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# IMPROVED PREDICTIONS OF SEVERE WEATHER TO REDUCE COMMUNITY IMPACT

## Annual report 2018 – 2019


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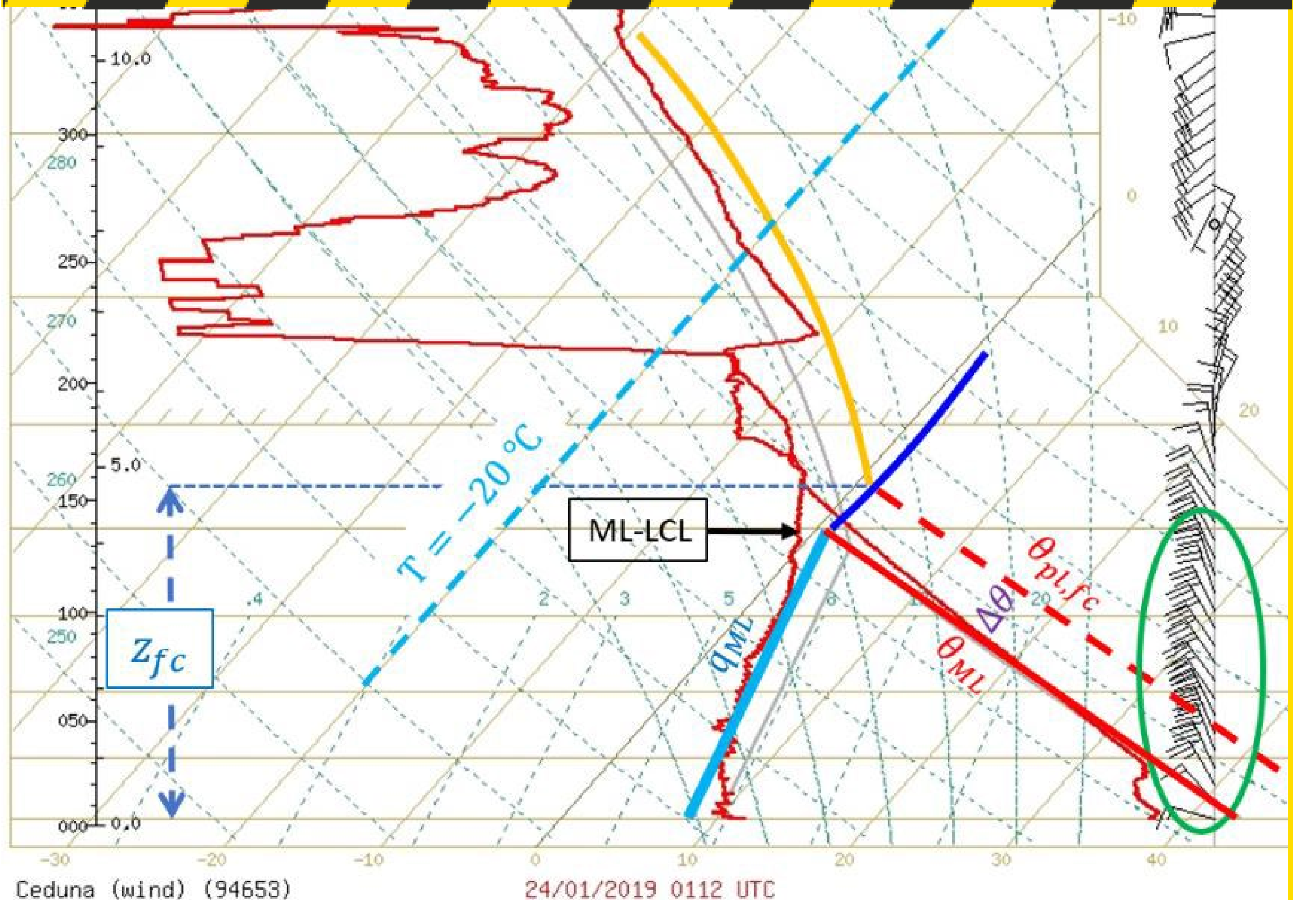
Bureau of Metereology & Bushfire and Natural Hazards CRC

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Cover: A sample atmospheric sounding (thin red lines and wind barbs) applied to an F-160 thermodynamic diagram, with quantities required for the PFT calculation overlaid

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# ACKNOWLEDGMENTS

We acknowledge the helpful feedback from our end users on the practical implications of what we do, and for guidance on the direction of the project. We thank our colleagues in Earth System Modelling at the Bureau for their work in maintaining the ACCESS system, and advice on using it well. We are also grateful to our colleagues in the Bureau's operational wing, particularly those based in Sydney and Adelaide, for helpful discussions on our case studies of severe weather events.

# EXECUTIVE SUMMARY

The project has completed the second year of its refresh and is progressing with some challenges. The first 3½ years featured a strong focus on developing underpinning science in some important areas, notably the transport of embers by bushfire plumes, and understanding the origin of the moisture when pyrocumulus clouds form – is it from the atmosphere, or from the fuel? We also conducted significant case studies, including an ensemble-based study of a severe east coast low, an analysis of the meteorology of the State Mine Fire of October 2013, and a study into tropical cyclone secondary eyewall formation.

This second phase of the project pivots towards utilisation. We will not neglect investigations into the underpinning science, or case studies, but we are looking to turn our previous discoveries and knowledge gained into useful products.

The first of these is a new thermodynamic tool for predicting the potential for pyrocumulonimbus (pyroCb) formation, the Pyrocumulonimbus Firepower Threshold, or PFT. This parameter depends on the atmospheric state, both the wind strength within the boundary layer and the full thermodynamic profile and aims to predict the minimum fire power (in GW) that is necessary to trigger deep convection. In favourable conditions, a fire of a few GW suffices, and at unfavourable times, 1000 GW would be insufficient. We have found that there is substantial variability in the atmospheric favourability in time and space, and that observed pyroCb often form during a narrow window of opportunity. We are presently preparing for a major utilisation exercise, a near-real time trial of the tool over the coming summer. We expect that the results from this trial will help to finalise the development of the tool, and ready it for operations.

Our case study of the tornado outbreak in South Australia that triggered events which cut power to the entire state showed that the tornado cluster was predictable by modern high-resolution numerical weather prediction (NWP) – indeed, the deterministic model predicted the precise location of one of the observed tornadoes. Encouraged by this success, we ran a 6-member ensemble simulation of the event, which showed that while the probability of tornadoes was well over 50%, the level and location of the activity was less certain. To assist with analysis of this event, we also developed a novel diagnostic of tornadic precursors in NWP systems. A journal article is almost ready for submission on this work.

A second case study is analysing the Tathra bushfire on the south coast of New South Wales, which led to the destruction of over 60 houses. Although occurring in strong northwesterly winds in the lee of the ranges, mountain wave activity appears to have been modest at the time of the greatest fire activity and probably not the major cause of the disaster. Rather, the extreme fire behavior appears to have been driven by strong, very unsteady and fluctuating winds, caused by roll-like circulations in the flow off the ranges, with the interaction between this flow and a later wind change also of interest. The weak role of mountain waves in this event illustrates the value of performing detailed case studies, as at first glance, several of the ingredients for a mountain wave event were present, and indeed active earlier in the day.

Unfortunately, our development of a parameterisation of long-range ember transport has made little progress this year, due to the unanticipated difficulty of the task and the illness of a staff member. We plan to resume work on that shortly.

In recognition of the delays on the ember transport parameterisation, and also of new opportunities that have arisen in pyrocumulus prediction, we have negotiated an altered project schedule with the BNHCRC.

# END-USER PROJECT IMPACT STATEMENT

**Paul Fox-Hughes**, *Bureau of Meteorology, Tasmania*

The project continues to do good science that has the dual benefits of providing insights into the behaviour of the atmosphere and having the potential for application in the protection of people and property. The PFT and PFT-flag, in particular, show great promise for utilisation and its very encouraging that trials have been planned, and I understand have already occurred, this southern Australian fire season. Equally, the cases studies of the South Australian severe thunderstorm and Tathra bushfire have both demonstrated the value of high-resolution, detailed case studies in understanding particular events, and generalising that understanding to other circumstances. With the recent introduction of NWP ensembles into operations at the Bureau, it is especially valuable to start to gain an appreciation of their potential use for forecasting the weather and its impacts. Its entirely understandable that little progress has been made in the last year on ember transport parametrisation, but the potential value of this work is very considerable and I'm sure the project team will make good progress during the coming year.

# INTRODUCTION

This project aims to study the dynamics, predictability and processes of severe weather, including fire weather. We seek also to improve forecasts of severe weather, and to better depict forecast uncertainty in these events, thereby facilitating better risk management and more cost-effective mitigation. Our studies span a range of time and space scales and require a range of different methods.

Extreme weather often occurs at relatively small scales – here, the devil really is in the detail. Even when the meteorology driving the event is not small scale, small-scale perturbations within the broader pattern can have a significant effect. Accurate forecasts and understanding of such small-scale processes requires high-resolution modelling. Developing and validating such modelling, and extending it to all hazards, is the first aim of this project.

Forecasts are seldom perfect, but they are nevertheless useful. Forecasts are especially useful in severe weather events, since they play an essential role in allowing communities, industry and emergency services to prepare and mitigate the impacts. Forecasting therefore underpins the work of emergency services and related agencies, and makes the PPRR (Prevention, Preparedness, Response and Recovery) process more efficient and effective. Because forecasts are inherently uncertain in the severity, location and duration of an event, preparation needs to be more widespread than the eventual impact – but this over-preparation comes at a cost. Detailed prediction of the probabilities of severe impacts would avoid the risk of failing to alert areas with the chance of an impact, while minimising the cost of over-warning. Thus the second aim of this project was to provide pilot predictions of not just the most likely course of events, but also the level of uncertainty, by identifying plausible alternative scenarios and their likelihoods.

A key aim of this project is to develop scientific understanding and to assist with the “lessons learned” from severe events. Our research thus adds to the collective wisdom of fire fighters, emergency services personnel and weather forecasters, improving our ability to manage these events and reducing the risk of adverse outcomes in the future.

# BACKGROUND

The principal numerical weather prediction (NWP) modelling system used in this project is ACCESS, the Australian Community Climate and Earth-System Simulator. ACCESS is used operationally within the Bureau of Meteorology and is based on the UK Met Office's NWP system. Several other overseas national weather services similarly use this system. ACCESS therefore benefits from a wide user base, and the discipline of operational use and continual verification. Our analyses of the East Coast Low of April 2015, which caused severe flooding and several deaths in the Hunter Valley and Dungog region, and of the South Australian tornado outbreak, have used ACCESS in very high resolution ensemble mode. The results of analysing these pairs of ensemble simulations has shed new light on the dynamics and predictability of these systems, are the subject of published papers, and have been presented in several venues including as an invited speech at the Australian Academy of Sciences.

For situations where extremely high-resolution modelling with a grid spacing of tens of metres, and the capacity to explicitly resolve atmospheric turbulence is needed, we use the UK Met Office's Large-Eddy Model (LEM). This specialised model is designed not for forecasting, but rather for understanding phenomena that are highly sensitive to turbulence, including boundary layers, fire plumes and convective clouds. We have previously used this model for ember transport, finding that the spread in landing position is greatly increased by the turbulence in the plume, and the maximum spotting distance can be more than double the mean for this reason. We are now using these sophisticated and computationally intensive ember transport calculations to inform the development of a physically realistic and computationally cheap parameterisation of ember transport for use in fire models. This parameterisation will require negligible computer time to run and will predict the landing distribution of embers from a plume, providing a physically realistic prediction of the potential for spotfire development.

We have completed a novel and groundbreaking study into the thermodynamics of pyrocumulus and pyrocumulonimbus, resulting in a deeper understanding of the underpinning processes. This work was inspired by, and confirmed, our previous large-eddy simulation results on pyrocumulus. We have now taken this work to the next stage by using the knowledge gained to develop a forecast tool for pyrocumulonimbus (pyroCb) formation. This tool is showing very positive verification results on pyroCb events around the world, and we are looking forward to testing it in a near-real time trial over the coming summer.

# RESEARCH APPROACH

The four subsections within this section discuss our progress on four major study areas within the overall project.

## PYROCUMULUS PREDICTION

In the last 12 months a very preliminary pyroCb prediction tool has been developed into a Version 1.0 tool, ready for a season of real-time trials. It was tested on more than 30 events, including both pyroCb and non-pyroCb producing fires. These tests identified substantial variation in pyroCb threat from day to day. They also identified that conditions highly favourable for pyroCb formation do not favour wildfires and vice-versa. Consequently, a method to combine the potential for intense fire development with the potential for pyroCb formation was identified to be necessary for pyroCb prediction. This report reviews the development of the original pyroCb prediction tool (the Pyrocumulonimbus Fire Power Threshold, PFT) and documents the development of the combined PFT and fire potential diagnostic, termed the PFT-flag.

### Introduction

In favourable atmospheric conditions, suitably large and hot fires can produce pyroCb cloud in the form of deep convective columns with many similarities to conventional thunderstorms. They may be accompanied by strong inflow, dangerous downbursts and lightning strikes, which may enhance fire spread rates and fire intensity, cause sudden changes in fire spread direction, and the lightning may ignite additional fires. Dangerous pyroCb conditions are not well understood and can be very difficult to forecast.

In recent BNHCRC research, a method for determining how favourable the atmospheric environment is for pyroCb development was developed. This method is combined with a plume-rise model (originally developed for pollutant dispersion prediction) to determine how much heat a fire must produce for pyroCb to develop in a given atmospheric environment. More specifically, this fire heat is the rate at which heat enters the fire plume (which has units of power), often termed the "power of the fire" or "firepower". A theoretical minimum firepower required for pyroCb to develop in a given atmospheric environment is calculated, termed the Pyrocumulonimbus Firepower Threshold (PFT).

Forecast spatial plots of PFT are being trialled that provide an indication of how the favourability of the atmosphere for pyroCb development varies in space and time over typical weather forecast periods. It is anticipated that such plots will provide useful guidance for fire weather forecasters and fire agencies. Preliminary studies have shown that the PFT can vary substantially from day to day, and that days that favour pyroCb formation do not necessarily favour large-hot fires. A PFT-flag is also under development that identifies when both pyroCb and large-hot fires are favourable.

## Background – Previous BNHCRC research

In previous BNHCRC research an idealised theoretical plume model was introduced (Tory et al. 2018, Tory and Kepert 2018) that can identify at what temperature and pressure (or height) condensation will begin to form in a fire plume. These condensation properties vary according to how much warmer the plume is than the environment (i.e., how buoyant the plume is). Plotted on a thermodynamic diagram, the condensation properties are represented by a single point, termed the Saturation Point (SP), and the SPs for a range of plume buoyancies form a SP curve (Figure 1, solid blue curve). Each SP curve is unique to an assumed mixed-layer environment comprising constant mixed-layer potential temperature ($\theta_{ML}$, Figure 1, thick red line) and specific humidity ($q_{ML}$, Figure 1, thick pale-blue line), and an assumed fire moisture to heat production ratio ($\varphi$). Fortunately, the SP curves are not sensitive to a range of realistic values of $\varphi$, and neither is the PFT.

The SP curve defines where a hypothetical ascending plume parcel begins to follow a moist adiabat on a thermodynamic diagram. For pyroCb formation any moist ascending parcel needs to remain buoyant (warmer than the environment, rightmost thin red line in Figure 1) until it reaches some designated height at which pyroCb is deemed to have been achieved. Here, that height is the so-called electrification level, -20 ℃ (Figure 1, pale-blue dashed line). The coolest moist adiabat that satisfies these criteria represents the coolest possible pyroCb plume-element pathway, and thus defines the pyroCb moist-adiabat limit (Figure 1, yellow curve). Where this moist adiabat and the SP curve meet is the free-convection height limit. Any buoyant plume element that reaches or exceeds this height will, in theory, freely convect to the electrification level. The intersection of these two curves defines the free-convection height ($z_{fc}$, Figure 1, fine blue dashed line), which is one of the key inputs to the PFT (see below). Another key PFT input is a measure of the plume-element buoyancy at this height. Specifically, it is the potential temperature difference ($\Delta\theta$) between the plume element at $z_{fc}$ ($\theta_{pl,fc}$) and $\theta_{ML}$, which can easily be read off the thermodynamic diagram (Figure 1). $\Delta\theta$ is a proxy for the plume buoyancy, and represents the buoyancy required for the plume to overcome any stable layers (inversions) that might inhibit the plume from reaching the electrification level. The third key PFT input is the average mixed-layer windspeed, which can be determined directly from the wind data available or estimated from the winds barbs on the edge of a thermodynamic diagram (Figure 1, highlighted in the green ellipse).

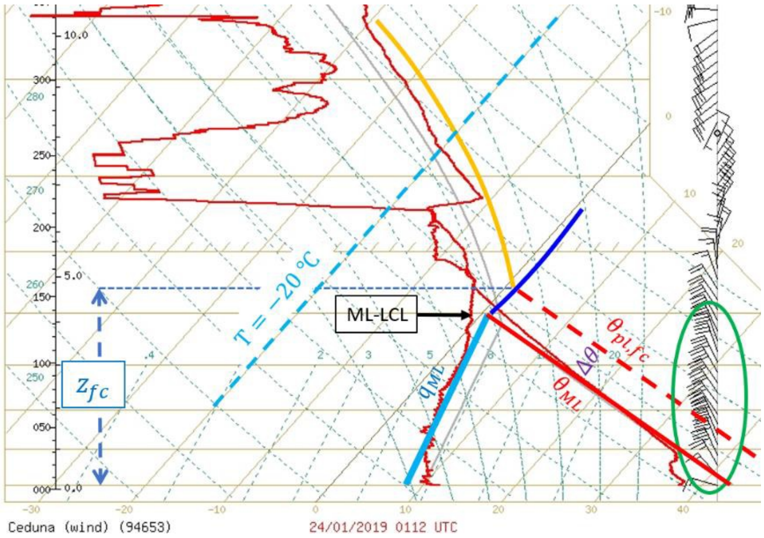


FIGURE 1: A SAMPLE ATMOSPHERIC SOUNDING (THIN RED LINES AND WIND BARBS) APPLIED TO AN F-160 THERMODYNAMIC DIAGRAM, WITH QUANTITIES REQUIRED FOR THE PFT CALCULATION OVERLAID: MIXED LAYER POTENTIAL TEMPERATURE ($\theta_{ML}$, THICK RED LINE); MIXED-LAYER SPECIFIC HUMIDITY ($q_{ML}$, THICK PALE-BLUE LINE); MIXED-LAYER LIFTING CONDENSATION LEVEL (ML-LCL, APEX OF THE $\theta_{ML}$ AND $q_{ML}$ LINES); SATURATION POINT CURVE (SP CURVE, BLUE CURVE EMANATING FROM THE ML-LCL); FREE-CONVECTION MOIST ADIABAT (YELLOW CURVE); ELECTRIFICATION LEVEL ($T = -20$°C, PALE-BLUE DASHED LINE); FREE-CONVECTION HEIGHT ($z_{fc}$, BLUE DOTTED LINE CORRESPONDING TO THE INTERSECTION OF THE SP CURVE AND FREE-CONVECTION MOIST ADIABAT); FREE- CONVECTION PLUME POTENTIAL TEMPERATURE ($\theta_{pl,fc}$, RED DASHED LINE); PLUME EXCESS POTENTIAL TEMPERATURE ($\Delta\theta$, DIFFERENCE BETWEEN $\theta_{pl,fc}$ AND $\theta_{ML}$); AND THE WINDS USED TO CALCULATE THE MIXED- LAYER WIND SPEED ($U$, GREEN ELLIPSE).

## PFT equations

The PFT is derived from an equation that describes the buoyancy flux distribution along the plume centerline for a Briggs plume (Briggs 1975, 1984) in a constant horizontal wind crossflow ($U$) and neutrally stable environment (Tory and Kepert 2018, Tory 2018). A schematic representation of a Briggs plume is shown in Figure 2. The plume geometry is described by two equations, an equation for the plume centreline height (Figure 2, yellow line) with downwind distance ($x$),

$$z_c = \left[\left(\frac{3}{2\beta^2}\right)\frac{B_{flux}}{\pi}\right]^{\frac{1}{3}}\frac{x^{\frac{2}{3}}}{U}, \qquad 1.$$

and an equation that describes an upright circular plume cross-section,

$$R = \beta z_c. \qquad 2.$$

Here $B_{flux}$ is the buoyancy flux at the plume source, which is proportional to the heatflux or firepower entering the plume. $\beta$ is a constant entrainment coefficient and $\pi$ is the circle constant. Eq. 2 describes the radius of the dynamic plume (pale blue lines, Figure 2), which includes the plume gases (internal plume) plus the surrounding environment lifted by the rising plume. The internal plume (dark blue lines, Figure 2) radius is smaller and is given by,

$$R' = \beta' z_c. \qquad 3.$$

Both entrainment parameters ($\beta$ and $\beta'$) have been measured in numerous observational and laboratory studies yielding $\beta = 0.6$ and $\beta' = 0.4$ (e.g., Briggs 1975, 1984). The PFT equation is based on buoyancy flux conservation within the internal plume, and thus $\beta'$ is the appropriate entrainment parameter in the following equations.

Assuming only some fraction of the plume area ($\alpha$) needs to reach the free-convection height, represented by a fraction of the plume radius, $\alpha'$ (Figure 2, red arrow), then the plume centreline expressed as a function of the free-convection height becomes,

$$z_c = \frac{z_{fc}}{1+\alpha'\beta'}, \qquad 4.$$

and the PyroCb Firepower Threshold becomes,

$$PFT = \left\{\frac{\pi C_p}{R_d}\left[\frac{\beta'}{1+\alpha'\beta'}\right]^2 \left(\frac{P_c}{\theta_{pl,fc}}\right)\right\} z_{fc}^{\;2} U \Delta\theta_{fc}. \qquad 5.$$

Here $C_p$ and $R_d$ are the Specific heat at constant pressure and gas constant for dry air. $P_c$ is the pressure at the plume centreline corresponding to the free-convection height, and $\theta_{pl,fc}$ is the plume potential temperature at the free-convection height (by definition $\theta_{pl,fc} = \theta_{ML} + \Delta\theta$). Equation 5 is a slightly more accurate PFT formulation than that provided in Tory and Kepert (2018). (Note, this work is still under development, and further tuning and changes are likely in the future.)

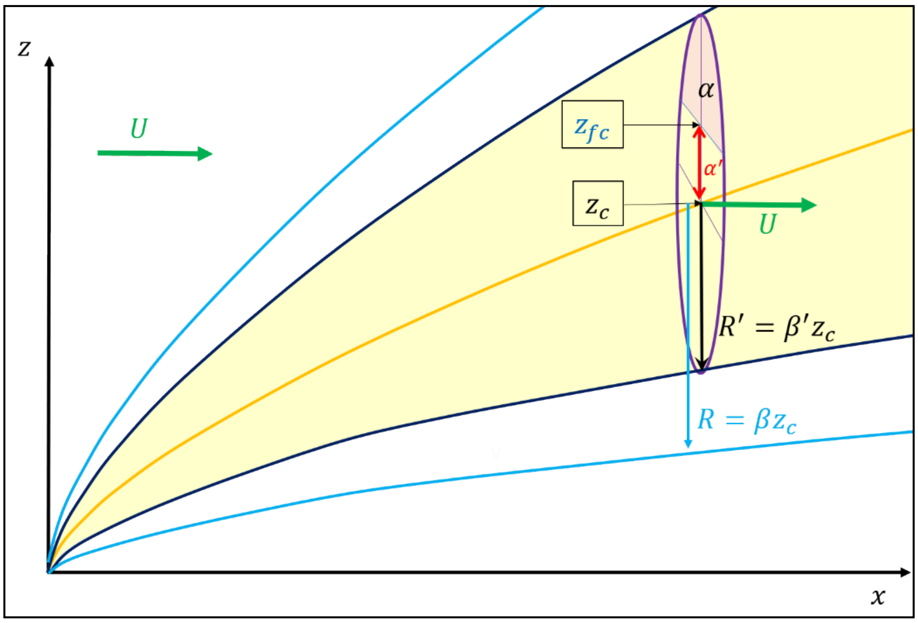


FIGURE 2: SCHEMATIC REPRESENTATION OF A BRIGGS PLUME, BENT-OVER IN THE DOWNWIND DIRECTION ($x$) BY A CONSTANT CROSSFLOW ($U$). THE INTERNAL PLUME (YELLOW SHADING) HAS A VERTICAL CIRCULAR CROSS-SECTION ABOUT THE PLUME CENTRELINE HEIGHT ($z_c$, YELLOW LINE) OF RADIUS $R'$, WHICH IS LINEARLY PROPORTIONAL TO THE PLUME CENTRELINE HEIGHT VIA THE CONSTANT INTERNAL PLUME ENTRAINMENT PARAMETER ($\beta'$). SIMILARLY, THE DYNAMIC PLUME (INSIDE THE PALE BLUE LINES) IS DEFINED BY THE DYNAMIC PLUME RADIUS AND ENTRAINMENT RATE, $R$ AND $\beta$. ONLY A FRACTION OF THE PLUME AREA ($\alpha$) IS REQUIRED TO REACH THE FREE- CONVECTION HEIGHT ($z_{fc}$), WHICH CAN BE EXPRESSED AS A FRACTION OF $R'$ ($\alpha'$).

### PFT equation insights

Since the entrainment coefficients ($\beta$ and $\beta'$) are constant, the plume centreline height (Eq. 1) at any given downstream distance $x$ is a function of only two variables, the buoyancy flux ($B_{flux}$), and the background cross-flow wind ($U$). Considering these variables independently, it is clear that the plume centreline height is much more sensitive to changes in the wind than the firepower. For example, to double the plume height at a given $x$ would require the windspeed to be halved, whereas it would require the firepower to be increased eight times. This result suggests that observed temporal changes in plume height and slope are more likely to be associated with variations in windspeed than fuel type and/or fuel loads.

The curly bracket term in Eq. 5 is constant, and the curved bracket term typically varies by 10% or less, which means the majority of PFT variation comes from the remaining terms: the free convection height, the background wind speed and the plume excess potential temperature (the buoyancy proxy). The relationship between the PFT and each of these three terms makes sense intuitively. The larger the free convection height, the more firepower required for the plume to rise to that height. The greater the windspeed, the more firepower is required to counter the tendency for the plume to be tilted over by the wind. The greater the buoyancy required for the plume to penetrate stable layers or inversions above $z_{fc}$, the more firepower that is required. The real insight provided by Eq. 5, however, is the relative power of each term and how they combine to determine an overall pyroCb formation threat. For example, if $z_{fc}$ decreases while $\Delta\theta_{fc}$ increases, perhaps with the passage of a cold front or sea breeze, Eq. 5 will determine if the net effect is more or less favourable for pyroCb formation.

## Results

### PFT spatial distributions

Spatial plots of PFT generated from computer forecast models can provide valuable insight into how the pyroCb threat varies in space and time (Figure 3). The PFT colour scale in Figure 3 is logarithmic in order to capture the substantial PFT variability at any given time across the landscape. Both cases presented show increased threat near a wind change. This is a very common result. Ahead of the wind change the winds are often very hot and dry (contributing to large $z_{fc}$) and the windspeeds are often very high (large $U$), which together contribute to large PFT (Eq. 5) corresponding to highly unfavourable conditions for pyroCb formation. If the wind change brings cooler and moister air to the fire ground (reduced $z_{fc}$), and a short-term (or longer) lull in the winds (reduced $U$), conditions become much more favourable for pyroCb formation. Furthermore, a shift in wind direction can lead to increased firepower as long flank fires become head fires.

The two PFT plots in Figure 3 also demonstrate very large differences in PFT in the vicinity of the fires at the time the pyroCb were observed (about 300 GW for Sir Ivan and 10 GW approaching Licola). This suggests pyroCb formation conditions are much less favourable for the Sir Ivan fire than the Licola fire, since 30 times the firepower would be required in the former than the latter. Indeed, conditions that highly favour pyroCb plume development (high humidity and light winds) do not favour large, hot fires, and vice-versa.

Fire-weather forecasters and fire-behaviour analysts using the PFT diagnostic would require some knowledge of the size and intensity of any going fires to be able to assess pyroCb formation potential. This knowledge is rarely available and will never exist for fires that have yet to be ignited. Without such knowledge they can only identify a relative threat, and the PFT forecast performance cannot be verified.

It may be many years before sufficiently reliable observations of firepower become available to enable a rigorous verification program to be undertaken. In the short term, a dataset of past events could be constructed, to identify fire-types that will produce pyroCb for a specific PFT forecast (e.g., a Sir Ivan-scale fire is required for pyroCb to form when the PFT = 300 GW). However, this approach is not ideal because it assumes the yet to be verified PFT is stable and performs consistently across the full breadth of fire weather conditions.

An unverifiable forecast tool such as the PFT has limited prediction value. It must be combined with other information to have value. Ideally, the pyroCb prediction tool would allow forecasters to know that a fire burning in a specific location at a specific time will or will not produce pyroCb.

Returning to Figure 3 one clear difference between the Sir Ivan and Licola fires is the fire-danger conditions. Sir Ivan had catastrophic fire conditions, which would support a much hotter fire than the very-high fire danger conditions present in Licola. Combining some measure of the fire danger conditions with the PFT could produce a verifiable prediction tool.

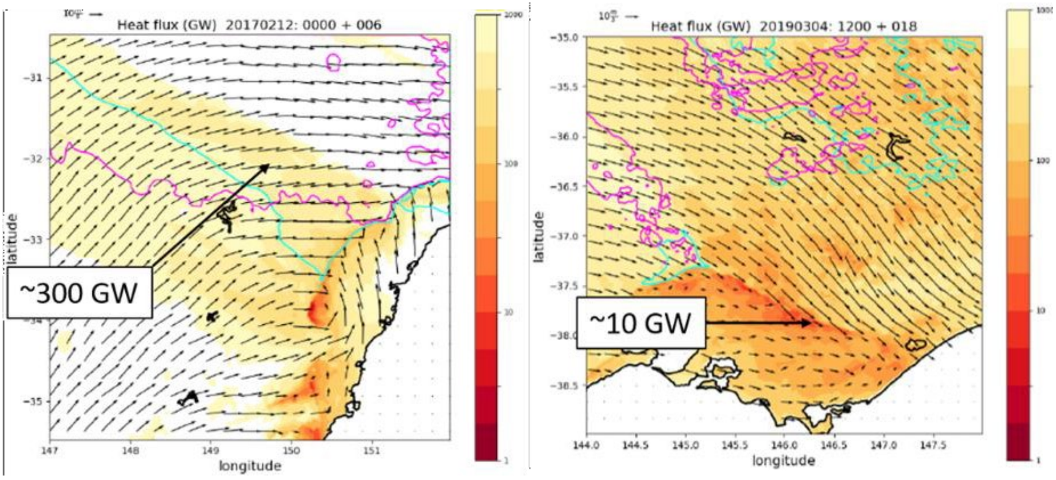


FIGURE 3: PFT FORECASTS FOR TWO PYROCB EVENTS, SIR IVAN (5 PM, 12 FEBRUARY 2017, LEFT) AND LICOLA (5 PM, 5 MARCH 2019, RIGHT). THE PFT SCALE IS LOGARITHMIC (UNITS GW). THE WIND BARBS REPRESENT THE MIXED-LAYER WIND VELOCITY. THE PFT LABEL FOR SIR IVAN POINTS TO THE FIRE SITE, WHEREAS FOR LICOLA IT POINTS TO A MINIMUM VALUE ON THE WIND CHANGE THAT IS ABOUT TO IMPACTLICOLA.

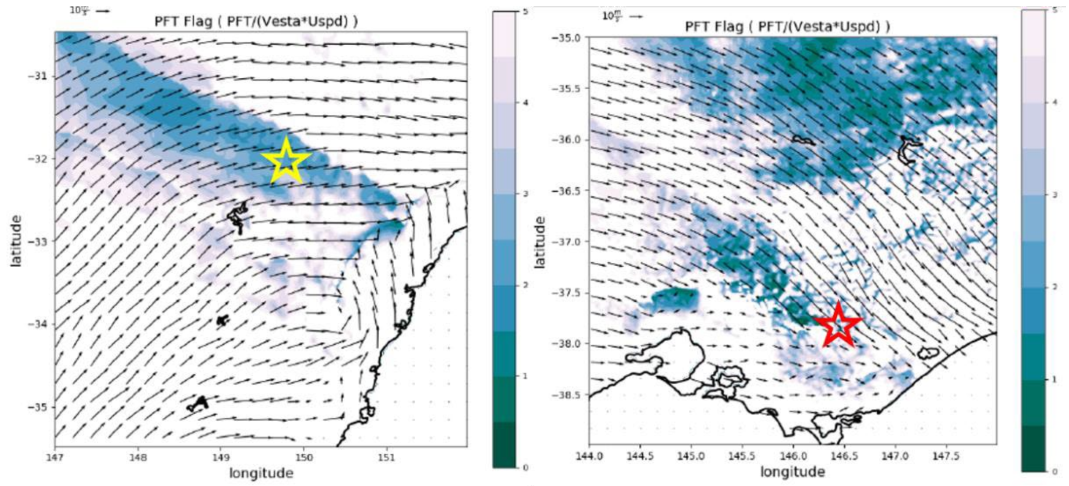


FIGURE 4: SAME AS FIGURE 3 BUT THE PFT-FLAG FORECASTS. THE STARS INDICATE THE FIRE LOCATIONS.

## PFT-flag formulation

The PFT-flag is designed to represent a ratio of pyroCb plume-development potential (PFT) to fire-intensity potential, to identify when a favourable combination of plume and fire potential is present. For simplicity, the PFT-flag uses only atmospheric variables readily available in Numerical Weather Prediction (NWP) models. The atmospheric components of a variety of fire-weather indices were tested, with the best performing being the product of the Project Vesta (Cheney et al. 2012) and the near-surface windspeed. The main test was for the PFT-flag to produce a similar value for the two extreme cases introduced above, Sir Ivan and Licola. Despite this very rudimentary testing regime the only changes required, after application to more than twenty cases, were the addition of low-wind and low fire-danger limits.

In order to separate the atmospheric component from the fuel components in the Vesta function, two assumptions need to be made. The near-surface windspeed is greater than 5 $km\ hr^{-1}$ ($1.39\ m\ s^{-1}$), and a constant term in the rate-of-spread equation is small compared to the windspeed/fuel term and can be ignored. The latter assumption is good for moderate to high fuel loads. Such fuel loads may be necessary to support deep flaming, observed in pyroCb producing fires (McRae and Sharples 2014). The resulting Vesta atmosphere-only equation can be expressed as,

$$V = 18.35 {V_M}^{-1.495} . V_U, \qquad 6.$$

where,

$$V_M = \begin{cases} 2.76 + 0.124RH - 0.0187T, \text{ Period 1} \\ 3.60 + 0.169RH - 0.0450T, \text{ Period 2} \\ 3.08 + 0.198RH - 0.0483T, \text{ Period 3} \end{cases} \qquad 7.$$

$$V_U = 1.531(\max(U_{10}, 3.0) - 1.39)^{0.858}. \qquad 8.$$

Here $V_M$ and $V_U$ are the fuel moisture and wind speed contributions to the Vesta function ($V$). The wind speed term uses the near surface or 10 m wind ($U_{10}$, units $m\ s^{-1}$). The fuel moisture term is a function of relative humidity ($RH$, units %) and air temperature ($T$, units ℃), which varies with time of day and time of year, expressed as three distinct periods (Eq. 7). Period 1 extends from midday to 5 PM from October to March. Period 2 is used otherwise for daylight hours, and Period 3 for night hours. Note, these periods are valid for southern hemisphere low- to mid-latitude regions. Application to the northern hemisphere, high latitudes requires additional consideration about when best to apply Period 1. (Experiments in the mid-summer Arctic, suggest Period 1 should apply continuously.)

For comparison with the better-known McArthur Forest Fire Danger Index (FFDI, McArthur 1967, Noble et al. 1980), $V = 15$ is roughly equivalent to an FFDI of 50, and $V = 30$ is similar to an FFDI of 100.

The PFT-flag is given by,

$$PFTflag = \frac{PFT}{V.U_{10}}. \qquad 9.$$

To avoid divide by zero errors and to eliminate the PFT-flag triggering in light-wind conditions, or low fire danger conditions the PFT-flag is set to a very large number (to indicate pyroCb is impossible) whenever $V \leq 2.0$ or $U_{10} \leq 2.0$. The smaller the PFT-flag value, the more favourable the combined plume and fire conditions are for pyroCb formation. When calculating PFT-flag, PFT in units of GW is used in Eq. 9 to generate manageable PFT-flag units for plotting (e.g., Figure 4).

Like the PFT, the PFT-flag is still in development and will undergo further tuning and editing in the future.

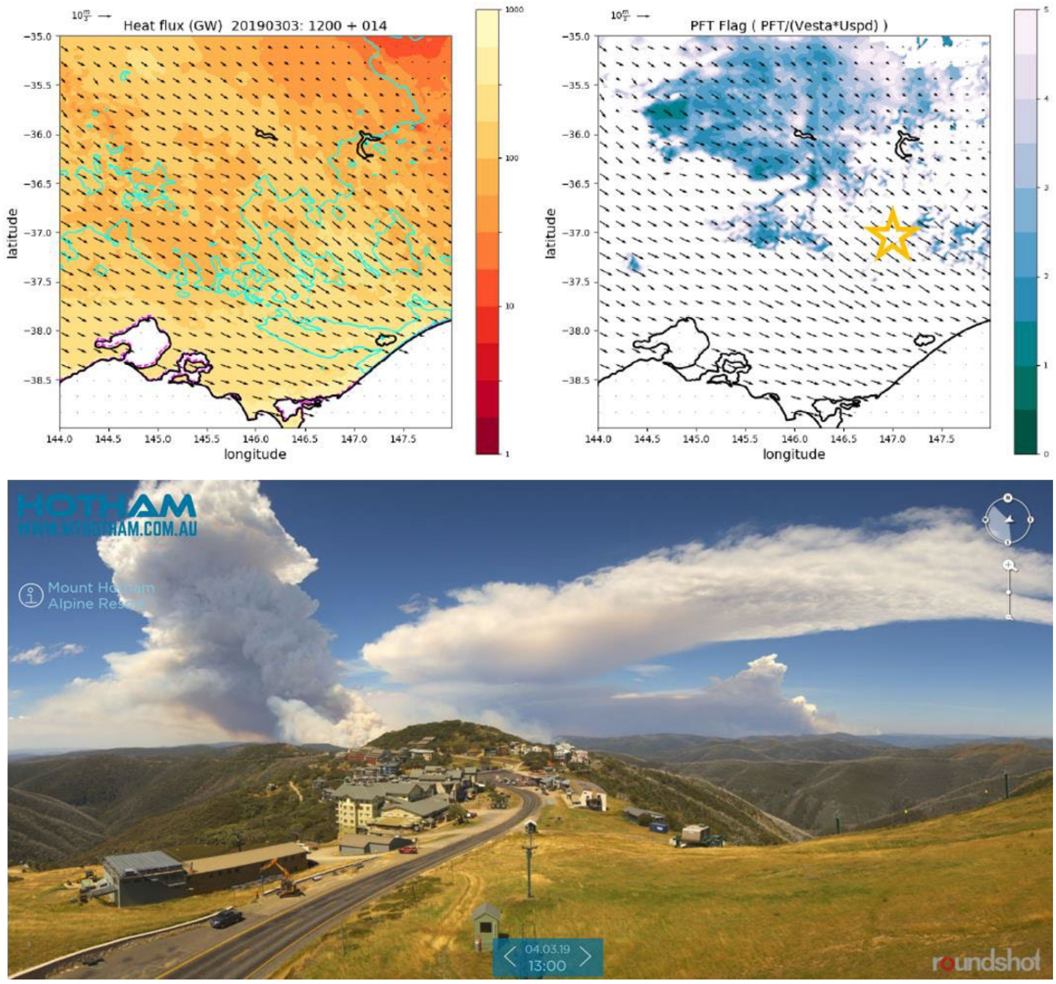


FIGURE 5: THE PFT (TOP LEFT), PFT-FLAG (TOP RIGHT) AND BELOW AN IMAGE FROM THE MT. HOTHAM WEBCAM OF THE MAYFORD-TUCKALONG TRACK FIRE (LEFT, MID-GROUND) AND THE MOUNT DARLING-CYNTHIA RANGE TRACK FIRE (RIGHT, DISTANT) AT 1 PM, 4 MARCH 2019. THE STAR MARKS THE LOCATION OF THE TWOFIRES.

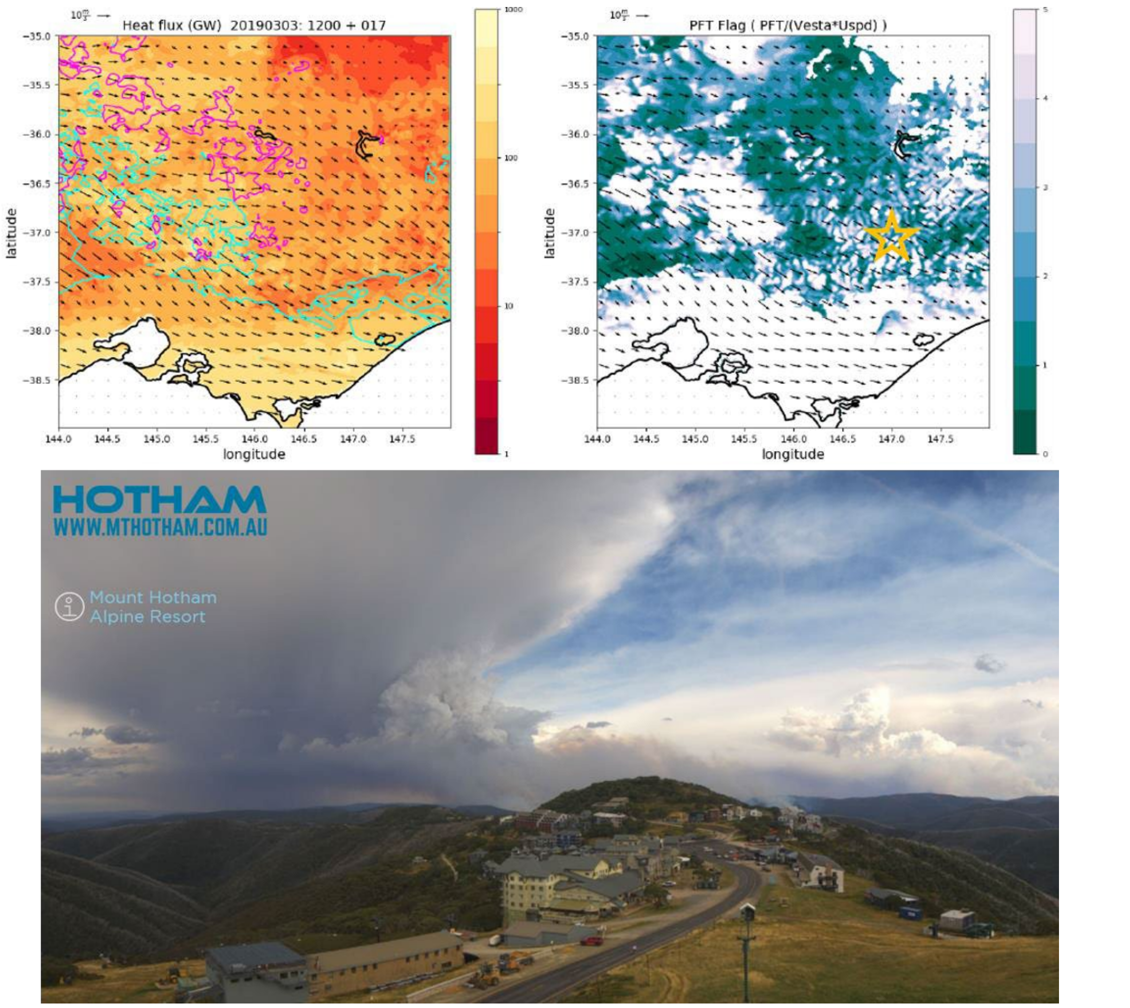


FIGURE 6: AS IN FIGURE 5, BUT THREE HOURS LATER (4 PM).

## PFT-flag results

A rigorous assessment of the PFT-flag is yet to be undertaken. At present a prediction of favourable pyroCb formation is based on a somewhat arbitrary choice of colour-scale in the PFT-flag plots. Both Sir Ivan and Licola yielded PFT-flag values between about 1 and 3 (Figure 4), which led to the choice of a colour-scale between 0 and 5. Initial interpretation of these values is as follows: less than 1 is highly favourable for pyroCb formation; between 1 and 3 is favourable; between 3 and 5 is possible; and greater than 5 is unlikely. This is very preliminary and is likely to change in the future.

As mentioned above many cases have since been examined, with very promising results. A good example is the dual fires that produced pyroCb in view of the Mt. Hotham webcam on 4 March 2019: The Mayford-Tuckalong Track fire and the Mount Darling-Cynthia Range Track fire. Early in the day, while impressive pyroCu developed, there was no indication of pyroCb, and the PFT-flag indicated pyroCb was unlikely in the immediate vicinity of the fires (although favourable conditions were indicated nearby, Figure 5). Throughout the afternoon, the PFT flag showed a steady southward progression of favourability, with the shading becoming increasingly darker (c.f., Figure 5 and Figure 6). Both fires produced pyroCb, with the northern fire (Mayford-Tuckalong Track closest to the camera) triggering about an hour earlier than the southern fire.

The sequence of 10-minute images (not shown) showed the two plumes produced multiple bursts of deep convection throughout the afternoon, progressively becoming larger and more energetic, with clear evidence of rain falling from the nearby fire plume, and a mature anvil in the more remote fire plume. This behaviour was well-matched by the ever darkening and southward progression of the PFT-flag shading. As a forecast tool the PFT-flag would have provided excellent guidance for pyroCb prediction on these two fires.

## Summary

A series of BNHCRC studies beginning with a little "blue-sky" research into the thermodynamics of smoke plumes, led to the ability to identify potential condensation heights in plumes, and the minimum plume buoyancy required for plumes to freely convect to the electrification level. With this knowledge equations for a theoretical minimum firepower required for pyroCb formation were derived using the Briggs plume model (PyroCb Firepower Threshold, PFT).

The work has culminated in the development of a diagnostic that seeks to determine when the atmosphere is conducive to both deep plume development and large, hot fires (PFT-flag). Originally designed as a flag to alert users when to examine the PFT, the PFT-flag may prove to be a more valuable prediction tool than the PFT itself. It was developed and tuned to identify the atmospheric conditions corresponding to two pyroCb events at opposite ends of the pyroCb spectrum. The first (Sir Ivan) occurred in catastrophic fire weather conditions, when pyroCb formation conditions were not especially favourable. The second (Licola) occurred in much milder fire weather conditions, when plume formation conditions were considerably more favourable. The PFT-flag has now been applied to more than 20 cases covering multiple days and time periods. While no rigorous performance assessment has yet been made the tool appears to be working surprisingly well. It not only identifies days of pyroCb occurrence, but also reproduces the diurnal variation in pyroCb threat, plus variations in threat associated with atmospheric features such as troughs, fronts and sea-breezes.

Both the PFT and PFT-flag are under continued development and will undergo real-time testing this coming southern Australian fire season.

# A CASE STUDY OF SOUTH AUSTRALIA'S SEVERE THUNDERSTORM AND TORNADO OUTBREAK (28 SEPTEMBER 2016)

## Introduction

On 28 September 2016 one of the most significant thunderstorm outbreaks recorded in South Australia impacted central and eastern parts of the state. Multiple supercell thunderstorms were embedded in a Quasi-Linear Convective System (QLCS; Weisman and Trapp 2003) aligned with a strong cold front that was associated with an intense low-pressure system. The storms produced at least seven tornadoes, destructive wind gusts, large hail and intense rainfall. Transmission lines were brought down in four different locations, which contributed to a state-wide power outage.

Accurate prediction and understanding of tornadoes and other hazards associated with severe thunderstorms is very important, for timely preparation and announcement of warnings. By conducting high-resolution simulations, this study aims to offer a better understanding of the meteorology of the South Australia's thunderstorm and tornado outbreak. It also contributes to improving knowledge of how to best predict similar severe weather events, which in turn enables better risk management and preparedness for such events. Updraft helicity, a severe storm surrogate that indicates the potential for updraft rotation in simulated storms is used to investigate the ability of the model to predict supercell and tornado likelihood.

## Modelling set-up

Here, a case study of the September 28 2016 event is conducted using high-resolution nested simulations of the Australian Community Climate and Earth-System Simulator (ACCESS) model. The model consists of a global model run (17 km that is nested down to 4.0 km, 1.5 km and 400 m (Figure 7), size chosen to capture the area where seven tornadoes were reported. Each domain has 80 vertical levels and the model top for nested domains is 38.5 km.

All simulations use Regional Atmosphere Mid-latitude first release (hereafter RA1M) science configuration (Bush et al. 2019), to assess model performance over the South Australia domain, and simulation results are compared to radar imagery. All simulations were initialised at 1500 UTC 27 September 2016 (+ 9.5 hours local time) and ran for 48 hours.

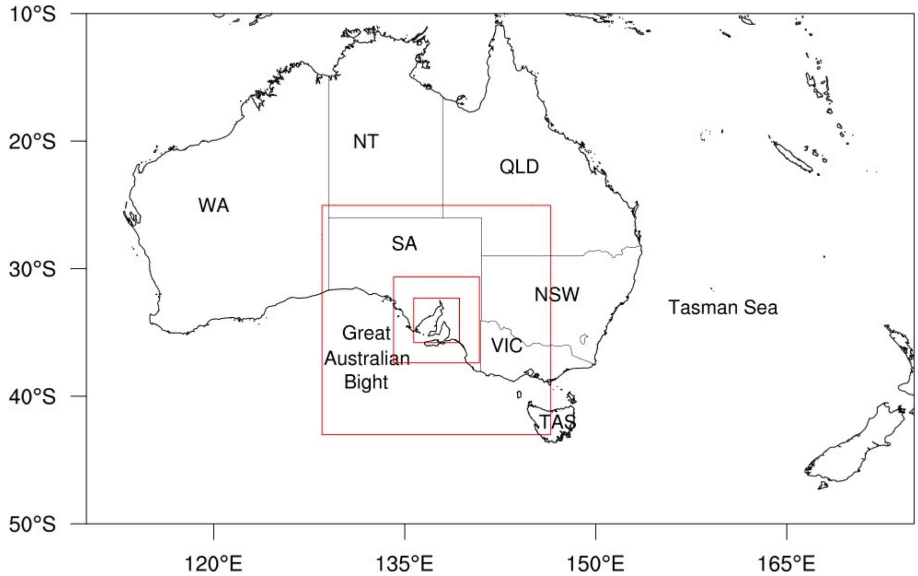


FIGURE 7: OUTLINE OF MODEL DOMAINS, WITH LARGER DOMAIN HAVING HORIZONTAL RESOLUTION OF 4 KM, AND SMALLER DOMAINS WITH HORIZONTAL RESOLUTION OF 1.5 KM AND 400 M.

## Results

To investigate how well the model represents severe thunderstorms, observed radar reflectivity (Figure 8, left) is compared to simulated reflectivity (Figure 8, right) from the 1.5 km model at 0600 UTC 28 September 2016. Figure 8a shows the line of thunderstorms that were associated with large hail and several reported tornadoes (Bureau of Meteorology 2016), and the overall timing and location of severe thunderstorms is captured well by the model (Figure 8b). Individual supercells are not likely to be depicted by the model as grid lengths on order of 1 km are not able to resolve supercell or tornado-like signatures.

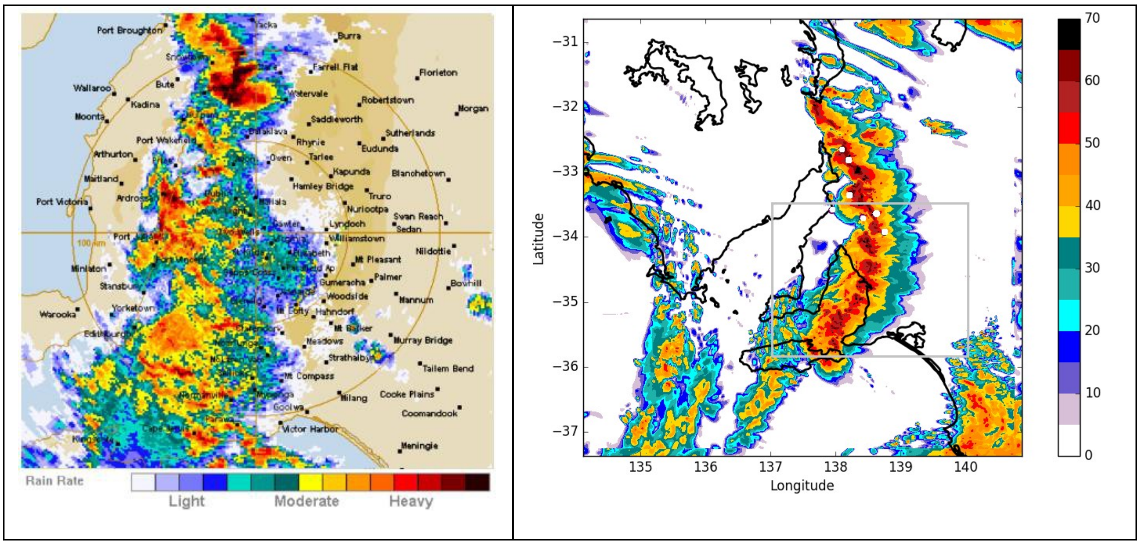


FIGURE 8: (LEFT) RADAR REFLECTIVITY (DBZ) AND (RIGHT) SIMULATED RADAR REFLECTIVITY AT 0600 UTC 28 SEPTEMBER 2016. THE WHITE DOTS ARE THE OBSERVED LOCATIONS OF THE TORNADOES AND THE GREY BOX MARKS THE APPROXIMATE DOMAIN OF THE LEFT PANEL.

Figure 9 shows simulated reflectivity from the 400-m simulation, where northern cells (black box in Figure 9) are stronger and better defined than the southern part of the convective system, indicated by differences in the simulated reflectivity. A close-up view of the simulated reflectivity and vertical velocity (Figure 10) in the northern part of the system (black box in Figure 9) reveals a hook-echo feature and a curved updraft that coincide with the location of one of the reported tornadoes (northernmost white dot in Figure 10). This indicates the presence of a mesocyclone (Davies-Jones 2015) at this location. The reported tornado is estimated to have started at approximately 0615 UTC 28 September 2016 (Bureau of Meteorology 2016, Sgarbossa et al. 2018), which is about 15 min later than in the simulation. This shows that the mesocyclone and features that indicate the possibility of a tornado are still reasonably well captured with the 400-m simulation.

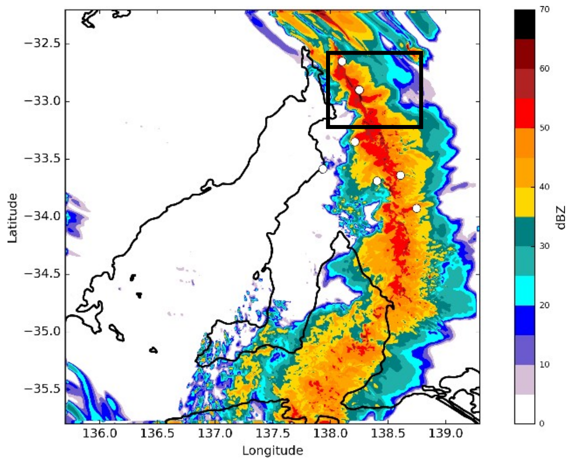


FIGURE 9: *0600 UTC 28 SEPTEMBER 2016 SIMULATED RADAR REFLECTIVITY (DBZ) AT 2 KM HEIGHT FOR THE 400- M SIMULATION. THE WHITE DOTS ARE THE OBSERVED LOCATIONS OF THE TORNADOES AND THE BLACK BOX DENOTES THE AREA SHOWN IN* FIGURE 10.

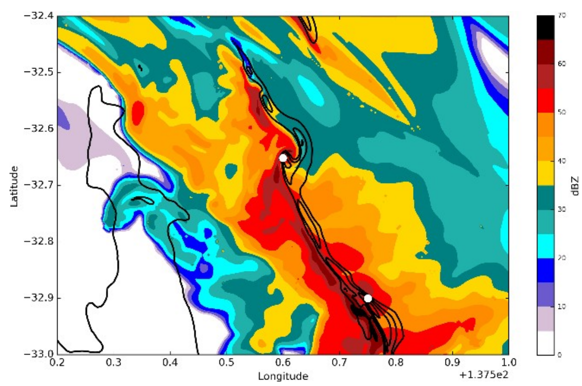


FIGURE 10: AS PER FIGURE 9, ONLY FOR THE AREA DENOTED BY THE BLACK BOX IN FIGURE 9.

Based on Kain et al. (2008), a model diagnostic field (updraft helicity) is used to investigate the ability of the model to identify the potential for supercell thunderstorms, within which tornadoes may form. Updraft helicity (UH) is the product of vertical vorticity and vertical velocity, integrated vertically from 2 km to 5 km:

$$\boldsymbol{UH} = \int_{2km}^{5km} \boldsymbol{w} \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) \boldsymbol{dz},$$

Where w is vertical velocity ($m\,s^{-1}$), ($\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$) is vertical vorticity ($s^{-1}$) and z is height (m). UH is negative for the Southern Hemisphere. While UH can be computed as an instantaneous value at a single model output time, Kain et al. (2010) developed hourly maximum UH that tracks the maximum value of the diagnostic at every grid point at any model time step within the previous hour (e.g., Clark et al. 2012, 2013; Sobash et al. 2016). Here, UH is computed as the output diagnostic in the Met Office UM model.

Figure 11 shows hourly minimum UH for the period between 0500-0600 UTC and 0600-0700 UTC 28 September 2016, which coincides with the time period of the reported tornadoes(Bureau of Meteorology 2016). It shows elongated swaths of hourly minimum UH exceeding -120 $m^2s^{-2}$ and reaching values < -400 $m^2s^{-2}$ in close proximity to the observed tornadoes (magenta dots in Figure 11). A long and coherent, vortex-like swath of hourly minimum UH < -500 $m^2s^{-2}$ coincides with the location of the northernmost observed tornado, where a mesocyclone was identified in simulated reflectivity and vertical velocity (cf. Figure 10). This indicates that the use of UH as a diagnostic field could provide useful guidance for identifying potential for tornado formation.

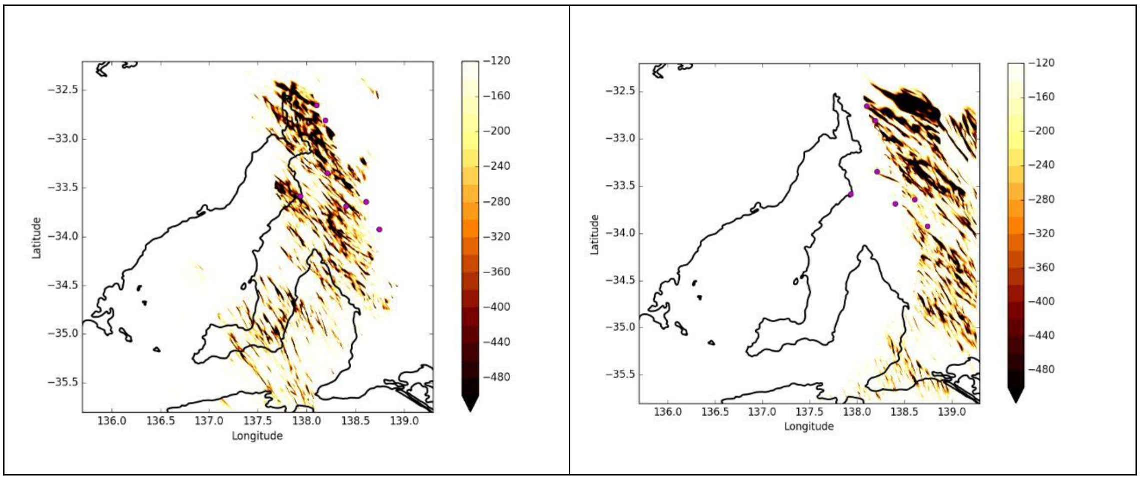


FIGURE 11: HOURLY MINIMUM UPDRAFT HELICITY (UH, $M^2$ $S^{-2}$) FOR THE PERIOD (LEFT) 0500-0600 UTC 28 SEPTEMBER 2016 AND (RIGHT) 0600-0700 UTC 28 SEPTEMBER 2016. THE MAGENTA DOTS DENOTE THE APPROXIMATE LOCATION OF OBSERVED TORNADOES.

Another parameter that is worth investigating as a tornado proxy alongside UH is the Okubo-Weiss (OW) parameter, defined as

$$OW = \xi^2 - (E^2 + F^2) = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)^2 - \left\{\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2\right\},$$

where $\xi$ is the vertical vorticity, $E$ is the stretching deformation, and $F$ is the shearing deformation (Okubo 1970; Weiss 1991; Markowski et al. 2012). The OW parameter highlights flow regions where rotation dominates over strain, and therefore can be used to identify rotation (or vortices) associated with tornadic storms (e.g., Markowski et al. 2012; Coffer and Parker 2017).

Figure 12 shows the OW parameter calculated as per the above equation, using layer averaging between 1 km and 4 km for the time interval between 0528 UTC and 0628 UTC 28 September 2016. It shows a coherent track of positive OW parameter that coincides with the location of the northernmost reported tornado, thus clearly identifying the mesocyclone in this simulation. This analysis shows that the OW parameter identifies the mesocyclone and rotation in simulated storms and gives a clear indication of a tornado path. This suggests it can be used as an alternative diagnostic alongside UH to assess tornado potential, thus potentially reducing false alarms.

## Future Work

We are analysing high-resolution ensemble simulations of this event, as deterministic simulations do not provide the information on the uncertainty associated with the timing, location and intensity of the tornadic storms or tornado pathlengths and can lead to increased false alarms and warnings (e.g., Hanley et al. 2016; Snook et al. 2019). We are also preparing a manuscript on this event.

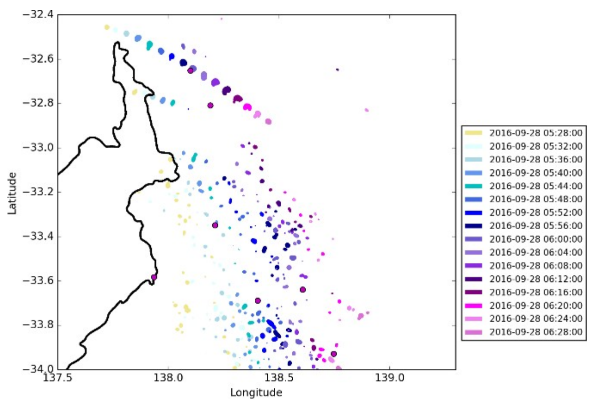


FIGURE 12: : THE OKUBO-WEISS PARAMETER (OW; POSITIVE VALUES ONLY), CALCULATED AS A 1 KM-4 KM LAYER AVERAGE FOR THE TIME INTERVAL BETWEEN 0528 UTC AND 0628 UTC 28 SEPTEMBER 2016. THE MAGENTA DOTS DENOTE THE APPROXIMATE LOCATION OF OBSERVED TORNADOES

# A CASE STUDY OF METEOROLOGICAL ASPECTS OF THE TATHRA BUSHFIRE (18 MARCH 2018)

## Introduction

On the 18th March 2018 a fire started at Reedy Swamp within the Bega Valley Shire on the New South Wales South Coast. Aided by the passage of a strong cold front, the fire burned into the town of Tathra during the mid-afternoon, leading to the evacuation of the township and the destruction of 70 homes and other structures.

Weather on the day was characterised by a hot, dry and gusty pre-frontal northwesterly airmass ahead of a cool, gusty coastal change in the late afternoon. Such conditions are notoriously difficult to forecast on the south coast due in-part to the influence of prominent topography upwind which comprise the highest mountain peaks on the Australian mainland.

The high impact nature of the Tathra bushfire event, coupled with the relatively common incidence of such wind changes and the difficulty they present to forecasters, has motivated this case study in consultation with the project end users. By conducting high-resolution simulations, this study aims to provide a better understanding of the atmospheric dynamics pertinent to the event. In particular, the study will have an emphasis on topographic influences and mountain wave structures hypothesised to have played a significant role in the severe weather conditions of the day. Further, this study will inform meteorologists responsible for fire weather forecasts to improve prediction of severe fire weather events and enable better risk management and preparedness during future fire seasons.

## Model Setup

The case study is conducted using high-resolution nested simulations of the Australian Community Climate and Earth-System Simulator (ACCESS) model. The analysis consists of a global model run (17 km) with three-level nesting (4 km,1.5 km and 400m). Each domain has 80 vertical levels and the vertical boundary for the nested domains is 38.5 km. All simulations were initialised at 1500 UTC 17 March 2018 (+11 hours local time) and ran for 24 hours.

## Preliminary Results

Though this study is in its early stages, several interesting features have already been identified from the 400m model output.

Firstly, the run predicts favourable weather conditions for the onset of intense fire behaviour, and especially the movement of the fire toward the township. The fire was observed to jump the Bega River at around 15:00 local time. The 400m model run shows a westerly wind boundary moving over the region at approximately 14:35, see Figure 13, which brought sustained strong northwesterly winds and drastically lower RH to the Tathra region.

The event was also characterised by the presence of defined horizontal convective rolls (extending up to around 3-4km above sea level) persisting lee of the ranges and to the coast, see the 2km windspeed in Figure 14. These streamer-like bands of high velocity air likely resulted in large spatial fluctuations in the surface wind speed and direction, as can be seen in Figure 13, as well as higher gust variability over the fireground. Additionally, these rolls were associated with significant regions of ascent (vertical velocity in the range of 3-8 m/s) which could contribute to long-range spotting of firebrands and the spread of the fire front.

Northwesterly airflow over the NSW ranges is also known to produce mountain wave patterns under certain conditions. The 400m model output shows significant lee wave banding present, Figure 15, a result of trapped lee waves developing in a stable atmospheric layer above the ridge-top altitude. These lee waves likely contributed to the elevated windspeeds observed at the Thredbo AWS in the late morning, where wind gusts in excess of 110 km/hr were recorded. However, the development of the boundary layer in the afternoon and especially the formation of convective roll structures appears to have attenuated the mountain wave energy in the lower atmosphere and hence minimised their influence on the fireground. This hypothesis, however, is still currently under investigation.

## Future Work

*Topographic effects.* Further analysis of the effect of topography on the boundary layer roll structure and the development of mountain waves.

*A comparison of the 1.5km and 400m resolution model runs*. For operational forecasting, the highest currently available horizontal resolution is 1.5km. A direct comparison between the case study 1.5km and 400m model output will help to assess the benefits of a higher resolution run for severe fire days.

The passage of the change over the region. Examination of the one-minute data at Merimbula Airport suggests that the cold front may have taken some time to fully establish the cooler, south-easterly change over the south coast. Conditions were seen to fluctuate between hot north-westerly and cooler easterly winds for around an hour after the forecast frontal passage. This was likely due to boundary layer rolls mixing continental air aloft to the surface, enabled in-part by the shallow nature of the initial change. This may also have occurred over the fireground and would have brought highly variable conditions under which to manage an active fire. As such, the effect of the passage of the change is currently being investigated.

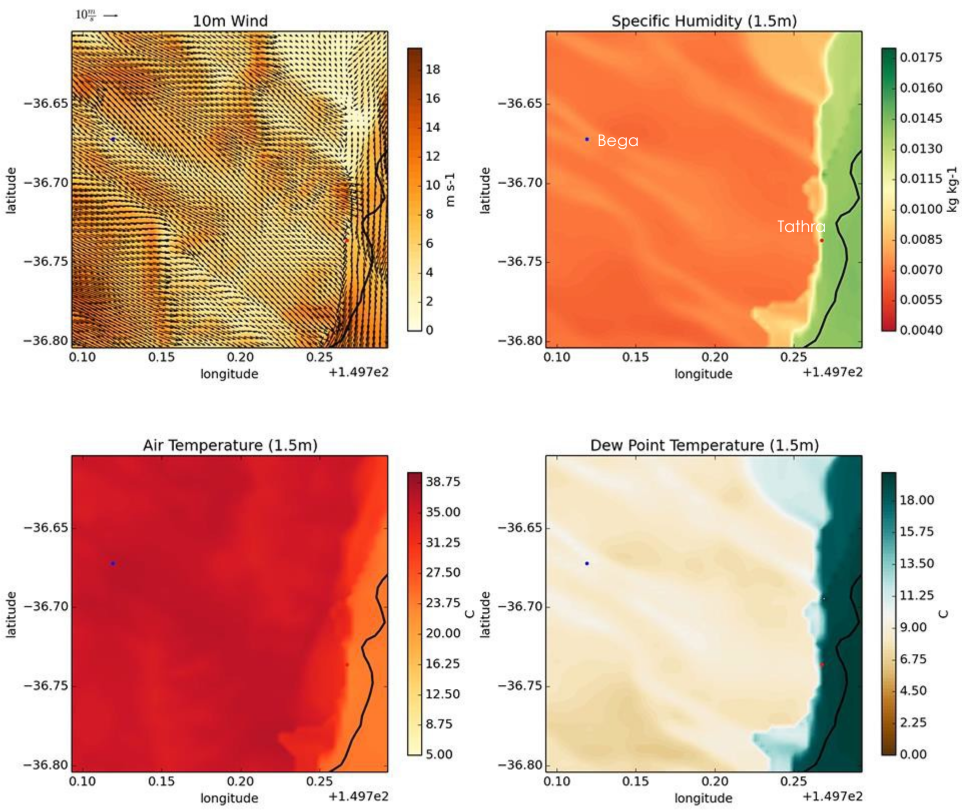


FIGURE 13: THE NORTHEAST/WESTERLY BOUNDARY IMPINGES ON TATHRA (RED DOT) AT 14:35 LOCAL TIME, SHOWN BY 10M WINDSPEED (TOP LEFT, WITH DIRECTION SHOWN AS ARROWS), HUMIDITY (TOP RIGHT), AIR TEMPERATURE (BOTTOM LEFT) AND DEW POINT TEMPERATURE (BOTTOM RIGHT). THE FIRE WAS OBSERVED TO JUMP THE BEGA RIVER AT AROUND 14:56 LOCAL TIME, ROUGHLY 20MIN LATER. THE BLUE DOT IS THE BEGA AWS.

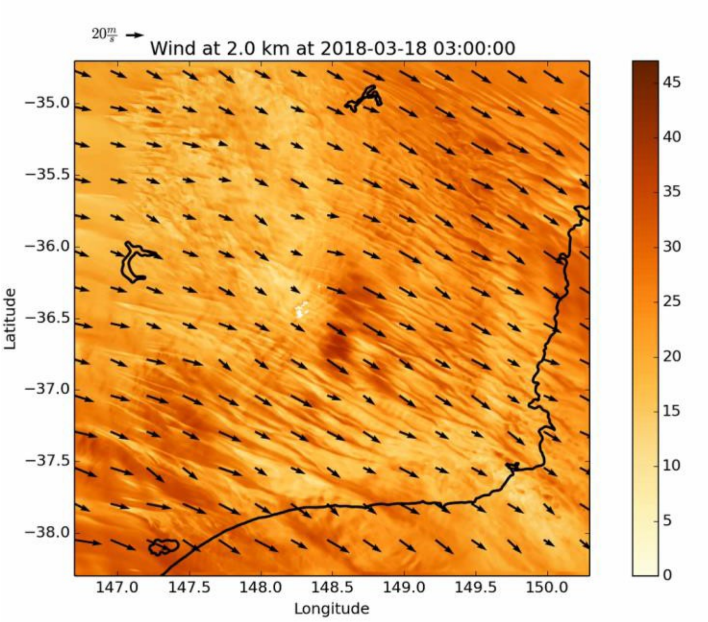


FIGURE 14: HORIZONAL CONVECTIVE ROLLS (DARK NW BANDS OF HIGHER WINDSPEED) EVIDENT IN THE WINDS 2KM ABOVE SEA LEVEL AT 14:00 LOCAL TIME. THE PASSAGE OF THESE STRUCTURES CAN PRODUCE ENHANCED PLUME UPLIFT, GUSTY WINDS AND ERRATIC FIRE BEHAVIOUR OVER A FIRE GROUND.

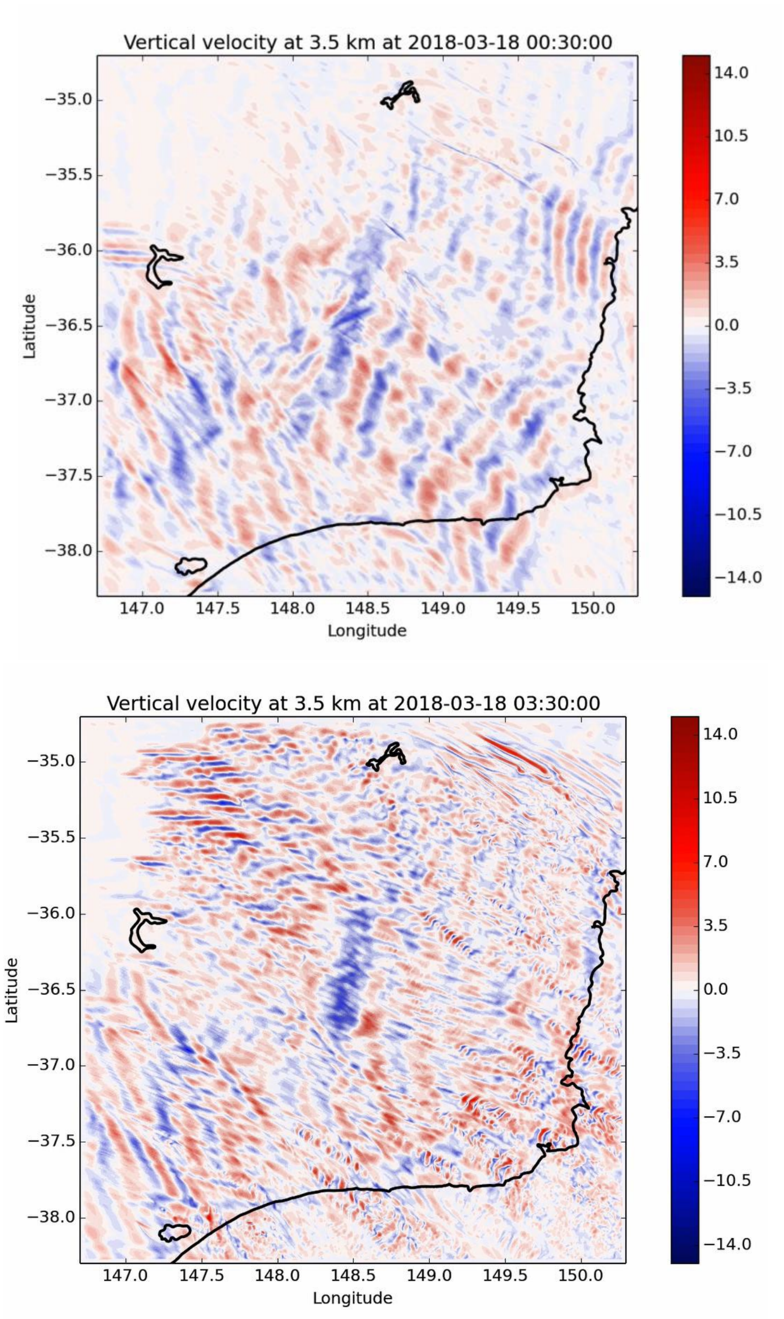


FIGURE 15 - VERTICAL VELOCITY (M/S) AT 3.5KM ABOVE SEA LEVEL AT 11:30 (TOP) AND 14:30 (BOTTOM) LOCAL TIME. AREAS OF AIR ASCENDING (RED) AND DESCENDING (BLUE) FORM A STRIKING LEE WAVE PATTERN IN THE IMAGE AT TOP. THE SIGNAL BREAKS DOWN AS CONVECTION BEGINS (BOTTOM) WITH SHORTWAVE FLUCTUATIONS IN ASCENT/DESCENT DOMINATING OVER TOPOGRAPHY AND NEAR THE COAST.

# KEY MILESTONES

Exceptional progress has been made in pyroCb prediction this year, and milestones associated with this part of the project are essentially on track.

The milestones associated with the case study on the SA Tornado outbreak are generally delayed a little, due largely to the decision to extend the initial case study to include ensemble simulations. The journal paper is nearly complete, but is presently on hold pending the return of a staff member from maternity leave.

The second case study, the Tathra bushfire, is progressing well, but had a delayed start. We are confident that it will produce the necessary outputs in a timely manner.

The ember transport parameterisation has been significantly delayed this year, due to the difficulty of the task and the illness, followed by departure, of the responsible team member. We have allocated a senior scientist to this task and remain confident of making good progress in the coming year.

Note that due to the above delays, we have recently renegotiated the project scope and schedule with the CRC.

# UTILISATION AND IMPACT

## SUMMARY

We are busy planning for the near-real time trial of the pyroCb prediction system to be held this summer. Much of the necessary IT infrastructure is in place, although we are still finalising the delivery method. We will recruit suitable end users to help assess the products.

We have gained significant experience with high-resolution NWP and developed a range of useful diagnostic tools. We believe there is potential to develop a semi-automated capability for quick-look case studies, leveraging off our experience, that would facilitate rapid turnaround analysis of severe weather events.

Operational ensemble numerical weather prediction has now come to Australia. As people gain experience and confidence with the new data, we expect that better outcomes will progressively be realised. A particular challenge will be providing people with experience with ensemble products in the relatively rare, but critically important, severe weather events. We now have ensemble simulations of an east coast low and a severe thunderstorm event that could be used as the basis for training exercises for all involved personnel.

## PYROCB PREDICTION

### Description

For pyroCb prediction, our major utilisation focus is on the near-real time trial planned for this summer, where we will issue maps of the PFT on several domains covering various areas of Australia. These maps will be issued at at least 6-hourly intervals for at least 36, and hopefully 72, hours ahead, and be based on the Bureau's operational NWP suite. We, and partners within fire agencies, will monitor the performance during the summer. We aim to assess not only the accuracy of the information, but also to gain insights into how best to present and interpret it.

We have already been collaborating with the Bureau's training section to help develop training in pyroCb processes for Bureau forecasters. We are hoping that the trial will also help us better understand how to adapt this training material for the different needs of fire agency staff as well.

### Extent of Use

- At present, testing with selected Bureau forecasters is underway. The main activity will occur over this coming summer.

### Utilisation Potential

- Further utilisation of the PFT will require more robust infrastructure and delivery mechanisms, but it is premature to develop this at this stage.

### Utilisation Impact

- Will be reported following the trial.

### Utilisation and Impact Evidence

- Will be reported following the trial.

## QUICK-LOOK CASE STUDIES

### Description

After almost a decade of experience with very high resolution NWP-based case studies, several factors have coincided to allow us to offer the development of a facility to perform semi-automated, rapid turnaround, quick-look case studies of severe weather events. These factors are the growth in computer power, the improvements in modelling infrastructure (particularly the scheduling software that manages the running of these complex systems), and the growth in our diagnostic suite.

These studies would involve running the model to 400-m resolution, centred over an event of interest, and producing a standard suite of diagnostic plots. As well as supplementing existing post-event analysis tools, they would help identify cases for in-depth study.

### Extent of Use

- None at present

### Utilisation Potential

- Considerable.

### Utilisation Impact

- To be determined.

### Utilisation and Impact Evidence

- Will be reported when and if implemented.

## ENSEMBLE PREDICTION

### Description

We have two high-resolution ensemble simulations of severe weather events, together with detailed analyses of the associated meteorology. Potentially, these could form the basis for emergency response simulations aimed at improving the use and uptake of ensemble information. This would be timely, as the Bureau has recently implemented its first operational ensemble NWP system. While at relatively coarse resolution and on a global scale, it, is expected to be supplemented by a moderately high-resolution system in the not too distant future.

## Extent of Use

- None at present

## Utilisation Potential

- Considerable.

## Utilisation Impact

- To be determined.

## Utilisation and Impact Evidence

- Will be reported when and if implemented.

# NEXT STEPS

For pyroCb prediction, our major upcoming focus is on the near-real time trial planned for this summer, where we will issue maps of the PFT onseveral domains covering various areas of Australia. These maps will be issued at at least 6-hourly intervals for at least 36, and hopefully 72, hours ahead, and be based on the Bureau's operational NWP suite. We, and partners within fire agencies, will monitor the performance during the summer. We aim to assess not only the accuracy of the information, but also to gain insights into how best to present and interpret it.

We have already been collaborating with the Bureau's training section to help develop training in pyroCb processes for Bureau forecasters. We are hoping that the trial will also help us better understand how to adapt this training material for the different needs of fire agency staff as well.

Work on the SA tornado outbreak is all but complete, with only the finalisation of a paper to go. We expect to submit that paper shortly.

That study and the earlier work on the east coast low of April 2015 both featured high-resolution ensemble simulations. We are exploring whether they can be used as a training resource, to help prepare forecasters and users for the coming of ensemble prediction to Bureau operations.

The Tathra bushfire case study has made excellent progress on the science, and we are aiming to begin writing a report shortly. It provides an excellent insight into the complexities of flow over topography. We expect that the report and presentations on this event will help to further raise consciousness of the issues that matter when managing fires in similar situations.

Finally, we will resume work on the development of a parameterisation of long-range ember transport shortly. While this work has been much delayed, we nevertheless remain confident that it is both achievable and important, and will be devoting significant resources to it.

# PUBLICATIONS LIST

## PEER REVIEWED JOURNAL ARTICLES

Tory, K. J., W. Thurston and J. D. Kepert, 2018: Thermodynamics of pyrocumulus: A conceptual study. *Mon. Wea. Rev.*, **146**, 2579–2598, doi:10.1175/MWR-D-17-0377.1.

Zovko-Rajak, D., K. J. Tory, R. J. B. Fawcett, J. D. Kepert and L. J. Rikus, 2018: High-resolution ensemble prediction of the Australian East Coast Low of April 2015. *J. South. Hemisph. Earth Sys. Sci.,* 165 – 183.

## OTHER PEER REVIEWED JOURNAL ARTICLES

Kepert, J. D., 2018: The boundary layer dynamics of tropical cyclone rainbands. *J. Atmos. Sci.*, **75**, 3777–3795, doi:10.1175/JAS-D-18-0133.1.

Zieger, S., D. J. M. Greenslade and J. D. Kepert, 2018: Wave ensemble forecasts for tropical cyclones in the Australian region. *Ocean Dynamics*, 23pp, doi:10.1007/s10236-018-1145-9.

## EXTENDED ABSTRACTS

Tory, K.J. and J.D. Kepert: Insights from the development of a pyrocumulonimbus prediction tool. Proceedings, Bushfire and Natural Hazards CRC & AFAC conference Perth, 5 – 8 September 2018, 277 – 288.

## TECHNICAL REPORTS

Tory, K.J., 2018: *Models of Buoyant Plume Rise*, BNHCRC, https://www.bnhcrc.com.au/publications/biblio/bnh-5267, 26pp.

## CONFERENCE PAPERS

Aijaz, S.A., J. D. Kepert, H. Ye, Z. Huang and A. Hawksford, Bias correction of tropical cyclone structure in global ECMWF-ensemble prediction system for NW Australia. Presented at the 35th AMS Conference on Hurricanes and Tropical Meteorology, Ponte Vedra, FL, April 2018.

Kepert, J.D., The boundary layer dynamics of tropical cyclone rainbands. Presented at the 35th AMS Conference on Hurricanes and Tropical Meteorology, Ponte Vedra, FL, April 2018.

Kepert, J.D., S Aijaz, H. Ye, Z. Huang, D. Greenslade, S. Zieger and A. Hawksford, Bias correction of tropical cyclone intensity and structure in an ensemble prediction system. Presented at NOAA Hurricane Research Division, Miami, FL, 23 April 2018.

Tory, K. J., W. Thurston, J. D. Kepert: Thermodynamics of pyrocumulus formation. Presented at the EGU General Assembly, Vienna, Austria, April 2018.

Tory, K. J., W. Thurston, J. D. Kepert: The modest role of pyrogeneous moisture in pyrocumulus development. Presented at the EGU General Assembly, Vienna, Austria, April 2018.

Tory, K. J. and H. Ye: Identifying future changes in regions of tropical cyclone formation. Presented by Jeff Kepert at the 35th AMS Conference on Hurricanes and Tropical Meteorology, Ponte Vedra, FL, April 2018.

Zovko-Rajak, D., K. J. Tory, R. J. B. Fawcett, and J. D. Kepert: High-resolution ensemble prediction of the Australian East Coast Low of April 2015. Presented at the AOGS 15th Annual Meeting, Honolulu, Hawaii, June 2018.

Zovko-Rajak, D., K. J. Tory, J. D. Kepert, J. Fisher and M. Bass: A case study of South Australia's severe thunderstorm and tornado outbreak (28 September 2016). Poster presented at AFAC Conference.

Zovko-Rajak, D., Improving predictions of severe weather and saving lives. Presented at the Science at the Shine Dome Annual Symposium - Predict, Respond, Recover: science and natural disasters, Canberra, 22 May 2018.

# TEAM MEMBERS

## RESEARCH TEAM

### Jeff Kepert

Jeff began his career with the Bureau as a forecaster, before moving into training and then research. As a researcher, Jeff has spent most of his career on tropical cyclone and bushfire meteorology, but also worked for a while on data assimilation. He is prominent nationally and internationally, having convened major conferences, edited journals and served on the Australian Standards Wind Loading committee.

Jeff particularly values working as a researcher for the Bureau, because it not only provides an environment to do high standard research on interesting weather, but also the opportunity and support to see that research used to improve our ability to manage severe weather, thereby saving lives, property and money.

### Kevin Tory

Kevin Tory is a member of the High Impact Weather Research team from the Bureau of Meteorology.

Kevin began his research career with the Bureau almost 20 years ago, and in that time has worked in a wide range of areas including: weather model verification, air quality modelling, tropical cyclone dynamics with a focus on their formation, tropical cyclone projections in a future warmer world, and bushfire meteorology. In this time, he has published regularly in prominent international journals, and has internationally recognised expertise in tropical cyclone formation and tropical cyclone detection.

Kevin enjoys working as a researcher in the Bureau, surrounded by experts in a wide range of weather-related fields, such as modelling, forecasting, observing and dynamical understanding. Having this highly valuable resource at hand is a major contributor to the quality of his research and other researchers in the organisation.

### Dragana Zovko Rajak

Dragana Zovko Rajak was born in Mostar, Bosnia and Herzegovina. She completed undergraduate studies in physics and geophysics at the University of Zagreb, Croatia, and her PhD at the School of Earth Sciences at the University of Melbourne in 2016. Her PhD thesis focused on examining possible mechanisms and sources of turbulence generation around thunderstorms using a three-dimensional numerical model. This work has important implications not only for the aviation industry but also for fundamental understanding of turbulence and cloud–environment interactions. Since 2016, Dragana has been a part of the High Impact Weather team at the Bureau of Meteorology. Her research involves application of numerical weather prediction systems to high impact weather, as well as understanding the physical processes that contribute to severe weather events in Australia, including east coast lows and severe thunderstorms.

### David Wilke

David Wilke is currently on an assignment of duties as a researcher in the High Impact Weather research team from the Bureau of Meteorology. David completed a PhD in fluid dynamics at the University of Adelaide in 2016 with a project considering blood flow in the umbilical cord. Since 2015 he has been working as a meteorologist in the NSW regional forecasting centre.

David's primary focus is running very high-resolution simulations of the Tathra bushfire in order to better understand the event and characterise the severe fire weather that developed. He is also part of a Bureau and Geoscience Australia team developing a prototype workflow for an impact forecast. This is an endeavour to combine numerical weather prediction output and information regarding the built environment into a spatial representation of impacts to inform forecasters and stakeholders of the effects of severe weather.

### Serena Schroeter

Serena is a researcher in the High Impact Weather Research team from the Bureau of Meteorology. Her research concentrates on the development and application of numerical weather prediction (NWP) systems to better understand atmospheric dynamics and physical processes contributing to severe weather events in Australia, as well as the downstream impacts that occur during these events. Serena's primary focus is developing a parameterisation for the transport of embers in bushfire plumes to aid in the improvement of operational fire spread predictions. She is also part of a Bureau and Geoscience Australia team developing an automated workflow to translate operational numerical weather prediction forecasts into a spatial representation of likely impacts of severe weather events on the built environment.

Serena is also a PhD candidate in Quantitative Marine Science at the University of Tasmania's Institute for Marine and Antarctic Studies. She is examining climate interactions with Antarctic sea ice in global coupled climate models to determine the cause of discrepancies between observed and modelled sea ice trends, to aid in future model development.

Serena has now left the team to pursue a postdoctoral appointment in climate science.

## END-USERS

Allen Gale, Department of Fire and Emergency Services, WA.

Andrew Grace, Attorney-General's Department.

Frank Crisci, SA Powernet.

Stephen Gray, Department of Fire and Emergency Services, WA.

John Bally, AFAC.

Lachie McCaw, Department of Environment and Conservation, WA.

Paul Fox-Hughes, Bureau of Meteorology.

Simon Heemstra, Rural Fire Service, NSW.

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