around Australia, plus an Australia-wide region, and sent to end-users including fire-weather forecasters (FWF) within BoM and fire-behaviour analysts (FBAn) in the state fire agencies. Additional high-resolution forecasts at hourly intervals were prepared on demand for high-threat days when possible (this process was manually initiated). The trial was very successful, exceeding our expectations. It provided very useful guidance to forecasters briefing emergency services and identified the potential for development of nearly all intense, MPC events. This success suggests that MPC are generally predictable, and that given the substantial simplifications and assumptions incorporated into PFT1, there may be a fairly distinct separation between typical favourable and unfavourable conditions from day-to-day. The success also means that improvements could focus more closely on timing and location (i.e., reduce the false-alarms without degrading the forecast by increasing the number of misses) and perhaps focus on refining the products to target specific types of MPC. To this extent the trial highlighted a number of promising development options.

The trial helped identify other important issues regarding MPC and FGT prediction and verification, three of which are addressed in detail in this report. The first issue stems from a general vagueness surrounding MPC with respect to:

- Threat variability (i.e., can we distinguish dangerous from benign);
- Understanding plume structure and behaviour and the relationship to specific threats (i.e., can we distinguish specific threats from plume observations);
- Limited methods for verification and observational confirmation; and a lack of clarity on what is being verified or confirmed.

Each point makes the forecasters task more difficult. The second follows from the first but incorporates the broader class of forecasting challenges. The general vagueness surrounding MPC mean there is an inevitable lack of clarity in messaging and the end-user perceived messages on the predicted MPC and associated threats. The forecast challenges have been exacerbated by the sudden increase in frequency of MPC events, from a few events per decade to tens of events per season. Compared with many other severe weather events forecasters have limited experience with MPC, and associated prediction tools and procedures are much less well-developed. The great unknown surrounding FGT and MPC in general and the unprecedented threat that fire agencies had to deal with, created a high-pressure forecast environment, in which decisions had to be made on minimal information. This resulted in PFT1 forecasts being used in the decision-making process more than we anticipated (rather than primarily being monitored to assess performance).

The third issue arose from questions regarding whether or not PFT1 products could be used to investigate the sudden increase in MPC events. Given that only atmospheric ingredients are included in these products, any climate application can only identify possible changes in atmospheric conditions, and only those conditions explicitly included in the PFT1 products. It became apparent during the trial, in consideration of the first and second issues, that any climate study should ideally be delayed until additional atmospheric phenomena important for MPC development be incorporated into the two diagnostics, and until we are clear about what we wish to identify (e.g., just FGT or the broader class of deep, MPC).

In this report PFT1 forecast product examples are presented in Section 2. The MPC definition issue and forecasting challenges are addressed in Sections 3 and 4, and illustrated with examples in Section 5. Using PFT1 products in climate studies is discussed in Section 6, and procedures developed to improve forecast performance of these tools for climate applications are presented in Section 7. The report is summarised in Section 8.

# 2 PFT1 FORECAST PRODUCTS: TWO MULTIPLE DEEP MPC CASES

The two cases used to illustrate the PFT1 products show forecasts for the two most active days of the season. The products are presented in Figs 2 and 3, with the PFT1 flag (panel a) used to give a summary indication of potential threat. Each figure also includes the PFT1 flag at 11 AM (panel d) to demonstrate how the tool captures the diurnal cycle of increasing favourability throughout the afternoon. They can only show snapshots of deep MPC threat at the forecast time, which means the six-hourly forecast interval did not always capture the actual threat time and location. (We anticipate moving to three-hourly forecasts in the near future, and hourly when possible.) Fig. 2 provides a clear-cut demonstration of the performance of the products, whereas Fig. 3 illustrates the limitations of the PFT1 flag during conditions of more borderline favourability, while still providing warning of potential deep MPC development.

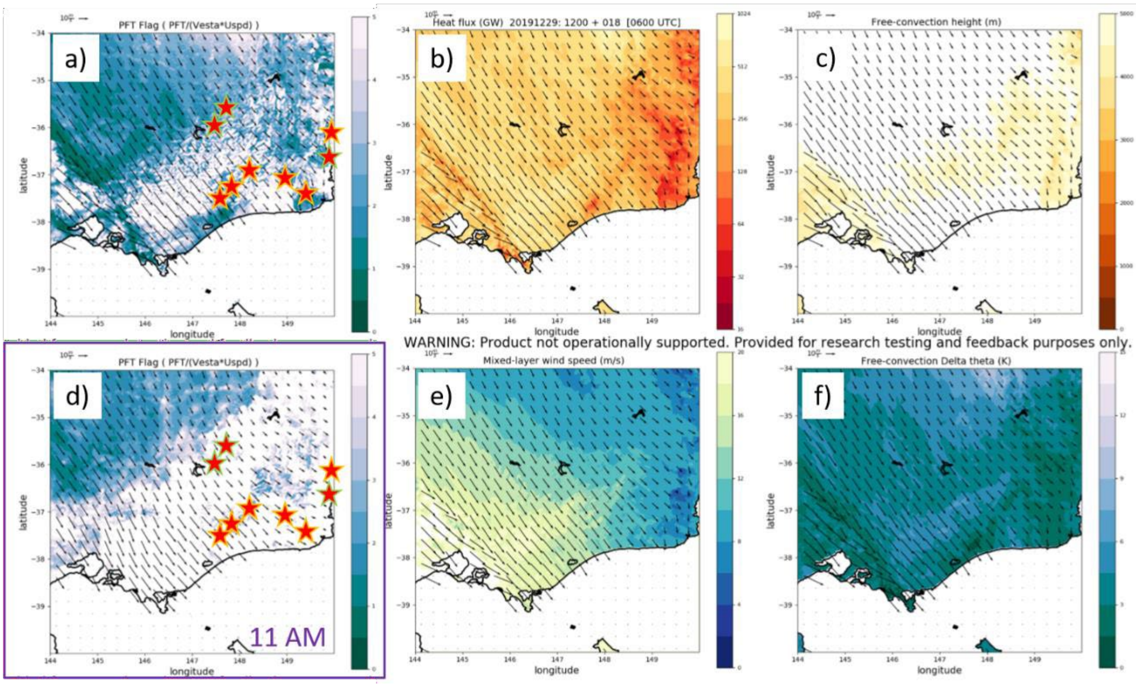


**FIGURE 2:** PFT1 FORECAST PRODUCTS FOR 30 DECEMBER 2019 AT 5 PM LOCAL TIME (0600 UTC) EXCEPT PANEL (D) WHICH IS 11 AM (0000 UTC). THE RED-GOLD STARS IN PANELS A AND D INDICATE THE LOCATION OF CONFIRMED FGT ASSOCIATED WITH FIRES (FROM LEFT TO RIGHT) BULLUMWAAL, ENSAY, DIGGERS HOLE, WULGULMERANG, CANN RIVER (THE CANN RIVER FIRE ALSO PRODUCED MULTIPLE FGT LATER THAT NIGHT, SECTION 5E) AND A FIRE EAST OF COOMA. THE RED-GREEN STARS SHOW LOCATIONS OF OTHER DEEP MPC. THE PANELS INCLUDE: (A),(D) PFT FLAG, ARBITRARY UNITS; (B) PFT, UNITS $GW$ (LOG BASE 2 COLOUR SCALE FROM 16 TO 1024); (C) FREE-CONVECTION HEIGHT, $zfc$, UNITS $m$ (COLOUR SCALE 0, 5000); (E) MIXED-LAYER WIND SPEED, $U$, UNITS $ms^{-1}$ (COLOUR SCALE 0 TO 20); (F) FREE-CONVECTION DELTA THETA, $\Delta\theta fc$, UNITS $K$ OR ℃ (COLOUR SCALE 0 TO 15). IN EACH PANEL DARKER SHADING INDICATES HIGHER FAVOURABILITY FOR DEEP MPC.

## EASTERN VICTORIA AND SOUTHEAST NSW 30 DECEMBER 2019

On 30 December 2019, the PFT1 flag suggested conditions were generally unfavourable for deep MPC development in the middle of the day (Fig. 2d), but became increasingly more favourable throughout the afternoon (Fig. 2a). A number of large and intense fires were burning at the time with six of them producing FGTs (red-gold stars in Fig. 2a, d). Cann River, indicated by the star furthest to the south east, produced a prolonged FGT later that night (discussed in Section 5e). The lowest values of PFT1 (most favourable for moist plume growth) are in the east (Fig. 2b), with more elevated values in the centre of the domain, and moderate values on and behind the wind change approaching from the south west. Spatial distributions of the three terms on the right-hand side of Eq. 1 (that contribute to PFT1) are depicted in Fig. 2c, e and f. They show the free-convection height is quite elevated throughout, mostly greater than 4.5 km. The reason for the low PFT in the east is the relatively light mixed-layer winds (plumes can stand up tall) and the very minimal $\Delta\theta fc$ (very small capping inversion for the plume to overcome). On the wind change conditions are similar except the mixed layer winds are strong, leading to only moderate values of PFT1. The semi-circle of stars marking the Victorian FGT locations, roughly coincide with low- to moderate-PFT1 due largely to the matching pattern of very low $\Delta\theta fc$. The PFT1 flag (panel a) is triggered throughout most of the domain where PFT1 (panel b) has moderate values, because the modified Vesta function that forms the denominator of the PFT1 flag reflects extreme fire danger (i.e., hot, dry and windy, not shown).

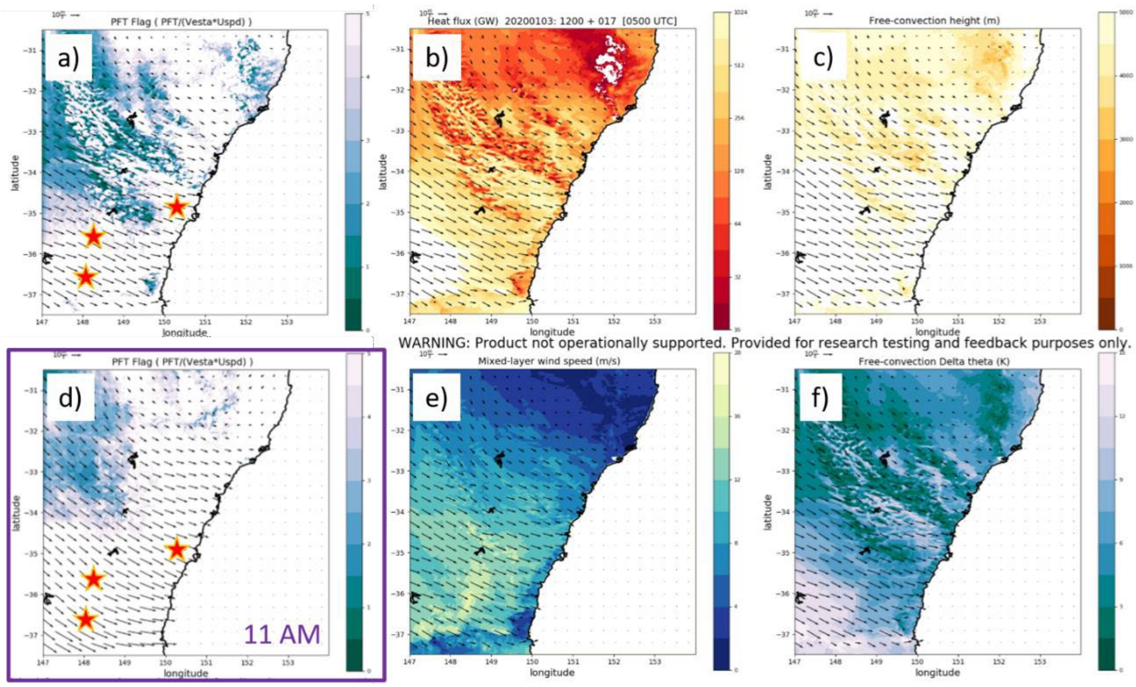


**FIGURE 3:** PFT1 FORECAST PRODUCTS FOR 4 JANUARY AT 4 PM LOCAL TIME (0500 UTC) EXCEPT PANEL (D) WHICH IS 11 AM (0000 UTC). THE STARS IN PANEL A) INDICATE THE LOCATION OF NOTABLE DEEP MPC ASSOCIATED WITH FIRES (FROM NORTH TO SOUTH) NEAR NOWRA, CABRAMURRA AND WEST OF MT. KOSCIUSKO (THE CABRAMURRA FIRE PRODUCED TWO NOTABLE BURSTS OF DEEP MPC).

## SOUTHEAST NSW 4 JANUARY 2020

On 4 January 2020 conditions were generally unfavourable for plume development in southeast NSW (e.g., large areas with no PFT1-flag shading, Fig. 3d), with PFT1 in the general area > 1000 GW for much of the day (not shown). Throughout the afternoon conditions became increasingly favourable (Fig. 3a), with bands of lower values of PFT1 approaching the fire locations (starred) from all sides (Fig. 3b). While the PFT1 flag did not definitively identify the location and timing of the observed deep MPC, there was enough indication of potential activity nearby to alert fire-weather forecasters. In the model a wind-change propagated inland from the south and east and impacted the southernmost fire location about 2 hours later, with the PFT1 flag triggered on the change (not shown). Thus, the PFT1 flag provided very useful guidance, and was successful in identifying the deep MPC threat on the wind change. However, it highlights the importance of higher frequency forecasts, especially as conditions favouring deep MPC may be as short-lived as a few tens of minutes. The speckled patterns in Fig. 3a, b and f, are indicative of model thunderstorm development, where cold, moist and windy outflows contribute to localized PFT1 and PFT1-flag maxima and minima. It can be difficult for NWP models to capture the location and timing of thunderstorms, and it is possible that they were closer to the fires at this time. Thunderstorm outflows could potentially help trigger FGTs.

Other intense fires were active on the day. One near Eden (37° S on the coast, near the small patch of PFT flag) produced abundant cumulus cloud. Another in Victoria (Abbeyard-Yarrarabula Fire) produced numerous large puffs of cumulus, but they did not appear to be very deep (not shown). For this Victorian fire the PFT1 flag suggested conditions would be unfavourable all day (not shown), but an approaching wind change bringing favourable conditions did not quite penetrate far enough inland.

# 3 MOIST PYRO-CONVECTION: LACK OF CLARITY

Cumulus clouds may form in smoke plumes on relatively benign fires or large fires, without any evidence of dangerous fire behaviour. Furthermore, it can be difficult for remote FWFs and FBAns to identify when plumes become dangerous or are about to become dangerous. Lightning formation is a very good indicator that intense updrafts have developed in the plume, and indeed most of the spectacular iconic events in recent times have produced lightning. However, dangerous plume-fire feedback can occur on plumes that do not produce lightning. For example, the Canberra FGT produced black hail and spawned an F2 tornado (Fromm et al. 2006) with no lightning recorded[2] (Dowdy et al. 2017). This suggests, lightning producing MPC (i.e., FGT) may only be a subset of the class of potentially dangerous MPC. Sharples et al. (2016) provide a useful definition for dangerous MPC: "violent pyroconvection that manifests as towering pyrocumulus or pyrocumulonimbus (pyroCb)", which draws on the expression "violent convection" used to describe fire storms characterized by potentially destructively violent surface indrafts and sometimes tornado-like whirls (National Wildfire Coordinating Group Wildfire Glossary - https://www.nwcg.gov/glossary/a-z). Rather than adopt these terms in this document, we choose to use very general descriptors so as not to contribute to further confusion in the future when presumably we have deeper understanding of MPC. Thus, we settle for the non-specific descriptor of 'deep MPC' when referring to potentially dangerous MPC, and by dangerous we mean the MPC presence makes the fire ground more hazardous.

Inconsistency in the use of the term pyroCb has also led to confusion, as mentioned in the introduction. The inconsistency appears to be borne out of two communities coming together with a shared interest in MPC, but an interest in two separate outcomes or effects of MPC: Escalation of dangerous fire behaviour and/or generation of meteorological hazards (the 'surface' community); and Deep aerosol injection and transport (the 'aloft' community). The surface community, FWFs and FBAns, appear to have adopted a common meteorological interpretation of cumulonimbus, i.e., thunderstorms, hence their pyroCb morphed almost exclusively into FGT. Lightning is an immediate indicator of FGT, but since they do not all produce lightning, careful post-event analysis of cloud height and structure is sometimes required to confirm FGT. In real-time, some forecasters relied almost solely on lightning observations to confirm FGT (there didn't appear to be a cloud-top height or temperature that forecasters used to declare FGT in the absence of lightning), which contributed to a FGT lightning focus among the surface community. The aloft community use a broader definition of cumulonimbus more in keeping with the Latin translation (heaped or piled rain-bearing cloud), to include any deep clouds with the potential to transport surface-based smoke into the upper troposphere or lower stratosphere (UTLS). The aloft community have the time to perform post-event analyses, whereas the surface community do not have this option when forecasting or nowcasting.

[2] Dowdy et al. (2017) note that although no lightning was recorded from the station observationsor spatial network of lightning detectors (GPATS) it does not necessarily mean there was no lightning.

In an attempt to tease out further sources of inconsistency and confusion, we begin by making the distinction between two hypothetical classes of MPC: (1) Benign - cloud formation in smoke plumes with minimal feedback to the fire and zero generation of meteorological hazards; (2) Potentially dangerous – deep MPC with strong feedback to the fire and/or meteorological hazards such as downbursts, tornadic strength vortices. These classes are depicted in a Venn diagram in Fig. 4 with grey and red shading respectively. Class 2 is further separated into categories matching the surface- and aloft-pyroCb community definitions (purple and blue ellipses, respectively) and an additional lightning producing category (green ellipse) representing a hypothesised fire-induced thunderstorm, in which there is no direct connection between the smoke plume and the Cb cloud (and hence no aerosol transport). The classes and sub classes are a first attempt to tease out and classify the MPC types mentioned in this document. Future research will no doubt show it to be a rather naïve classification attempt, but that just highlights the need for improved understanding of MPC.

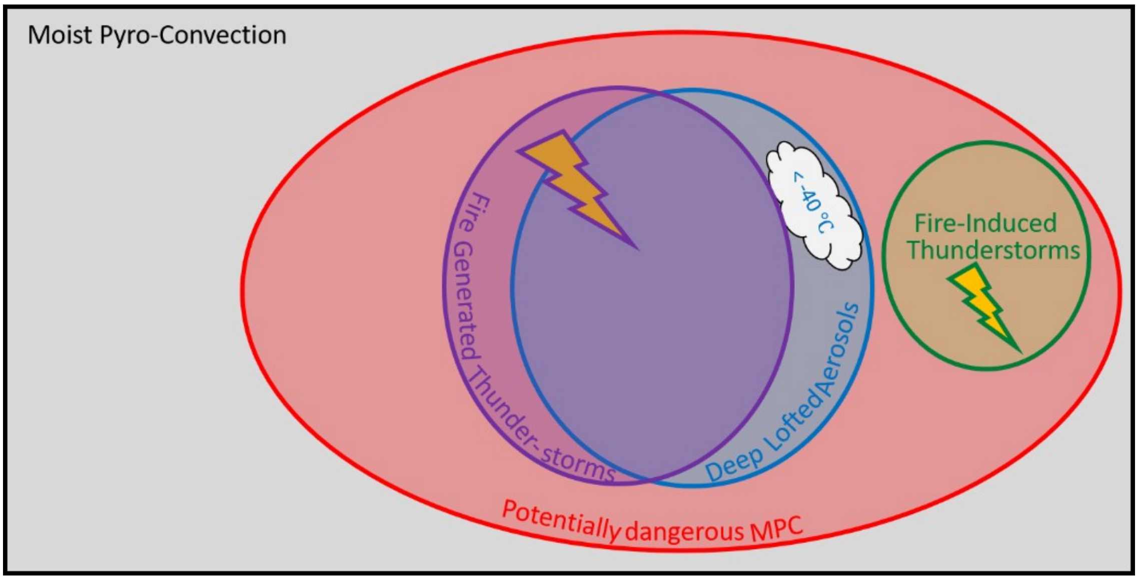


**FIGURE 4:** DEPICTION OF THE DIFFERENT MOIST PYRO-CONVECTION (MPC) TYPES DESCRIBED IN THE TEXT. THE BENIGN MPC IS INDICATED BY GREY SHADING, AND POTENTIALLY DANGEROUS LIES IN THE RED ELLIPSE. THREE SUBSETS ARE DEPICTED IN THE POTENTIALLY DANGEROUS. THE FIRE-GENERATED THUNDERSTORMS (FGT, PURPLE) LARGELY OVERLAP WITH MPC THAT PRODUCE DEEP LOFTING OF AEROSOLS (BLUE) TO ILLUSTRATE THE TWO OFTEN OCCUR TOGETHER, BUT BOTH CAN EXIST IN ISOLATION. THE <-40 °C CLOUD ICON, AND LIGHTNING BOLT REPRESENT THE CRITERIA USED TO DEFINE THE TWO SUBSETS. THE FIRE-INDUCED THUNDERSTORM SUBSET REPRESENTS THUNDERSTORMS THAT WOULD NOT HAVE OCCURRED WITHOUT THE FIRE, IN WHICH THERE IS NO EVIDENCE OF DEEP LOFTED AEROSOLS, SUGGESTING THERE IS NO DIRECT LINK BETWEEN THE SMOKE PLUME AND ELEVATED CUMULONIMBUS CLOUD.

A greater understanding of MPC is important, not only to recognise dangerous from benign MPC, but to recognise when benign MPC might become dangerous. At present not enough is known about MPC for FWFs and FBAns to make confident judgements about MPC threat, which necessarily leads to a high incidence of false alarms. There are likely many factors we are not yet aware of that could be used to discriminate between dangerous and benign MPC, plus other factors we can speculate on. For example, deep cloud formation evident in satellite measured cloud-top temperatures, is an indicator of strong vertical motion in plumes, and raises a red flag to forecasters for the potential for dangerous MPC. But how deep is dangerous, and how close to the fire is dangerous? How deep and close does this cloud need to be before we start to see dangerous plume-fire feedback? In contrast, lightning occurrence is a very clear indicator that the MPC has become deep and intense, and the somewhat blurred line between benign and potentially dangerous has likely been crossed (although the question of "how close" is dangerous remains). It is likely that this concrete indicator, among a sea of uncertainty, also contributed to the FGT lightning focus in the surface community mentioned above.

The difference in focus between the two communities was illustrated early in the RTT when a thunderstorm developed over a coastal fire in Queensland about 80 km inside the tropic of Capricorn (Shoalwater Fire, 4 December 2019, Fig. 5) in which there was no evidence of smoke in the upper clouds. Lifting over the plume may have released conditional instability in an elevated layer triggering the thunderstorm, without smoky air being ingested into the cumulonimbus cloud. While it was deemed to be non pyroCb by the aloft community, due to the lack of smoke in the cloud, the question was posed whether a cumulonimbus cloud that develops because of the fire (without a direct connection to the smoke plume) should be considered pyro-convective, especially if associated cumulonimbus hazards have the potential to impact people on the fire ground. To incorporate this possibility into the MPC family the green ellipse is included in Fig. 4, representing Fire-Induced Thunderstorms (FIT)[3].

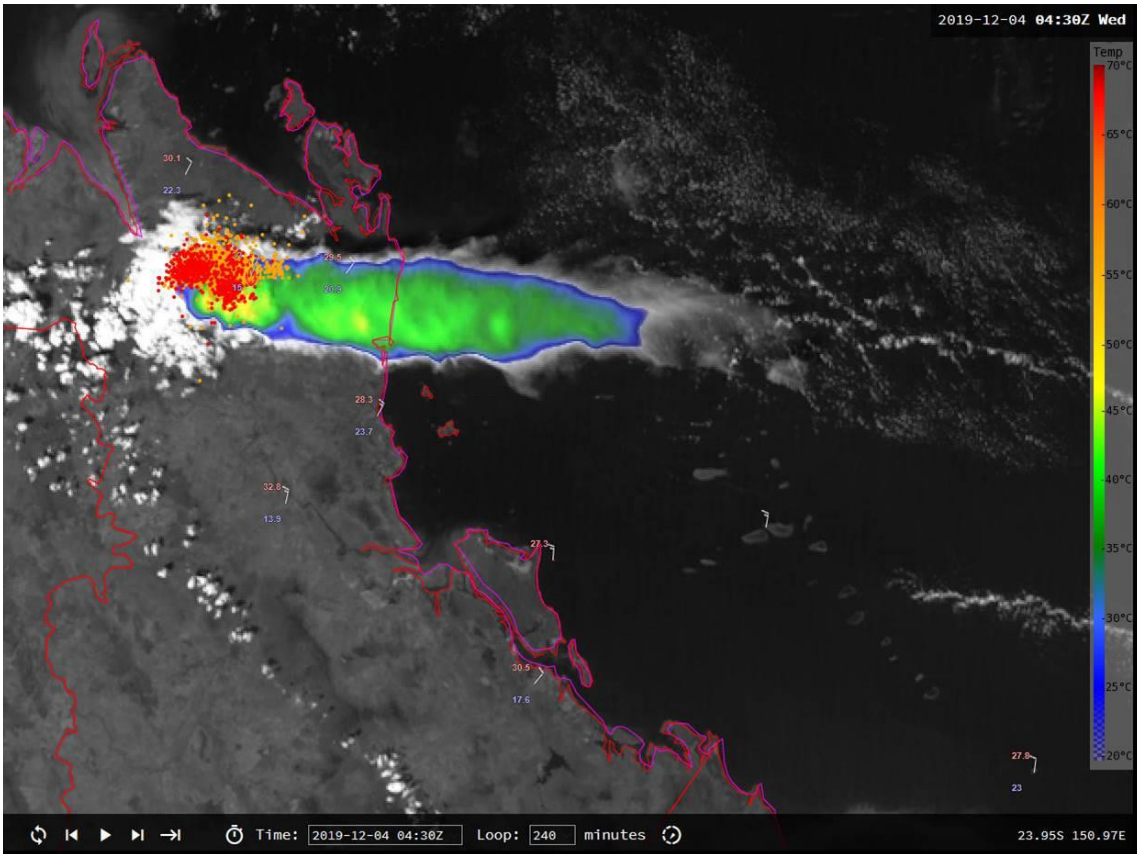


**FIGURE 5:** HIMAWARI INFRARED IMAGERY WITH COLOUR ENHANCEMENT AND LIGHTNING STRIKE DATA, SHOWING A CUMULONIMBUS OVER THE SHOALWATER FIRE AT 2:30 PM LOCAL TIME (0430 UTC) 4 DECEMBER 2019. NO SATELLITE EVIDENCE OF SMOKE WAS FOUND IN THE HIGH CLOUD, PROMPTING SPECULATION THAT THE STORM MAY HAVE BEEN TRIGGERED BY LIFTING OVER THE SMOKE PLUME (E.G., THE FIT CATEGORY IN FIG. 4).

When conditions are conducive to regular thunderstorm development in the vicinity of fires, it can be hard to determine if the fire played any role in initiating

[3] An equivalent fire-induced towering pyrocumulus category could also be included for symmetrywith the blue ellipse, but to avoid including too many hypothetical categories, only categories that match events discussed in the report have been included.

the thunderstorms (e.g., fires in the Nundle area in NSW, 5 January 2020), which means separating FIT from regular Cb may be just as difficult as separating FIT from FGT. Early in the trial, there were a few examples of relatively deep MPC with no lightning in northeastern NSW. One discussed in Section 5c exhibited minimum cloud-top temperature of only -30 ℃. Without further evidence it is not clear where these events fit into the Fig. 4 categories (although it is of minimal importance for this report). These distinctions, of course, may not be important for people on the fire ground, if all they need to know is whether it is safe to be on the fire ground. But if specific FGT prediction is required, then these and other cases later in the season further south, highlight the need to consider a minimum set of criteria for cloud electrification (Section 4b).

# 4 FORECASTING CHALLENGES

In this section a number of forecasting challenges and issues are described, based on first-hand conversations and e-mail reports from FWFs and FBAns. To maintain anonymity these issues have been presented in general terms and attribution has not been given to sources. The opportunity for FWF and FBAns to use the PFT1 in real time varied between jurisdictions, due to substantial differences in numbers of deep MPC events between the states. In NSW, the progression of intense fires from the north to the south over a six-month period, provided the greatest opportunity for FWFs in particular to test and learn how to use the PFT1 to full advantage, followed by Victoria and Western Australia. Queensland had a relatively brief window of active MPC events early in the season to test PFT1, whereas South Australia and Tasmania had very few. The choice to test/use PFT1 was voluntary and depended on users completing a training exercise, which resulted in varied uptake between forecast offices and state fire agencies. The uptake may also have been reduced by the sudden start to the fire season requiring an early shift to full operations mode before many potential users were able to complete the training.

## TESTING THE PFT, AND THE FGT FORECAST FOCUS ON LIGHTING

It is unlikely the FGT lightning focus, identified in the previous section, negatively impacted forecast performance during the PFT1 real-time trial, because the conservative messaging of experienced forecasters combined with the conservative plume-top temperature closure assumption built into PFT1 resulted in threats being communicated for almost all potentially dangerous MPC events. However, PFT1 forecast usage in the real-time trial was not without challenges. In its first season the PFT1 products were untested, and their reliability under a myriad of conditions unknown. Until very recently, potentially dangerous MPC (Fig. 4, red ellipse) occurred rarely, and as a consequence there has been little opportunity to develop and test related forecast products and establish objective forecast procedures. Furthermore, the lack of a clear distinction between its sub-classes, and the prominence of FGT in recent literature and media articles, led to a tendency to view FGT as synonymous with the broader class of potentially dangerous MPC, and produced the aforementioned forecast focus on FGT lightning.

The sudden increase in deep MPC and FGT occurrence in southern Australia (and around the world) during the longest and most destructive fire season on record, demanded unprecedented attention and the need to provide unprecedented numbers of FGT forecasts in high-pressure forecast environments. Without well-established forecast products, observational tools, and objective procedures, fire-weather forecasters needed to make crucial predictions with limited guidance[4]. Perhaps the only objective quantifiable data available in near real-time for confirming deep MPC were remotely-sensed cloud-top temperature and lightning observations, plus radar data when nearby. The tendency to associate FGT with potentially dangerous MPC, and to define FGT by lightning occurrence meant that forecasts were verified on the

[4] Other severe weather events such as conventional thunderstorms and tropical cyclones havebenefited from decades of development of forecast products and procedure, and observational tools.

presence or absence of lightning. Consequently, forecasts and nowcasts became even more focussed on identifying lightning producing MPC, rather than the broader class of potentially dangerous MPC.

## INCORPORATING CONVENTIONAL THUNDERSTORM KNOWLEDGE INTO THE FGT FORECAST PROCEDURE

The mysterious nature of FGTs meant that it was unclear if, or even how, traditional thunderstorm forecast knowledge should be incorporated into FGT forecast procedure. Also, it would not have been clear to most forecasters which thunderstorm processes had been incorporated in PFT1. For example, PFT1 does not incorporate the potential impacts of mid-troposphere humidity and stability on cumulus cloud development (although there are plans to incorporate this in the next version, PFT2 see Section 7.) For conventional thunderstorms, forecasters have an intuitive feel for this process when analysing thermodynamic diagrams, and some objective tools are also available[5]. It was not clear if these processes should be applied directly or in modified form to MPC, or if it was valid to apply them at all.

Confounding the situation further was the need for forecasters to identify deep MPC that might develop into FGT. Warnings needed to be issued prior to lightning formation. The only readily available indicator was cloud-top temperature, from which the rather conservative threshold of -20 ℃ was adopted, presumably to ensure the majority of FGTs were identified. There were many instances of cloud-top temperatures significantly colder than this with no lightning recorded. Uncertainty surrounding the specific nature of FGT may have contributed to an over-reliance on, or an over-expectation of the performance of, this threshold. Furthermore, the PFT training may have inadvertently reinforced this threshold, by highlighting the -20 ℃ cloud-top temperature closure assumption.

The -20 ℃ cloud-top temperature threshold is based on a simplification of a set of conditions required for Cb formation. It is generally accepted that charge separation in clouds requires a mix of super-cooled water, small ice crystals and graupel in an updraft greater than about 7 $m\ s^{-1}$, and that the main charging area temperature is between about -15 and -25 ℃[6]. It became clear over the course of the real-time trial that while the -20 ℃ CTT threshold was good for identifying potentially dangerous MPC, it was not reliable for identifying FGT. This realisation was perhaps best illustrated on 1 and 2 February in southeast NSW in which the threshold indicator failed for opposite reasons on consecutive days (see Section 5a).

Objective measures used by the Storm Prediction Center in Norman Oklahoma (Bright et al. 2005) highlight a more complete set of requirements for

[5] Thermodynamic diagrams show the magnitude of the potential instability for moist convection,termed Convective Available Potential Energy (CAPE) represented by the area between the environment temperature trace and the temperature trace of a rising parcel of condensing cloud air. The shape of the CAPE area on the thermodynamic diagram, along with the humidityof the middle-troposphere gives an immediate feel for whether mixed-layer-based moist convection is likely to survive the negative impacts of entrainment that weakens plume buoyancy. The objective tools quantify some of these effects (e.g., CAPE normalized by the depth between the level of free convection and equilibrium level).

[6] See, https://web.archive.org/web/20161130080723/http://www.lightningsafety.noaa.gov/science/science_electrication.htm

electrification. These measures included two requirements in addition to the cloud-top temperature threshold:

1. Cloud base warmer than -10 ℃, to ensure the presence of super-cooled water.
2. A minimum 100—200 $J\ kg^{-1}$ CAPE in the 0 to -20 ℃ layer, to represent sufficient buoyancy to generate an updraft velocity >= 7 $m\ s^{-1}$ in the main charge separation layer (-15 and -25 ℃)[7].

It is possible that the cloud base temperature threshold and updraft velocity thresholds may differ for FGT, due to different cloud microphysics caused by smoke particles (e.g., Reuter et al. 2014[8]). Applying the first of these conditions would exclude FGT formation for at least one of the early-season deep MPC events (and perhaps others[9]), in which CTT of -30 ℃ that did not produce lightning (Section 5c). There is an implicit recognition in the second condition for the need to account for buoyancy losses from entrainment, since it only takes about 25 $J$ $kg^{-1}$ to accelerate an air parcel to 7 $m\ s^{-1}$, and perhaps double that when accounting for the work required to displace denser environment air around the rising plume (e.g., Morrison et al. 2016a). The remaining potential energy is presumably to account for lost plume buoyancy from evaporation of cloud moisture and dilution, when cooler drier air is mixed into the plume.

This discussion highlights the limitation of parcel theory, especially where it is applied to moist (i.e., condensing) plumes such as used in the calculation of CAPE, fire-CAPE and PFT1. The thermodynamic properties of the moist, rising parcel are assumed to conserve moist static energy without any mixing between the parcel and the environment the parcel rises through. This greatly simplifies the calculation of CAPE, fire-CAPE and indeed PFT1. Despite the known limitations, parcel theory has persisted with CAPE calculations for decades due to difficulties in incorporating the effects of entrainment and choosing an appropriate entrainment rate (which can vary substantially for different types of convection). Fortunately, for the PFT, which is designed to identify a threshold firepower necessary for deep MPC, a constant entrainment rate representing deep vigorous moist convection can be employed, which reduces the degrees of freedom sufficiently to close the problem (Section 7a). Addressing the mid-troposphere entrainment issue in the PFT is likely to improve PFT performance, since elevated values of mid-troposphere relative humidity has been found to be an important discriminator between intense pyroCb events and high-firepower non-pyroCb events (Peterson et al. 2017).

[7] It is not uncommon for lightning to occur in tropical convection with cloud-top temperature aswarm as -10 ℃ (Sgarbossa 2020, personal communication).

[8] In a cloud microphysics modelling study, Reutter et al. (2014) found the formation of rain, graupel and hail is delayed in plumes with high smoke concentrations, resulting in higher concentrations of snow and ice in the upper cloud regions, and much less hail and graupel in themiddle-level cloud. If Reuter et al.'s mid-level cloud layer corresponds with the main charge separation layer, then reduced charge separation might be expected.

[9] A manual PFT analysis of a Wagga sounding on the morning of the Green Valley Fire event, which produced an EF3 tornadic-strength vortex, showed very dry conditions suggesting plumesaturation at about -12 ℃.

# 5 ILLUSTRATIVE EXAMPLES

In this section deep MPC cases are chosen to illustrate issues raised in the previous two sections, including limitations of parcel theory and methods used for predicting lightning formation. Two examples of FGTs not identified by the PFT1 flag are also investigated. The cases highlight areas for improvement, plus they provide valuable insight into MPC dynamics and how regional and temporal variations in atmospheric phenomena can affect MPC development.

Early in the season many MPC cases were observed in NSW and Qld exhibiting cloud-top temperatures less than the -20 °C threshold in which no lightning formed. It is likely that in many of those cases plume saturation occurred at temperatures cooler than the -10 °C threshold temperature (or an equivalent FGT threshold if one exists) necessary to ensure the presence of super-cooled water (Bright et al. 2005). However, many more examples continued to appear throughout the season further south when plume saturation would have been much warmer than -10 °C , in which case electrification was being inhibited for some other reason. Indeed, it was so common that the -40 °C cloud-top temperature threshold (used by the aloft community) appeared to be a more reliable lightning indicator than the -20 °C threshold. We hypothesise that one reason for these latter exceptions, is insufficient buoyancy to accelerate updrafts to speeds necessary for charge separation, due to plume buoyancy losses associated with entrainment.

## LIMITATIONS OF PARCEL THEORY

On the weekend of 1 - 2 Feb 2020, two events occurred on consecutive days that defied both the -20 °C and -40 °C cloud-top temperature thresholds. Thanks to Zach Porter and David Wilke for collating images and soundings for these events. On the Saturday cloud-top temperatures of -45 °C were observed with no lightning[10] after the Orroral and Clear Range fires merged (in a region with good lightning observations), and on the Sunday, lightning was observed in a plume about 30 km downstream of the Erskine Creek fire, with cloud-top temperatures no cooler than -15 °C. The following analysis is primarily included to demonstrate the limitations of parcel theory, but it also includes speculation on the unexpected lightning behaviour, while acknowledging that we don't understand charge separation in smoke plumes well enough to offer a complete or consistent argument.

A visual inspection of the thermodynamic diagrams on 1 and 2 Feb (Figs 6 and 7 respectively), provide a likely explanation for the unexpected behaviour, but only after taking into consideration plume buoyancy losses from entrainment. Indeed, parcel theory could not explain the observed cloud-top temperatures. On both days, parcel theory takes the minimum-buoyancy free-convection parcel to levels much higher than the observed CTT. On both days very dry air was located above about 600 hPa, where it would be expected that entrainment of this air would erode the plume buoyancy.

[10] FGT did develop on the Creewah fire further south on the Saturday, as anticipated by fire-weather forecasters.

Figure 6 shows a Canberra sounding at 1300 local time (0200 UTC). An estimated Saturation Point curve (solid blue line) has been added based on estimates of mixed-layer potential temperature (red) and specific humidity (cyan), representing the average thermodynamic qualities of air entrained into a hypothetical smoke plume penetrating the mixed layer. Based on the theory that underlies PFT1, any plume that rises high enough will saturate somewhere on this curve. PFT1 assumes a freely convecting plume element with just enough buoyancy to exceed the -20 ℃ level would follow the moist parcel path indicated by the thick gold curve, which reaches neutral buoyancy near the -60 ℃ level (not shown). For comparison, the thin gold curve represents the parcel path that reaches the observed cloud-top temperature of -45 ℃. Note, how the latter curve would need to penetrate both the capping inversion near 600 hPa and another inversion near 450 hPa. Assuming the sounding represents the MPC environment (about 60 km to the south), these lines cannot represent actual thermodynamic plume-element pathways, since the former rises too high and the latter would not have sufficient buoyancy to breach the capping inversion and possibly the inversion near 450 hPa. Thus, parcel theory cannot explain the plume rise here.

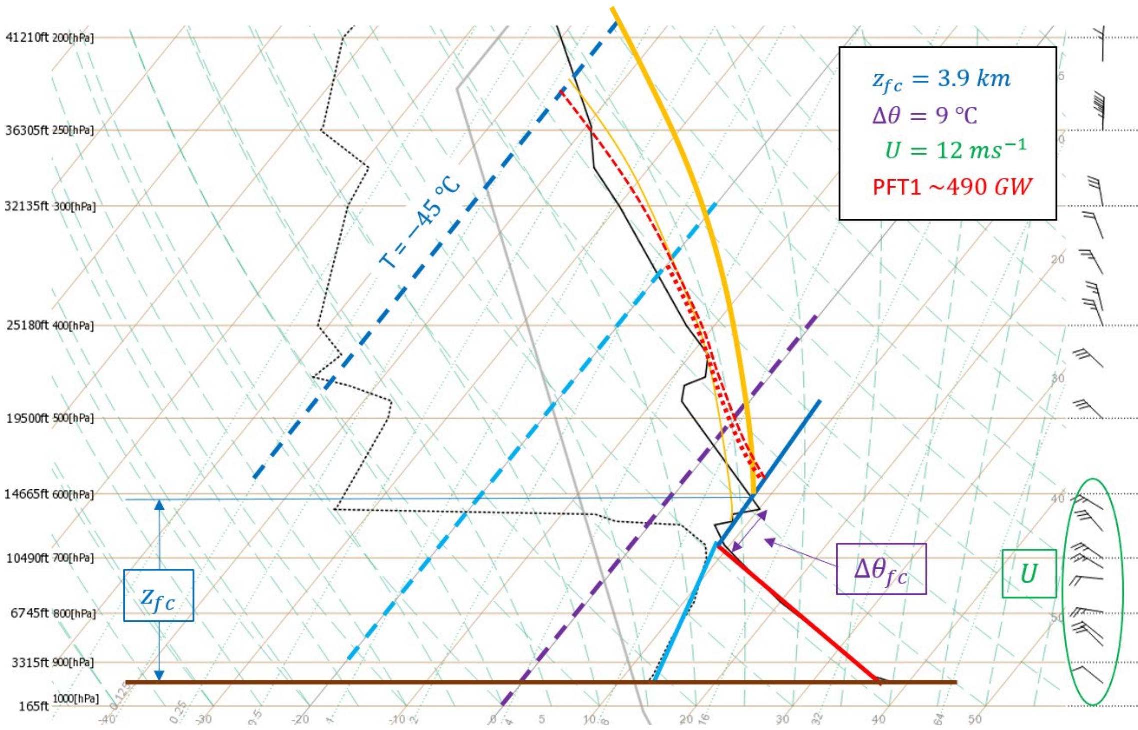


**FIGURE 6:** CANBERRA SOUNDING 1 PM LOCAL TIME (0200 UTC). THE SOLID AND DOTTED BLACK LINES REPRESENT TEMPERATURE AND DEWPOINT TEMPERATURE RESPECTIVELY. THE 0, -20 AND -45 ℃ TEMPERATURE LINES ARE INDICATED BY PURPLE, CYAN AND BLUE DASHED LINES RESPECTIVELY. THE SOLID RED AND CYAN LINES SHOW A MIXED LAYER TEMPERATURE AND DEWPOINT TEMPERATURE OF CONSTANT POTENTIAL TEMPERATURE AND SPECIFIC HUMIDITY THAT REPRESENT THE AVERAGE QUANTITIES ENTRAINED INTO A HYPOTHETICAL PLUME RISING THROUGH THE MIXED LAYER. THE SOLID BLUE LINE IS AN APPROXIMATE SATURATION POINT CURVE. THE GOLD LINES ARE MOIST PARCEL PATHS EMERGING FROM THE SP CURVE, ONE WITH MINIMUM BUOYANCY JUST ABLE TO BREACH THE CAPPING INVERSION AND EXCEED THE -20 ℃ LEVEL (THICK, USED IN PFT1), AND THE OTHER (THIN) REPRESENTS A PARCEL PATH CORRESPONDING TO THE OBSERVED CLOUD- TOP TEMPERATURE OF -45 ℃. THE THIN RED DASHED LINE IS A HYPOTHETICAL PARCEL PATH THAT REACHES THE OBSERVED CLOUD TOP TEMPERATURE WITH SOME OVERSHOOTING, AND TAKES INTO ACCOUNT BUOYANCY LOSSES ASSOCIATED WITH ENTRAINMENT. THE THICK RED DOTTED LINE IS AN EQUIVALENT BUOYANT PARCEL PATH WITH SUFFICIENT BUOYANCY TO EXCEED THE -20 ℃ LEVEL (SUCH AS MIGHT BE USED IN PFT2). THE THREE INGREDIENTS FOR A MANUAL PFT1 CALCULATION ARE ILLUSTRATED, AND THEIR ESTIMATED VALUES SHOWN IN THE LEGEND.

If we assume plume buoyancy losses due to entrainment of dry air evaporating cloud moisture, then the saturated plume temperature trace would veer to the left with height as depicted in the dashed red line. This is a hypothetical plume-element pathway that meets the following criteria: it rises to a level matching the observed coolest cloud-top temperature of -45 ℃, assuming some overshooting, with buoyancy losses maximised at lower levels where the environment saturation specific humidity deficit (i.e., the capacity for evaporation) is largest. The area between these parcel paths, or plume-element pathways, and the environment temperature trace (solid black line) within the 0 to -20 ℃ layer (purple to cyan dashed lines), represents the CAPE corresponding to the second criterion for electrification described in Section 4b. From an inspection of Fig. 6, it is clear that this electrification CAPE is much larger for a parcel following the thick gold line, than the red dashed line. We speculate that actual parcels followed paths similar to the red dashed line, in which there was insufficient buoyancy to accelerate the plume air to charge-separation speeds in that layer, especially given the inversion in the middle of that layer.

Figure 7 shows the Sydney sounding from 1400 local time (0300 UTC) with a similar set of lines overlaid as depicted in Fig. 6. A marine boundary layer is evident in the lowest 800 m, which would not have been present at the fire location. To account for this difference the surface temperature (38 ℃) and surface dewpoint temperature (15 ℃) determined from the Portable Automatic Weather Station (PAWS, RF55) located at Faulconbridge (elevation 410m, about 20 km north of the fire) were used to improve the estimate of the average thermodynamic conditions the plume was rising through, and the associated SP curve. As in Fig. 6 the 0 and -20 ℃ temperature lines are marked by the purple and cyan dashed lines, and the observed cloud-top temperature (-15 ℃) is indicated by the blue dashed line. Once again, the parcel path matching the observed cloud-top temperature (thin gold line) would have had to penetrate multiple stable layers (the capping inversion, plus two inversions near 550 and 470 hPa). While the two gold curves in Fig. 7 are a similar distance apart to those in Fig. 6, the difference in height of their respective equilibrium levels is substantial (almost 5 km) and much greater than seen in Fig. 6. The hypothetical path of an entraining moist-plume element (red dashed line) has much larger buoyancy below 600 hPa than above, which may have been sufficient to accelerate the plume air to charge-separation speeds prior to reaching the 0 to -20 ℃ layer suggested in Section 4b, and indeed prior to reaching the main charge-separation temperature range (-15 to -25 ℃). Of note, is the almost parallel approach of the red dashed curve with the temperature trace suggesting a more gradual loss of buoyancy, compared to that expected when plumes intersect an inversion such as the tropopause, which perhaps explains the lack of an observed anvil cloud (e.g., see Fig. 8).

Both of these cases suggest it can be important to incorporate buoyancy losses from entrainment. Furthermore, if it is necessary to predict FGT specifically, then more specific Cb conditions, such as those introduced in Section 4b should be incorporated.

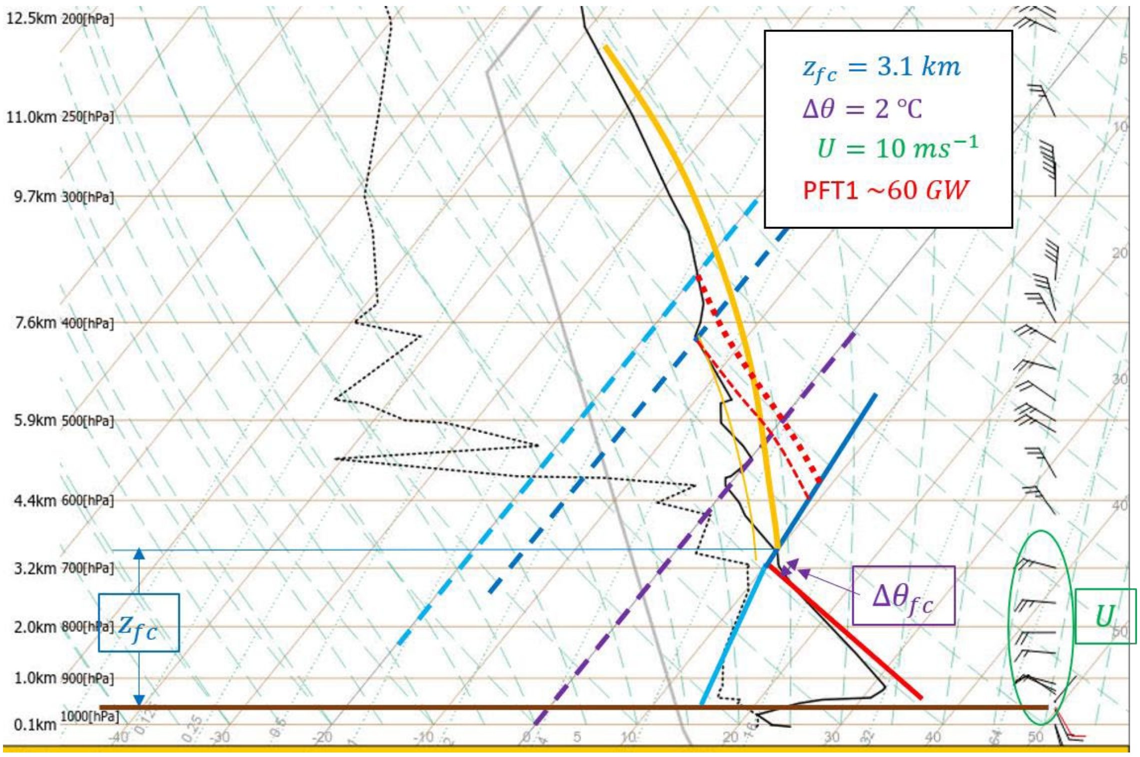


FIGURE 7: AS IN FIG. 6 BUT FOR THE SYDNEY SOUNDING 2 PM LOCAL TIME (0300 UTC) SUNDAY 2 FEB. OBSERVATIONS FROM A PAWS (RF55) LOCATED AT FAULCONBRIDGE (ELEVATION 410M, 20 KM NORTH OF THE FIRE) WERE USED TO ESTIMATE THE ACTUAL CONDITIONS BELOW 1.0 KM, ELIMINATING THE MARINE BOUNDARY LAYER.

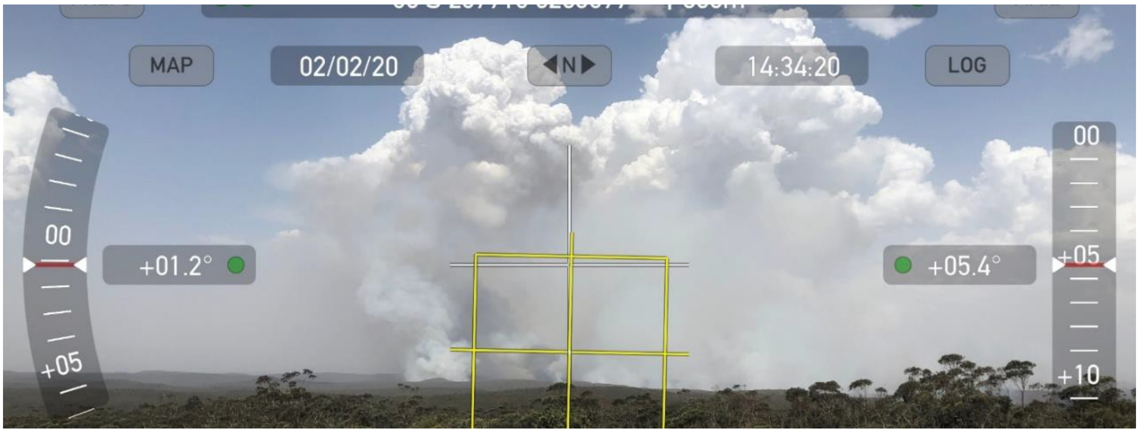


FIGURE 8: LOOKING NORTH TOWARDS ERSKINE CREEK FIRE 1434 LOCAL TIME. LIGHTNING WAS OBSERVED BETWEEN 1407 AND 1417 LOCAL TIME.

## EXAMPLES IN WHICH PARCEL THEORY IS REASONABLE

Another series of interesting MPC events occurred a week later on the Lake King and Bald Rock fires in the Forrestania complex in Western Australia. Thanks to Brett Beecham for collating photos and e-mail correspondence documenting these plumes. These events provide an opportunity to compare the previous deep MPC events, which have similar temperature traces, with cases in a much moister mid-troposphere environment in which parcel theory is a reasonable assumption. Figure 9 shows the Kalgoolie sounding at 0000 UTC (0800 local time) about 300 km northwest of the fires. Convection was initially relatively shallow, with cloud-top temperature similar to the Feb 2 event (depicted in Fig. 7), but a few hours later episodes of deeper convection developed with similarities to the Feb 1 event (depicted in Fig. 6). However, no lightning was detected throughout. The temperature trace is similar to the Feb 1 event (cf. Fig. 6) with both showing condensation levels near 600 hPa, a mid-troposphere inversion and plumes topping out near 250 hPa. The main difference is the former is very dry above 650 hPa, and the latter is very moist. Consequently, minimal buoyancy losses from entrainment would be expected in the Forrestania fires, which is represented in Fig. 9 by hypothetical moist plume-element paths (red dashed lines) of similar slope to the parcel paths (thin gold lines).

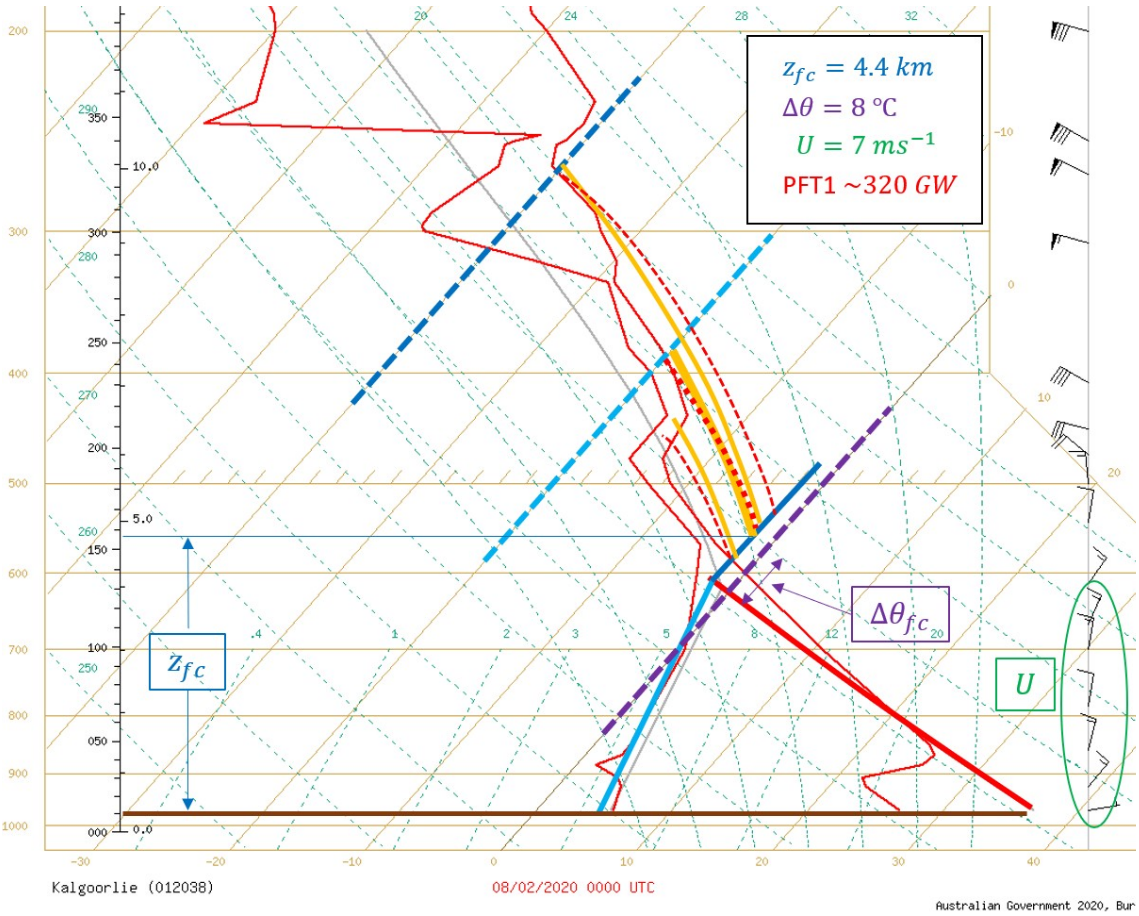


**FIGURE 9:** AS IN FIG. 6 BUT FOR THE KALGOORLIE SOUNDING 0800 LOCAL TIME (0000 UTC). THE TWO RED DASHED LINES REPRESENT HYPOTHETICAL MOIST-PLUME ELEMENT PATHS TAKING INTO ACCOUNT BUOYANCY LOSSES ASSOCIATED WITH ENTRAINMENT, COINCIDENT WITH OBSERVED CLOUD TOP TEMPERATURES AT 0400 UTC (SHALLOW), AND TWO PERIODS OF DEEPER CONVECTION AT ABOUT 0600 AND 0800 UTC (TOPPING OUT AT -40 ℃). THE THIN GOLD LINES INDICATE SIMILAR PARCEL PATHS (ZERO ENTRAINMENT), AND THE THICK GOLD LINE IS A PARCEL PATH USED IN THE PFT.

Consistent with the sounding, the observed cloud base was about 4 km and the early moist convection was seen to rise only a few km before over-shooting tops and an anvil formed (Fig. 10a), presumably when the plume encountered the stable layer near 450 hPa (Fig. 9). Hypothetical entraining and non-entraining plume paths (the shorter red dashed and gold lines respectively) represent this observed MPC in Fig. 9. The first indication of deeper convection was about two hours later about 0600 UTC (Fig. 10b), which was repeated at 0800 UTC with cloud-top temperatures observed at -40 ℃. The longer red dashed and gold lines represent hypothetical entraining and non-entraining plume paths in Fig. 9, corresponding to this deeper convection. More deep convection developed later that evening (cloud-top temperatures about -35 ℃) with the arrival of a wind change.

Accounts and photographs from observers at the fires, combined with the Kalgoorlie sounding, allow some speculation for the absence of lightning.

Although we need to keep in mind that the Kalgoorlie sounding represents the environment 300 km from the fire and 4 – 6 hours earlier than the two deep MPC events.

**FIGURE 10:** MOIST PYRO-CONVECTIVE PLUME ON THE LAKE KING FIRE WESTERN AUSTRALIA, SATURDAY 8 FEBRUARY 2020. (A) 11:46 AM LOCAL TIME (0346 UTC), PHOTO TAKEN FROM A GRANITE OUTCROP AT 32.28° S, 119.66° E, LOOKING SOUTH- SOUTHEAST, AT AN ESTIMATED DISTANCE OF 58 KM FROM THE FIRE. (B) 02:11 PM LOCAL TIME (0611 UTC), SIMILAR LOCATION TO (A). PHOTO: CHRISTINE HARPER, DEPARTMENT OF BIODIVERSITY, CONSERVATION AND ATTRACTIONS.

The earlier convection, likely had cloud-top temperatures similar to the Feb 2 event (-15 ℃, cf. Figs 7 and 9), and not exceeding the general cloud-top temperature threshold of -20 ℃ would have been unlikely to have produced lighting anyway. However, it is worth continuing the comparison to help understand the rare lightning occurrence of the Feb 2 event. An important difference between the two is the condensation level was about 12 ℃ cooler in the Kalgoorlie sounding corresponding to a shallower moist unstable layer and potentially much less CAPE.

The later convection had cloud-top temperatures similar to the Feb 1 event, but the similarities seem to end there. The hypothetical entraining plume path would suggest there should have been considerably more plume buoyancy below and within the electrification layer, i.e., conditions should have been more favourable for lightning formation. Indeed, all the lightning formation boxes for conventional thunderstorms should have been ticked, highlighting that we have much to learn about cloud electrification in smoky plumes.

## COLD CLOUD BASE EXAMPLE

A fire in northeastern NSW (Bees Nest Fire, 6 September 2019) generated MPC with cloud-top temperatures reaching -30 ℃ with no lightning detected. Thanks to Zach Porter and David Wilke for providing the images and soundings, and accounts of the plume behaviour. The sounding taken upwind of the fire (Fig. 11) suggests the cloud base would have been much cooler than the -10 ℃ threshold (green dashed line) considered to be necessary for super-cooled water (Section 4b). Unlike the cases illustrated in Figs 6 and 7, the position of the moist-plume path assuming parcel theory (gold lines) are reversed, with the line corresponding to the observed cloud-top temperature (thin line) considerably more buoyant than that required to satisfy the PFT1 requirement (thick line). A range of possible entraining plume-element paths lie between the two red dashed curves, each incorporating some over-shooting to the -30 ℃ line. Only minimal buoyancy losses due to entrainment have been considered, in recognition of the almost saturated conditions below about 470 hPa, and the reduced capacity for evaporation above about 460 hPa, where the saturation specific humidity deficit is less than 1.5 $g\ kg^{-1}$.

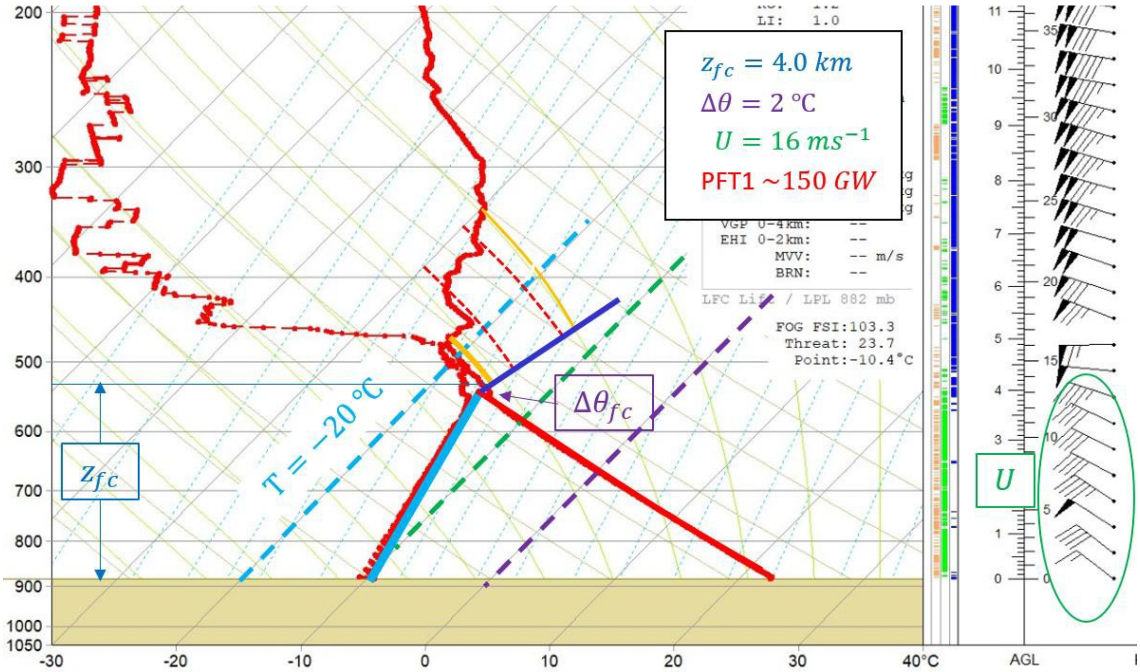


**FIGURE 11:** AS IN FIG. 6 BUT FOR THE BALD KNOB SOUNDING 5 PM LOCAL TIME (0700 UTC), 6 SEPTEMBER 2019. AN ADDITIONAL TEMPERATURE LINE IS INCLUDED AT -10 ℃. THE THICK RED DOTTED LINE HAS BEEN OMITTED BECAUSE IT WOULD BE ALMOST IDENTICAL TO, AND HENCE OBSCURE, THE THICK GOLD LINE.

These potential plume-element paths show very "fat CAPE", and suggest that despite the relatively shallow cumulus layer, the moist plume may have experienced strong vertical accelerations and overshooting, which is perhaps evident in Fig. 12. The overshooting in this example has interesting implications for plume height estimates. It is common to use cloud-top temperatures to infer cloud-top height by using the height of the environment trace where it intersects with the cloud-top temperature line. In Fig. 11, it can be seen this would yield an estimate of about 340 hPa (about 7.5 km), whereas the cooler estimated plume-element path intersects the -30 ℃ line near 380 hPa (about 6.5 km). Indeed, it was reported that smoke plumes were "seen pulsing to 7 – 8 km".

It is important to note that the very cold cloud base is due to uncharacteristically dry air ($qML$~2.5 $g\ kg^{-1}$) rather than especially high temperatures ($\theta ML$~35 ℃). A manual PFT assessment (not shown) of the Wagga sounding on the morning of the Green Valley Fire (on the NSW/Vic border, 30 December 2019), also identified very dry air ($qML$~3 $g\ kg^{-1}$) in a slightly warmer, but typical southern Australian fire-weather environment ($\theta ML$~40 ℃), in which the diagnosed cloud base was cooler than −10 ℃ , and lightning was also not observed.

This finding has implications for dry lightning prediction. It is recognised that dry air and high cloud bases are a signature of dry lightning events, because they tend to produce minimal precipitation that reaches the ground (e.g., Dowdy and Mills 2012). In these environments, less moisture is available for precipitation formation, and the deep, dry layer of air below cloud base has the capacity to evaporate much of the precipitation that does form. Indeed, the 850 hPa dewpoint depression and 850 to 500 hPa temperature lapse evident in Fig. 11, 28 ℃ and 38 ℃ respectively, fall comfortably inside Rorig and Ferguson's (1999) dry lightning thresholds of ≥ 10 ℃ and ≥ 30 ℃, respectively. These thresholds have been confirmed to be appropriate for southeastern Australia (Dowdy and Mills, 2012). However, the above results would suggest that if the air is too dry and warm, the cloud base can be too cold for cloud electrification to occur.

A consequence of the cold cloud base is the very shallow layer between the SP curve and the −20 ℃ threshold cloud-top temperature used in PFT1. The corresponding minimum buoyancy parcel path in Fig. 11 (thick gold line) is very shallow and very close to the environment temperature trace implying very minimal CAPE. In reality, plume-elements on this parcel path, might produce only puffs of shallow cumulus, with minimal feedback on the smoke plume below and even less feedback on the surface winds in the vicinity of the fire. It may be that in the future we require a suitable minimum threshold to ensure the PFT represents convection with sufficient vigour to be dangerous (e.g., a parcel path similar to the red dashed lines).

## PFT FLAG "MISSED" EVENT

In the early hours of Saturday 21 December (about 2 AM Local Time) the Martha Vale fire near Swifts Creek produced a "spectacular pyroconvective event" that produced lightning with a central core of cold cloud-top temperatures surrounded by a very large low-level smoke shield. Thanks to Musa Kilinc for information and images on this event. Forecast model PFT1 values in the vicinity at this time were about 250 GW, but due to milder nocturnal conditions (cooler, moister and lighter winds) predicted by the ACCESS models, the fire-danger conditions were not high enough to trigger the PFT1 flag. Kevin Parkyn and Musa Kilinc, who were working in the State Control Centre at the time, noted that the model near-surface conditions under-represented the fire danger (a common occurrence), and used model temperature, humidity and wind speeds derived from higher elevations (1500—3000 m) to better represent the true fire danger. We expect these more elevated values would have triggered the PFT1 flag.

Kevin and Musa estimated the cloud top height to be about 11 km at 2 AM, with lightning observed downwind. Earlier, between 7 and 11 PM, Musa estimated the fire power to be around 100 GW, during which time pyrocumulus was observed with cloud-top heights of about 8 km. Escalation of the fire was evident in the 11 PM linescan (Fig. 13). Between 11 PM and 2:30 AM, rough firepower estimates of up to 1000 GW were made, four times the minimum required for FGT formation, according to PFT1 forecasts. This demonstrates that while the PFT1 flag failed in this event, PFT1 was successful. Furthermore, while we expect an under-representation of fire danger conditions by the model was responsible for the PFT1 flag failing in this event, we note that nocturnal events fall outside the parameter space PFT1 flag was designed and tested in[11].

[11] An adaptation to the PFT flag is currently being considered that should address the nocturnal "miss" issue.

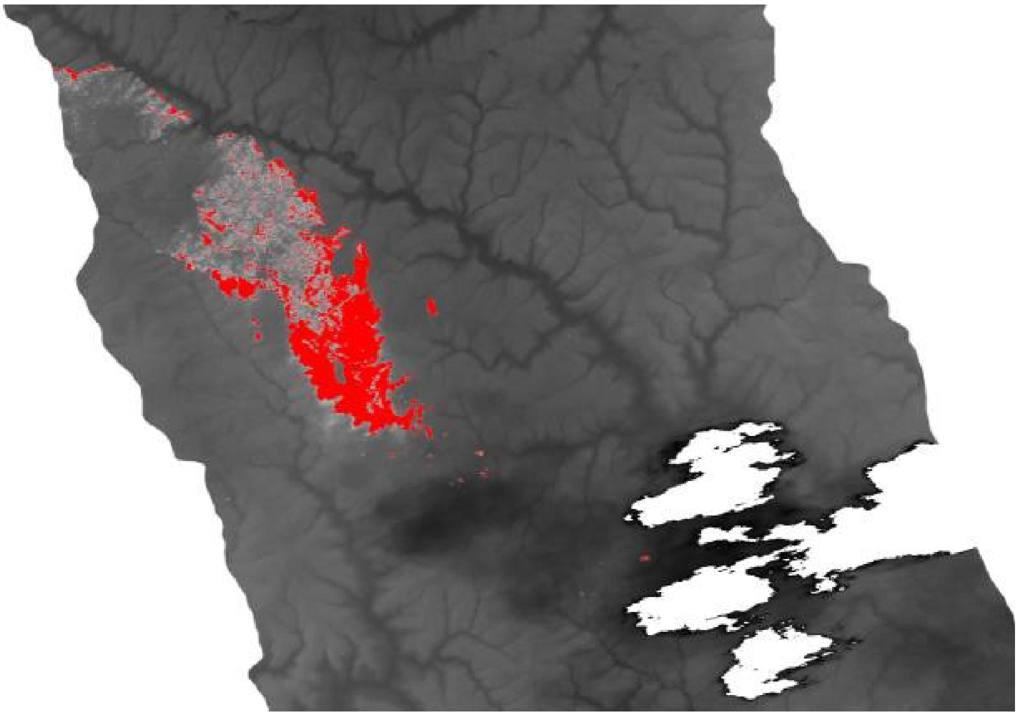

**FIGURE 13:** LINESCAN, 11 PM LOCAL TIME (1200 UTC) INDICATING DEEP FLAMING EXTENDING ABOUT 5 KM DOWNWIND (WINDS FROM THE NORTH-NORTHWEST), AND A FEW KM IN WIDTH, WITH EVIDENCE OF SPOT FIRES MORE THAN 5 KM DOWNWIND. COURTESY MUSA KILINC, COUNTRY FIRE AUTHORITY, VICTORIA.

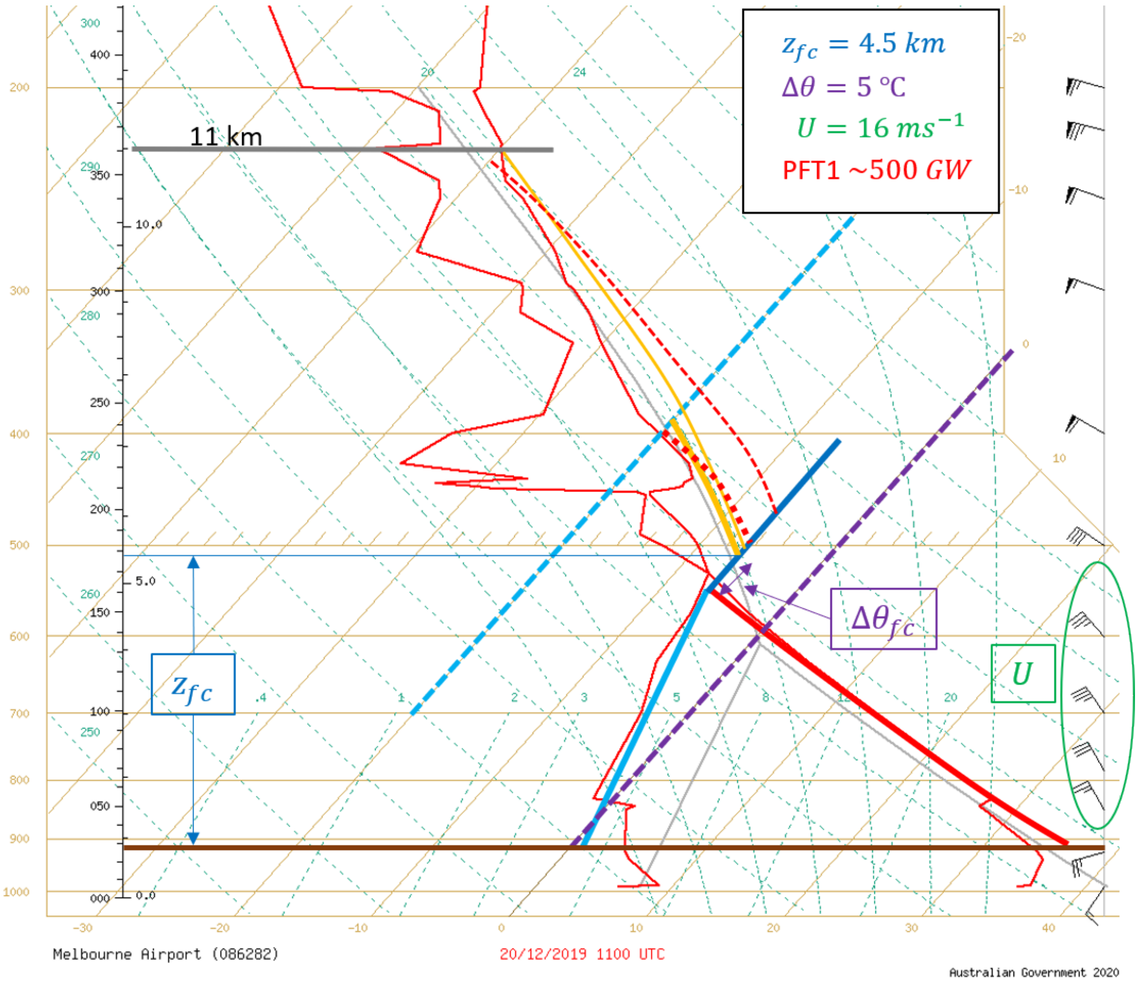


**FIGURE 14:** AS IN FIG. 6 BUT FOR THE MELBOURNE AIRPORT SOUNDING, 10 PM LOCAL TIME (1100 UTC) 20 DECEMBER 2019, ABOUT 230 KM WEST OF THE MARTHAVALE FIRE. ESTIMATED CLOUD TOP HEIGHTS AT 1500 UTC INDICATED BY THE GREY LINE.

Figure 14 shows the Melbourne Airport sounding at 10 PM, about 230 km west of the Marthavale fire and about four hours prior to the most active pyroconvection. A visual estimate of the main PFT1 ingredients from the sounding, compared with the model forecast PFT ingredients at Marthavale (not shown) suggest the sounding likely represents the actual above-surface Marthavale environment reasonably well. The sounding suggests condensation would occur at about 4.5 km (above ground level) with a moderate Delta theta of about 5 K, and strong mixed-layer winds estimated at 16 m/s, yielding a PFT estimate of about 500 GW, suggesting conditions are generally unfavourable for deep MPC. Indeed, the model forecast PFT1 was more than 500 GW at midnight, gradually dropping below 300 GW by 2 AM (when the deepest convection was observed) and continued dropping to below 250 GW. The hypothetical plume-element parcel trace depicted in the thin red dashed line was constructed after taking into account Musa's firepower estimates that are double the estimated PFT1 (calculated from Fig. 14), and observations of 11 km cloud-top height. Only minimal buoyancy losses due to entrainment have been incorporated below 450 hPa, since the air was reasonably moist there. This hypothetical plume-element path suggests substantial fire-CAPE would have been present in the charge-separation region. Furthermore, although the associated cloud base is quite elevated (about 6 km above sea level), it would still be 3 or 4 ℃ warmer than the -10 ℃ threshold for sufficient super-cooled water.

## PFT "MISSED" EVENT

Another case of nocturnal FGT that the PFT1 flag missed was the Cann River fire that eventually burned through the town of Mallacoota. Thanks to Musa Kilinc for images and event descriptions. Unlike the previous example, the following analysis suggests the PFT1 assessment very likely underestimated the potential for FGT and deep MPC in general. In the very early hours of 30 December the fire had burned all the way to the coast, west of Mallacoota, and the two flanks were expanding slowly to the east and west. As in the previous example, the PFT1 flag identified benign fire danger conditions, and PFT1 suggested 100 to 200 GW would be required for deep MPC, much more than would be expected from the large, but essentially smouldering fire (although no firepower estimates are available for confirmation). Infrared satellite imagery with lightning data overlaid, shows a substantial active FGT at 4:30 AM (Fig. 15) with an extensive cold shield representing a broad anvil, with very cold cloud-top temperatures embedded, and abundant lightning. This FGT persisted for hours overnight. We postulate that the event was caused by a perfect mix of conditions in which favourable burning conditions dominated the fire ground (maximising firepower), while favourable plume formation conditions were drawn into the lower portion of the plume from over the sea. We propose that hot dry and windy conditions fanned the expansive smouldering region (Fig. 15, inside the magenta lines), adding non-trivial firepower to the plume in addition to that coming from flaming on the flanks. Meanwhile, inflow of cool, moist maritime air contributed to a convergence line over the fire ground (enhancing the plume vertical motion) and entrainment of this air dramatically reduced the condensation height. PFT1 calculated in this maritime air would also have been much reduced. Based on our experience of PFT1 gradients on wind changes, we suspect the maritime PFT1 could be 5—10 times smaller than the land values appearing in the PFT1 forecasts.

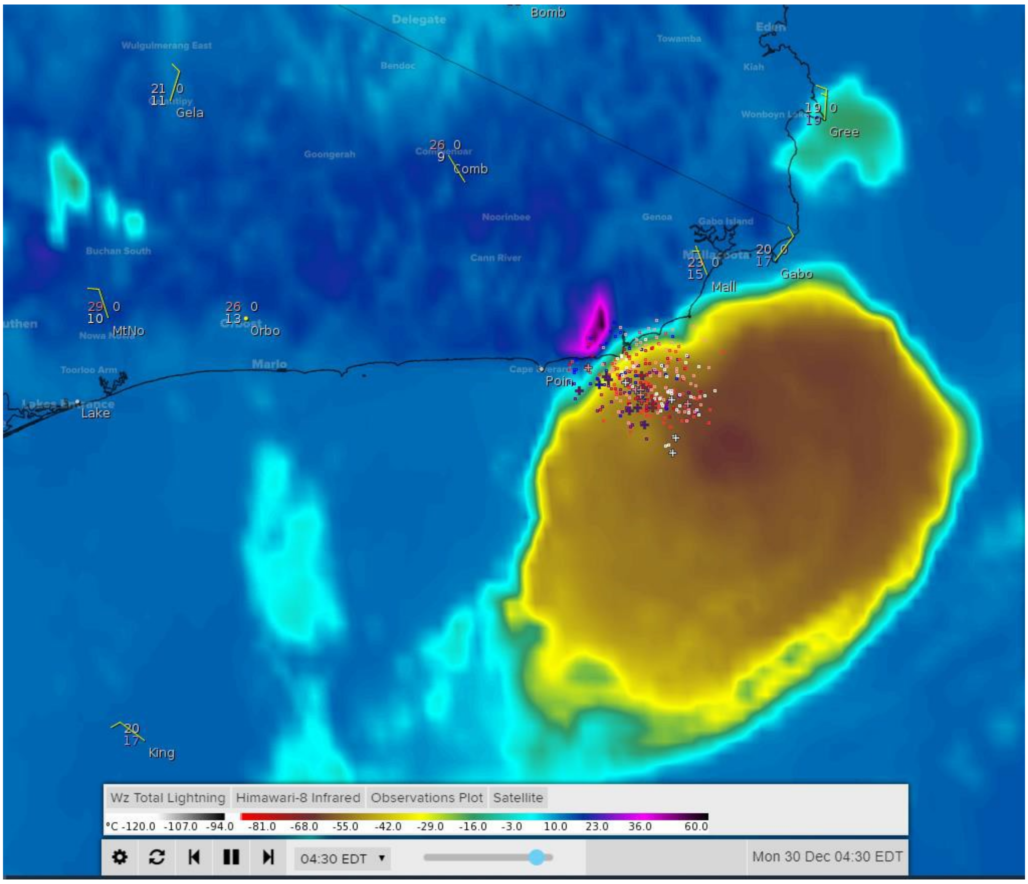


**FIGURE 15:** HIMAWARI-8 INFRARED IMAGERY AT 4:30 AM LOCAL TIME (17:30 UTC) WITH LIGHTNING DATA OVERLAID SHOWING THE FGT CLOUD INITIATED BY THE CANN RIVER FIRE. A SUBSTANTIAL AREA OF SMOULDERING IS EVIDENT WITHIN THE ENCLOSED MAGENTA SHAPE. IMAGE COURTESY OF ANDY ACKLAND, COUNTRY FIRE AUTHORITY, VICTORIA.

If the above hypothesis is correct, then we potentially have an example of plume-enhanced winds dramatically impacting the PFT, but presumably only because there was a large, near-stationary PFT gradient near the coastal interface. Presumably, this could also occur with translating PFT gradients, such as on a wind change, but it might not be noticed if enhanced inflow essentially advances the wind change by a few minutes. Furthermore, PFT1 gradients are usually obvious on PFT1 forecast plots, informing users of the potential for a sudden change in MPC behaviour.

This event raises the question of whether the PFT should be calculated some distance offshore, to give an indication of the land-sea PFT gradient, for times when large fires are burning in coastal areas. The decision to not calculate PFT1 over sea grid points was based purely on reducing computation time, which has unwittingly introduced an unknown PFT1 gradient on all coastlines.

# 6 CLIMATE IMPLICATIONS

There has been a dramatic increase in FGT observations (and MPC more generally) in recent years in Australia and globally. While changes in observing tools and techniques will explain a small part of this increase, it is likely that changes in climate have produced unprecedented burning conditions, through increased temperature and lower relative humidity (e.g., Dowdy 2018), and may also have contributed to atmospheric changes that favour MPC in some parts of southern Australia (Dowdy and Pepler 2018, Dowdy et al. 2019, Di Virgilio et al. 2019). Di Virgilio et al. (2019) found that the proportion of large and intense fires that produce FGT increases for elevated levels of both the C-Haines and the MacArthur Forest Fire Danger Indices (FFDI). Furthermore, this combination of elevated index values has been occurring more frequently over recent decades in southeastern Australia, and will likely continue to increase (Dowdy and Pepler 2018, Dowdy et al. 2019). The elevated C-Haines and FFDI index combination represent a less specific measure of FGT favourability than the PFT1 products, since they represent peak afternoon values over a relatively broad region, and they incorporate fewer atmospheric properties relevant to plume development than the PFT1 products. It follows that the application of PFT1 products to reanalysis and climate model data should complement these existing studies, and will have the potential to explore more deeply possible causes for the recent observed increase in deep MPC and FGT frequency. The application will be more challenging due to the much higher spatial and temporal variability of the PFT1 products. Furthermore, due to the more comprehensive representation of plume dynamics implicit in PFT1, it will be important to decide which MPC types are to be investigated prior to undertaking the study. For example, if a specific focus on FGT lightning is desired, then including cloud-base temperature thresholds, minimal fire-CAPE thresholds and plume buoyancy loss from entrainment would be important.

Furthermore, we need to have confidence that a tool such as the PFT1 flag, is as reliable as possible in identifying a specific set of atmospheric conditions that support the chosen MPC formation. Optimisation of a metric may change when shifting from forecast mode to climate mode. In the latter there is a higher tolerance for false alarms than misses, whereas in the former balancing false alarms and misses produces a better climatology. In climate mode the product needs to be almost completely objective, since no value-adding from expert forecasters is available to exclude obvious non-events. This climatological need, as well as a general desire to improve the forecast product, is guiding plans for the future development of PFT forecast products.

Identifying false-positives for the PFT1 flag is difficult because there is a suite of implied assumptions necessarily built into a tool that is a function of atmospheric variables only. These include the presence of abundant dry fuels, ignitions and the opportunity for fires to become very large. The development so far, may have also built-in as yet unknown assumptions, via features that are common to most of the events investigated (e.g., complex terrain and similar fuel types). For this reason, it is important to continue investigating cases and for refining the PFT products for known influences on fire and plume behaviour. Insights from the real-time trial identified two potential areas for development that will benefit both climatological studies and pyroCb forecasting. The first, addressed earlier, takes into consideration the environment above the plume condensation level – in particular how entrainment of air into the moist plume weakens the plume buoyancy. The second is to introduce limits to the fuel moisture equation used in the PFT1 flag to minimise false-positives during cold outbreaks. Feedback from forecasters suggested maintaining the relatively broad focus on deep MPC, rather than refining the PFT1 products to specifically target FGT, is desirable since it provides a more general indication of potential MPC threat.

# 7 PFT DEVELOPMENTS UNDERWAY

In order to prepare a version of the PFT for climate applications, the Earth System and Climate Change Hub of the Australian Government's National Environmental Science Programme supported a study to better represent buoyancy losses to entrainment in the moist plume, and to minimise triggering of the PFT1-flag during cold-outbreaks. When implemented, this new version of the PFT (hereafter PFT2) will be available for application to reanalysis and climate model data, and will better represent the threat of deep MPC in forecast mode.

## INCORPORATING BUOYANCY LOSSES DUE TO ENTRAINMENT INTO THE MOIST PLUME

A simple model for plume entrainment and its impact on plume buoyancy was designed to be incorporated into the existing PFT1 framework. A single parameter determines the mass of entrained air (from the environment into the moist plume) specified as a fraction of plume mass per km of plume ascent. In each model layer (or layer between data levels if using real sounding data) the plume air and entrained air are assumed to be well mixed, and the plume temperature is adjusted after taking into account evaporation (or condensation if the environment is very moist). Closure is achieved by assuming the plume remains saturated after mixing, which implies there is always sufficient cloud moisture to be evaporated to bring the plume to saturation.

Like PFT1, a minimum plume-top height determined from a cloud-top temperature threshold is required, and the plume element path is required to be buoyant everywhere between the SP curve and the minimum cloud top level. The difference between the two PFTs is most evident in the difference in plume-element paths depicted in the various thermodynamic diagrams presented in this document (Figs 6, 7, 9, 11 and 14). The parcel theory paths of PFT1 (thick gold curved lines) are replaced by paths adjusted for entrainment (thick red dotted lines), which generally leads to increased values of $\Delta\theta fc$ and $zfc$. It follows that PFT2 values will be larger than PFT1, although the opportunity to retune or rescale remains. In most of the cases shown in this report the difference will be small to moderate, but some could be relatively large (e.g. Fig. 7).

The procedure for calculating the entraining plume path is as follows. Beginning at the minimum cloud-top position on the environment temperature trace (-20 °C in Figs. 6, 7, 9, 11 and 14), the hypothetical plume-element path is reconstructed in reverse (i.e., descending), with temperature added on each level to represent temperature losses from entrainment in the layer immediately below. Where this parcel path intersects the SP curve, the free-convection height, $zfc$, and plume potential temperature increment, $\Delta\theta fc$, are calculated, in the same manner as in PFT1.

## REDUCING PFT1-FLAG TRIGGERING DURING COLD OUTBREAKS

It became apparent during the trial that the PFT1 flag was being triggered in cold, wet and even snowy outbreaks in green vegetation. While this did not bother forecasters, for whom it was obvious where the flag could be dismissed, it has the potential to undermine results when applied to reanalysis or climate model data, wherein no expert subjective assessments could be made. Mindful that intense fires can burn in very cold conditions (e.g., the mid-winter Norwegian forest fires in January 2014, Gabbert 2014), it was decided that any adjustments to the flag should not be heavily temperature dependent. Also, in the interests of maximising portability and ease of use, on other platforms and models, there was a strong desire to limit the ingredients to common variables, available in all atmospheric forecast and climate models and reanalysis data, at a single time step. We wanted to avoid the need to calculate quantities integrated over time, such as drought indices, which would greatly increase the processing complexity, and quantities such as soil moisture deficit, which can be highly specific to individual models.

An example of a problematic PFT1 flag triggered during a cold-air outbreak is illustrated in the left panel of Fig. 16, corresponding to the Bees Nest fire (Section 5c). Two distinct patches of PFT1 flag are evident. The patch to the north east successfully flagged the Bees Nest deep MPC. The other patch is associated with the cold outbreak. Some masking is evident to the south of this patch where the vegetation was green and the air particularly cold and moist (e.g., in southwestern Victoria), due largely to high values of relative humidity. However, at the time green vegetation extended further north throughout most of western Victoria and across the border into South Australia, with very dry conditions in NSW to the north (not shown). Thus, south of about 34° S in Fig. 16, intense wild fires capable of generating deep MPC, would be extremely unlikely, if not impossible. It was important that any adjusted PFT flag did not mask out regions further north where the vegetation was known to be very dry.

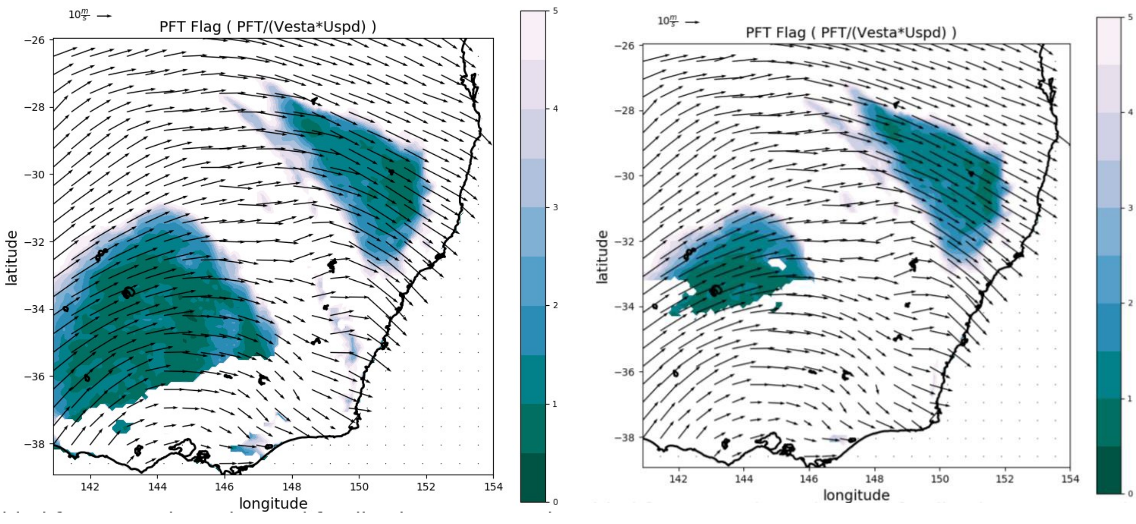


**FIGURE 16:** PFT1 FLAG 6-HOUR FORECASTS AT 5 PM LOCAL TIME (0600 UTC) 6 SEPTEMBER 2019, CORRESPONDING TO THE BEES NEST FIRE DISCUSSED IN SECTION 5C. LEFT PANEL IS THE ORIGINAL PFT1 FLAG AND THE RIGHT PANEL HAS AREAS MASKED OUT WHERE THE FUEL MOISTURE IS GREATER THAN 10 %.

Extensive testing of a variety of parameters designed to mask out the PFT1 flag during cold out-breaks was performed. These included near-surface relative humidity and temperature, plus thresholds of the Vesta function itself (used in the PFT1 flag) with minimal success. Testing of various combinations of soil moisture (at three model depths) was also attempted, despite it breaching the desired specification to use only atmospheric variables, again with no success. Finally, perhaps the most obvious quantity to test in hindsight, the fuel-moisture equation calculated within the Vesta function (used in the PFT1 flag) was tried. This fuel-moisture equation is a function of near-surface temperature and relative humidity. Fig. 16 shows how applying a > 10 % fuel moisture mask (right panel) has dramatically reduced the size of the cold-outbreak flagged area (cf. the original PFT1 flag in the left panel), leaving only a flagged region in the known dry area.

# 8 SUMMARY

A suite of PFT1 forecast tools that were designed to aid in the prediction of pyrocumulonimbus (pyroCb), were tested in a real-time trial over the 2019/2020 southern Australian fire season. The trial highlighted a number of important issues, including the need to review not only the pyroCb definition, but the phenomena we wish to predict. The term pyroCb had subtle but important differences in meaning and understanding for different users, and there is a lack of clarity and understanding when moist pyro-convection becomes dangerous. While this issue has been raised in the past, the confusion persists, suggesting there is a need for a broader discussion of the issue. In an attempt to avoid adding to the confusion, an overly general term, moist pyro-convection (MPC), was introduced to cover all possible phenomena in which fires generate or initiate cloud formation, with a slightly more specific term, 'deep MPC' introduced to indicate towering cumulus with the potential to produce on-ground hazards (in addition to regular fire hazards). These are illustrated in Fig. 4 with additional sub-classes depicted to illustrate how the various types of MPC discussed in the report relate to one another.

Having a clear understanding of the phenomena we wish to identify is also important if PFT products are to be used for climate research to study how changes in atmospheric variables might influence the frequency of a particular type of MPC.

The pyroCb definition uncertainty coupled with the uncertainty of when deep MPC become dangerous, introduced confusion in the forecast procedure. With lightning perhaps the only definitive indicator to verify when MPC have become potentially dangerous, a tendency to focus on lightning producing fire-generated thunderstorms (FGT) evolved over the season. While lightning indicates intense-plume updrafts have developed with a high likelihood of hazards, not all hazardous MPC produce lightning.

Despite the uncertainties and the FGT lightning focus, and the many challenges faced by FWFs and FBAns, forecasting of deep MPC in general was very successful, and the PFT1 products performed very well with few events missed. The dramatic increase in numbers of potentially dangerous MPC in recent years, from rare to frequent, meant FWFs and FBAns have had less experience working with deep MPC than other more common weather and fire phenomena, and have limited tools and less-well established procedures at hand. The combination of unprecedented numbers of events requiring unprecedented numbers of forecasts in a very high-pressure environment with limited guidance, contributed to prediction methods and processes that varied from state to state, and between individuals in the same office. Testing new products such as the PFT1 forecast suite in this environment was perhaps not ideal, especially since it was not clear how to verify its performance. Additionally, because there were no other tools of this type available, the balance between using and monitoring was tipped more on the usage side than we anticipated. Furthermore, individual usage and interpretation varied among FWFs and FBAns contributing to subjectivity and variability in messaging. The relative frequency of events in each jurisdiction also had an impact on how PFT1 products were used and the value they provided to the forecast process. In NSW, the progression of intense fires from the north to the south over a six-month period, provided a good opportunity for FWFs in particular, to test and learn how to use the PFT1 to full advantage, whereas FWFs in less-active states, such as SA and Tasmania, did not get this opportunity.

The FGT lightning focus may have proved a distraction for some FWFs, as considerable effort was employed to try and predict lightning with few tools at hand, and an uncertainty whether conventional thunderstorm tools and knowledge was valid for FGT (e.g., if the cloud electrification process is greatly affected by smoke). This was confounded by enigmatic behaviour when very deep MPC on one day failed to produce lightning and very shallow MPC the next day produced abundant lightning. In examining this behaviour, it became apparent that parcel theory, used to represent moist plume-rise, could not explain observed cloud-top temperatures, and using parcel theory in PFT1 would bias PFT1 towards over-prediction when the middle troposphere was dry and/or relatively stable. It also became clear that a general lightning-prediction rule-of-thumb, cloud-top temperatures < -20 ℃, was not a good predictor of lightning in MPC, although it was a good indicator of deep MPC. A cloud-top temperature threshold of -40 ℃ was a more reliable indicator of FGT.

Case studies presented in Section 5 were used to illustrate the limitations of parcel theory, and the apparent inconsistencies in lightning formation in deep MPC. They showed that reliance on cloud-top temperature alone was problematic, and that it may be necessary to consider minimum cloud-base temperatures (to ensure the presence of sufficient super-cooled water), and minimum plume buoyancy (to accelerate the plume updraft to charge-separation speeds). Other cases showed that even with all these ingredients, lightning did not form, suggesting we still have much to learn about cloud electrification in MPC.

Two "missed" events were also presented in Section 5. In the first, an intense nocturnal FGT on the Marthavale fire, PFT1 was successful but the PFT1 flag was not triggered. During the hours leading up to and following the FGT, firepower estimates in real time suggested a large increase in activity from 100 to 1000 GW, during which time PFT1 dropped from about 500 to 250 GW, indicating a cross-over from very much less to very much more firepower required for deep MPC formation around the time the FGT developed. Model-predicted near-surface conditions were too cool, moist and calm for the PFT1 flag to be triggered. Actual near-surface conditions were much warmer, drier and windier.

The second missed event also occurred over night when model-predicted near-surface conditions were probably too mild. However, in this case it seems possible that either the plume dynamics caused a local onshore flow reversal, or the model failed to predict onshore flow, which would have entrained cooler and moister maritime air into the plume. Also, if combined with a semi-stationary convergence line between the terrestrial and maritime airmasses, the plume lift may have amplified. Together, a lowered plume condensation level and increased plume-rise height may have been expected, suggesting the actual PFT1 may have been an order of magnitude smaller (i.e., conditions much more favourable than the model predicted).

The dramatic increase in observed FGT and deep MPC in general in southern Australia and globally, particularly in the last two years is likely to be associated with warming and drying of forests contributing to very high fuel loads and more frequent extreme fire conditions. It is also possible that atmospheric conditions have become more favourable. If PFT tools that are purely functions of atmospheric variables can be demonstrated to be good predictors of deep MPC events, then they can be applied to reanalysis data dating back a few decades to see if a significant atmospheric change can be identified, and can also be applied to climate models to assess possible future changes. For climate applications PFT products need to be more objective than for forecast applications (e.g., forecasters can easily dismiss obvious non-events), and it is also desirable to reduce false alarms to best represent the true climatology of deep MPC. To this end, support from a National Environmental Science Programme project, contributed to the development of methodologies to largely eliminate false alarms from cold-air outbreaks, and to incorporate the negative impacts of entrainment on moist-plume buoyancy.

In preparing this report, a number of areas for future investigation have been identified.

- An improved understanding of MPC generally, plus their hazards (how, where and when they form) and concrete understanding of what it is we wish to predict.
- Further development of MPC forecast procedures and tools.
- Further development of the PFT for climate applications.

Specific lessons learned when using PFT1 include:

- The -20 ℃ plume-top assumption is a good indicator for deep MPC, but not FGT specifically.
- Parcel theory used for moist plume-rise will over-predict deep MPC conditions when the middle troposphere is dry and/or relatively stable.
- Incorporating moist-plume entrainment in a future PFT will address the above point.
- To predict FGT lightning specifically would require a greater focus on cloud electrification processes, and will require a better understanding of cloud electrification in smoky plumes.
- High spatial and temporal resolution forecasts of PFT products are often needed to identify deep MPC threat, when favourable conditions are tied to relatively small-scale transient features such as wind change lines.
- The PFT1 flag, which is a function of near-surface atmospheric variables, is susceptible to common nocturnal forecast model biases in these variables, leading to the under-prediction of fire-danger severity and the potential for deep MPC development.
- Offshore PFT values may need to be considered for fires burning very close to the coast, when a coastal PFT gradient is present separating warm and dry terrestrial air from cool and moist maritime air.

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