



FIRE COALESCENCE AND MASS SPOT FIRE DYNAMICS: EXPERIMENTATION, MODELLING AND SIMULATION

Annual project report 2018-2019

Jason Sharples¹, James Hilton², Andrew Sullivan³

UNSW Australia¹, CSIRO Data61², CSIRO Land and Water³



UNSW
AUSTRALIA





Version	Release history	Date
1.0	Initial release of document	31/03/2020



Australian Government
Department of Industry, Science, Energy and Resources

Business
 Cooperative Research Centres Program

All material in this document, except as identified below, is licensed under the Creative Commons Attribution-Non-Commercial 4.0 International Licence.

Material not licensed under the Creative Commons licence:

- Department of Industry, Science, Energy and Resources logo
- Cooperative Research Centres Program logo
- Bushfire and Natural Hazards CRC logo
- All other logos
- All photographs, graphics and figures

All content not licenced under the Creative Commons licence is all rights reserved. Permission must be sought from the copyright owner to use this material.



Disclaimer:

UNSW, CSIRO and the Bushfire and Natural Hazards CRC advise that the information contained in this publication comprises general statements based on scientific research. The reader is advised and needs to be aware that such information may be incomplete or unable to be used in any specific situation. No reliance or actions must therefore be made on that information without seeking prior expert professional, scientific and technical advice. To the extent permitted by law, UNSW, CSIRO and the Bushfire and Natural Hazards CRC (including its employees and consultants) exclude all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

Publisher:

Bushfire and Natural Hazards CRC

March 2020

Citation: Sharples JJ, Hilton JE, Sullivan AL (2019) Fire coalescence and mass spot fire dynamics: experimentation, modelling and simulation - Annual project report 2018-2019, Bushfire and Natural Hazards CRC, Melbourne.

Cover: Grampians Fire, February 2013. Source: Randall Bacon, CFA



TABLE OF CONTENTS

EXECUTIVE SUMMARY	3
END-USER STATEMENT	4
INTRODUCTION	5
PROJECT BACKGROUND	7
Level set methods for interface modelling	8
WHAT THE PROJECT HAS BEEN UP TO	10
Milestone delivery	10
Research Progress	10
Presentations	14
End-user engagement	14
Progress of the PhD scholar	14
PUBLICATIONS LIST	15
CURRENT TEAM MEMBERS	16
Additional team members	16
REFERENCES	17



EXECUTIVE SUMMARY

This report outlines the progress of the *Fire Coalescence and Mass Spot Fire Dynamics* project, which is one of the projects within the Next Generation Fire Modelling cluster. Specifically, the report summarises progress of the first year of the second phase of the project, which has been extended over 2018-2021.

All milestones from the 2015-2018 phase of the project have now been delivered, and the project is continuing to build upon this work in delivering important insights into the dynamics of fire behaviour and fire line interaction. Phase 2 of the experimental program is in progress, and will extend recently published work from Phase 1. The project continues to yield important and significant insights into the behaviour of coalescing fires, and these insights are enhancing our understanding of the processes driving fire propagation and the way we model dynamic fire behaviours.

In particular, the research has continued to develop the pyrogenic potential model by incorporating the effects of pyrogenic vorticity. This has resulted in the world's first capability to model dynamic modes of fire propagation such as vorticity-driven lateral spread using a two-dimensional simulation framework. This means that explicitly modelling such effects in operational timeframes is now a feasible option. Coupled fire-atmosphere simulations continue to provide fundamental insights that will be drawn upon to inform further the development of the pyrogenic potential model.

In the past year, the project team have delivered a number of research outputs, including conference presentations and posters and a journal publication (currently under review). A number of other publications are in preparation. The project team has also delivered on a number of key utilisation activities. These have mainly involved discussions with key end-users about the prospects of the research being incorporated into education materials and training resources for firefighters and fire behaviour analysts.

After providing some background information on the project's aims and methodology, this report provides details on the progress of the project to date. In particular, this includes:

- Milestone delivery;
- New research developments;
- Utilisation activities;
- Details on presentations that have been delivered by members of the project team;
- Details on publications and publications in preparation;

At the time of writing, the project is on-schedule.

A/Prof. Jason Sharples
Project Leader
School of Physical, Environmental and Mathematical Sciences,
UNSW Australia



END-USER STATEMENT

Brad Davies, *New South Wales Rural Fire Service, NSW*

The project continues to apply an innovative multi-streamed approach to better understand and efficiently model dynamic fire behaviours associated with fire coalescence and mass spotting. In particular, the project team have developed computationally efficient approaches to model dynamic fire behaviours such as spot fire coalescence, fire line merging and vorticity-driven lateral spread. The project is now well into developing ways in which the research can be incorporated into operational practice.

Over the past year, the project team has engaged with end-users through seminars, forums, workshops, online events and direct discussion with the Project Leader. The project continues to produce excellent research publications, and project members are consistently available to assist end-users in their interpretation. Discussions around research utilisation, including the development of operational products, and education and training materials have progressed, and additional ways this exciting work can be utilized are continuing to emerge as the research evolves. The research is directly relevant to many of the issues encountered in managing catastrophic fires and is strongly enhancing our understanding and predictive capacity of dynamic fire behaviours.



INTRODUCTION

Fire behaviour in dry eucalypt forests in Australia (and in many other vegetation types to a lesser extent) is characterised by the occurrence of spot-fires—new fires ignited by the transport of burning debris such as bark ahead of an existing fire. Under most burning conditions, spot-fires generally play a minor role in the overall propagation of a fire, except perhaps when spread is impeded by breaks in fuel or topography which spot-fires enable the fire to overcome. However, under conditions of severe and extreme bushfire behaviour, spot-fire occurrence can be so prevalent that spotting becomes the dominant propagation mechanism and the fire spreads as a cascade of spot-fires forming a 'pseudo' front (McArthur 1967).

It has long been recognised that the presence of multiple individual fires affects the behaviour and spread of all fires present. The convergence of separate individual fires into larger fires is called coalescence and can lead to rapid increases in fire intensity and spread rate, often in directions at odds with the prevailing wind. This coalescence effect is frequently utilised in prescribed burning via multiple point ignitions to rapidly burn out large areas.

The zone between two coalescing fires is known as the convergence or junction zone and can be a very dangerous place to be for firefighters and may lead to highly erratic fire behaviour as witnessed during the 2003 Canberra fires. Fire behaviour under such conditions may be dominated by dynamic feedback processes between the energy released by each fire and the coupling of that energy with the atmosphere.

All existing operational fire behaviour models assume that a fire will burn at an approximately constant (quasi-steady) rate of spread for a given set of environmental conditions. While recent work showed that an individual fire starting from a point accelerates to this steady state, little research has been undertaken into the behaviour of multiple simultaneous adjacent ignitions under wildfire conditions or the effects of the dynamic feedbacks involved. No operational fire spread models currently account for the dynamical aspects of fire spread, particularly fire-fire interactions. This inability to accurately predict the behaviour of mass spotting events and the interactions of multiple adjacent fires places firefighters at risk and the general public in danger. With the projected climate change impacts expected to produce more extreme bushfires and a prevalence of mass fire behaviour, this deficiency in our understanding and operational systems represents a considerable knowledge gap.

The effects of dynamic processes on fire spread cannot be calculated using tables, spreadsheets or simple calculators. To comprehensively account for the effects of dynamic fire spread it is necessary to model the phenomenon using a physics-based model that incorporates complete descriptions of the key processes, including interactions between the fire, the fuel, topography and the surrounding atmosphere (e.g. WFDS (Mell et al 2007), FIRETEC (Linn et al 2002)). Unfortunately, such a modelling approach is computationally intensive and expensive, with associated model run-times that prohibit operational application (Sullivan 2009).



This project addresses these issues by investigating the processes involved in the coalescence of free-burning fires under experimentally controlled conditions, quantifying the physical mechanisms involved in these, and investigating the potential of geometric drivers of fire line propagation with the aim of developing a physically simplified proxy for some of the more complicated dynamical effects, particularly those driven by pyroconvective interaction between different parts of the fire(s). This approach enables development of models that are able to effectively emulate the dynamics of fire spread without the need to explicitly model fire-atmosphere or fire-fire interactions in a computationally costly manner.

PROJECT BACKGROUND

To enhance our knowledge of the effects of intrinsic fire dynamics on fire spread this project employs sophisticated mathematical modelling techniques in combination with fire experiments spanning laboratory and landscape scales. In particular, the project will develop computationally efficient fire spread models which include physically simplified proxies for complicated dynamical effects.

The overarching analytical approach adopted in this project is to treat fire as an evolving interface. This is not new – many researchers have treated fire in such a way, but the methods they have used have often been confounded due to the changes in topology that can be encountered when fire lines merge or when pockets of unburnt fuel develop (Bose et al. 2009). Such occurrences are rife when spot fires coalesce (see Figure 1), and so employing a methodology that is able to successfully deal with these types of behaviours is crucial to effectively and efficiently model spot fire development. We therefore employ a level set approach, which is well known to be able to deal with such complexities (Sethian, 1999).

In addition to its ability to deal with topological changes, the level set method also allows for the easy inclusion of additional dynamic drivers, which we aim to include as two-dimensional proxies for more complicated three-dimensional effects.

Phase 2 of the project builds on work completed in phase 1 by members of the project team, who have investigated the use of potential flow to simulate instances of dynamic fire propagation such as fire line merging (Sharples et al. 2013; Hilton, 2014).

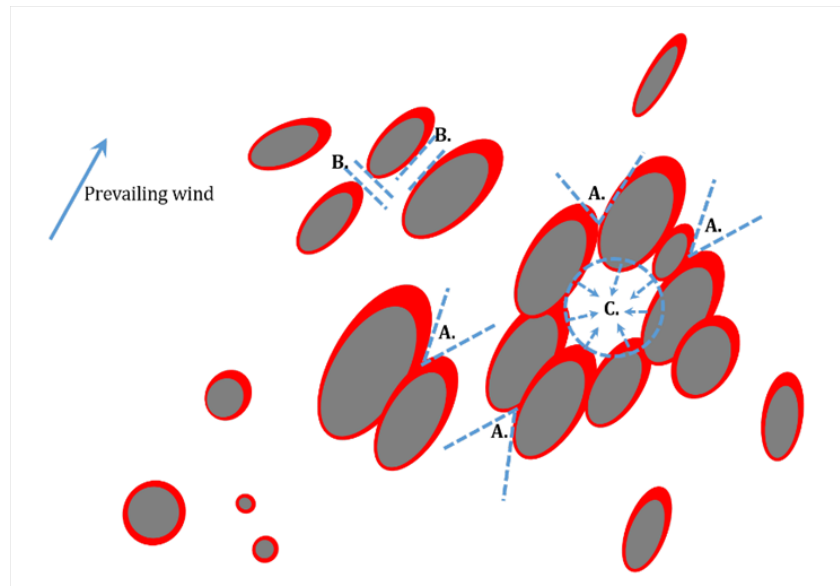


Figure 1: Schematic representation of coalescing spot-fires and forms of interaction between individual spots. Examples of fire line interactions include (A) intersecting oblique lines, non-intersecting converging fire edges (B) and collapsing or constricting perimeters (C). These can be oriented at any angle to the prevailing wind.

To complement model development the project also includes a targeted experimental program. This will involve analysis of experimental fires burning under controlled laboratory conditions, analysis of available field experiments and numerical experiments using couple fire-atmosphere models.

LEVEL SET METHODS FOR INTERFACE MODELLING

Level set methods provide a feasible method for dealing with the types of behaviours encountered when spot fires coalesce. Figure 1 shows a schematic representation of coalescing spot fires and the types of topological issues that can arise due to the discontinuous nature of spot fires.

Fire simulation incorporating pyrogenic potential

A main focus of the research has been the continued development of the 'pyrogenic potential' model. This model adopts the notion that the pyroconvective interactions between different parts of the fire line (or fire lines) arise due to development of pyrogenic indrafts. These indrafts are modelled as a two-dimensional surface flow with a sink everywhere along the fireline. This is shown schematically in Figure 2. The figure shows that the air flowing horizontally into a fire's plume can be treated as an two-dimensional incompressible flow everywhere except along the fire line, where it becomes a purely vertical flow (the two-dimensional flow disappears along the fire line, which is then treated as a 'sink' for the flow).

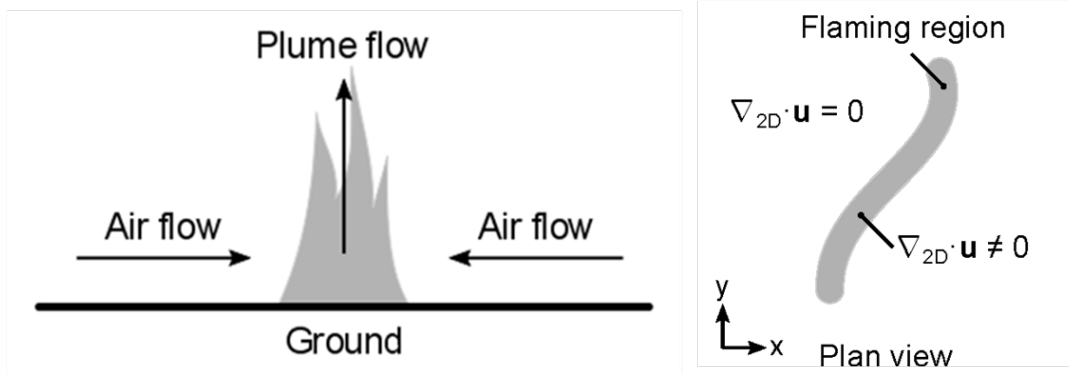


Figure 2: Left: Schematic view of the indraft into a fire plume. Right: Schematic view of a fire line as a sink for the horizontal indraft into the fire's plume.

Initial limitations of the model, which required the indraft flow to be irrotational, have been overcome through use of a near-field approximation via the Helmholtz decomposition. In this sense we assume that we can write it as the gradient of a pyrogenic potential function ψ . In the presence of an ambient wind, the fire's propagation is then driven by the sum of the ambient wind and the pyrogenic indraft $\nabla\psi$. This gives rise to the upgraded level set formulation, in which fire line curvature has been removed, and instead the level set equation is coupled with a Poisson equation for the pyrogenic potential:

$$\frac{\partial \phi}{\partial t} = s \|\nabla \phi\| + (\mathbf{u}(\gamma) + \mathbf{U}_p) \cdot \nabla \phi, \quad \mathbf{U}_p = \nabla \psi + \nabla \times \boldsymbol{\eta} \quad (3)$$

where $\nabla^2\psi = \rho$ and $\nabla^2\eta = \omega$.

Here $\rho = kf(R, \varphi, \nabla\varphi)$, where k can be considered a tuning parameter, and f is a function of the local rate of spread R , and the level set function and its derivative. The term ω represents sources of vertical pyrogenic vorticity.

We refer to the model in equation (3) as the 'pyrogenic potential model' or the 'near-field model'.

Note also that the advective effect of the ambient wind on fire propagation is modeled as follows:

$$\mathbf{u}(\gamma) = \begin{cases} \gamma(\hat{\mathbf{w}} \cdot \hat{\mathbf{n}})\hat{\mathbf{w}} & \text{if } \hat{\mathbf{w}} \cdot \hat{\mathbf{n}} > 0, \\ 0 & \text{if } \hat{\mathbf{w}} \cdot \hat{\mathbf{n}} \leq 0. \end{cases} \quad (4)$$

Here $\hat{\mathbf{w}}$ and $\hat{\mathbf{n}}$ are the unit vectors pointing in the direction of the wind and normal to the interface, respectively. The model defined by (3) and (4) has been applied to a number of different fire behaviour scenarios. It has successfully reproduced the observed behaviour of a number of experimental fires (across scales from 1 metre to 10s of metres), and is able to emulate expected dynamic fire behaviours, such as fire line merging.

More recently, the near-field model has been applied to modes of dynamic fire propagation such as vorticity-driven lateral spread.

Laboratory experiments

Phase 2 of the laboratory experiments using the CSIRO Pyrotron facility will be conducted. These experiments will be broken down into the following three categories:

- Parallel fire line experiments
- Ring fire experiments
- Multiple spot fire experiments

The ring fire experiments are currently in progress.

Field experiments

In addition, the project will draw upon data collected by Portuguese Researchers as part of Project Firewhirl: Vorticity Effects in Forest Fires (on which Sharples is a co-investigator).

Numerical experiments

Development of the near-field model will continue to be informed by a number of targeted numerical simulations using a coupled fire-atmosphere model.

In particular this work will consider the fundamental in-draft patterns produced by small fire sources to investigate the scalability of the near-field model.



WHAT THE PROJECT HAS BEEN UP TO

MILESTONE DELIVERY

At the time of writing, the project has completed 17 of the phase 2 milestones, which includes some for the July-September 2019 quarter. In particular, all milestones for quarters 1.4, 2.1, 2.2 and 2.3 have been delivered. This report will constitute completion of the remaining milestone for quarter 2.4.

As such, the project is on schedule with its milestone delivery. No delays are expected going into the immediate future.

RESEARCH PROGRESS

The research has mainly progressed through further development of the near-field model. Two main aspects of this research are worth reporting:

1. Comparison with coupled fire-atmosphere output; and,
2. Application to simulation of patterns of fire propagation associated with vorticity-driven lateral spread.

Coupled fire-atmosphere simulations

A coupled fire-atmosphere model was used to model the wind field produced by a static circular heat source. All physics options were turned off and the model was run without turbulent diffusion. The model was initialised with no moisture and with a vertical temperature profile consisting of a 1000-metre-deep dry-adiabatic layer at a constant potential temperature of 300 K, topped by a stable layer with potential temperature increasing at 4.5 K per kilometre to the model top. A circular static sensible-heat flux with radius 100 metres and intensity $I = 5 \times 10^4 \text{ Wm}^{-2}$ was introduced at the centre of the computational domain and the model was run for one hour to collect wind field data.

Figure 3 shows the radial profiles of wind speed output from the coupled model at 2 metres AGL, and two analytical solutions with different values of ν , which describes the relative strength of the pyrogenic indraft. Note that the analytical solutions are identical to what would be produced by the two-dimensional near-field model. The coupled model's profile has the same general form as the analytic solutions, although it peaks at a radial distance very close to $r = a/2$, whereas the analytical solutions peak at $r = a$.

These results will continue to be explored to identify optimal parameterisations for the two-dimensional near-field model.

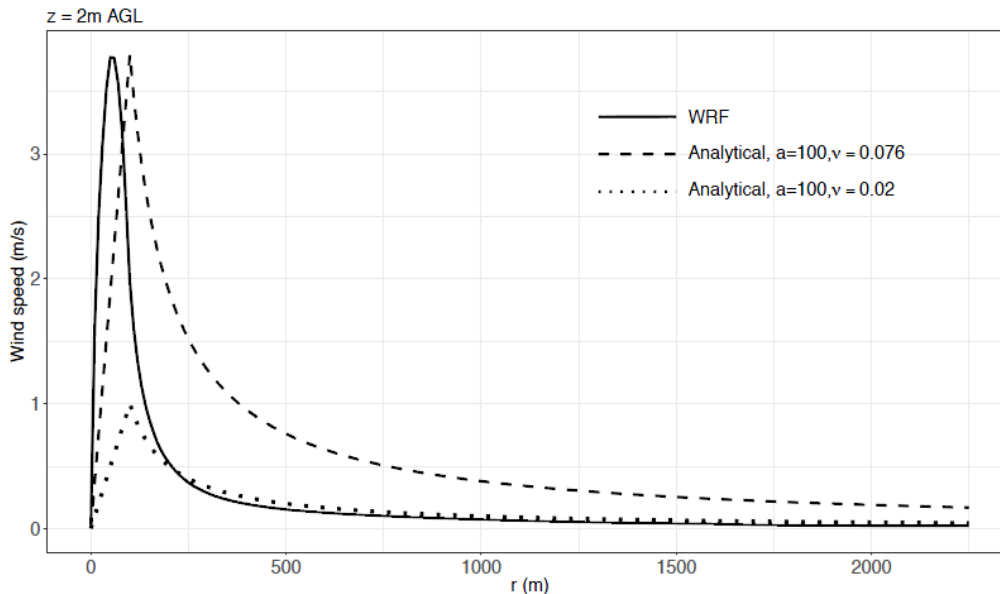


Figure 3: Comparison of radial profiles of near-surface wind speed resulting from static circular heat source of $a = 100$ metres radius (r is measured from the centre of the heat source). The solid line is the WRF solution at 2 metres AGL with $I = 5 \times 10^4 \text{ Wm}^{-2}$. The broken lines are analytical solutions for a point heat source. The values of ν are arbitrary: $\nu = 0.076$ makes the peak of the analytical solution approximately equal to that of WRF, while $\nu = 0.02$ makes the analytical solution approximately match the WRF solution for $r > 200$ metres. Figure taken from Thomas et al. (2018).

At the time of writing the project team is working to reconcile the pyrogenic wind field generated by the coupled fire-atmosphere model and the two-dimensional fire propagation models that have been developed.

Fire simulation incorporating pyrogenic potential

A main focus of the research in the first year of phase 2 has been extending the pyrogenic model to incorporate rotational flow effects. Specifically, this work has permitted the inclusion of pyrogenic vorticity. This in turn has facilitated development of a two-dimensional simulator that is able to emulate dynamic modes of fire propagation such as vorticity-driven lateral spread (VLS).

This particular mode of fire propagation can pose a significant danger to firefighter and civilian safety, and has been implicated in the development of violent pyroconvection. The distinctly dynamic nature of VLS means that it has not been possible to model the phenomenon using current operational fire simulation platforms, which rely on the assumption of quasi-steady fire spread.

Hilton et al. (2018) detailed a two-dimensional fire spread model that incorporates an induced 'pyrogenic' air flow close to the ground (mid-flame height). The model has the distinct advantage of being very computationally efficient. In the near-field (i.e. not too far away from the fire), the induced flow can be modelled as the combination of an irrotational flow and a rotational flow, the latter of which can be interpreted as pyrogenic vorticity. This provides a



computationally efficient way to simulate vorticity-driven wildfire propagation. Figure 4 gives a basic example of how a point source of vertical vorticity influences the propagation of a nearby fire.

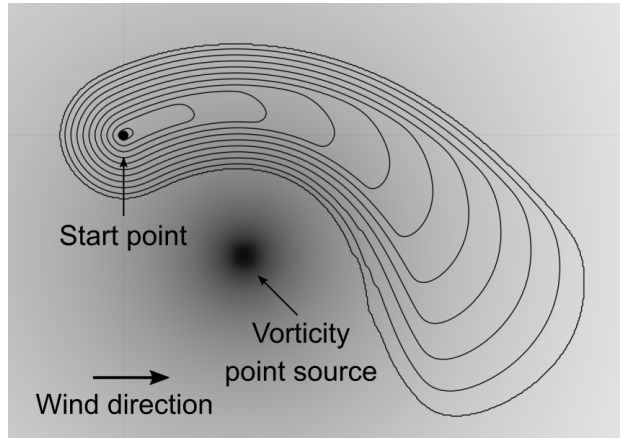


Figure 4: Example application of the pyrogenic potential model with vortex source term to a dynamic wildfire simulation. The black lines show isochores of a fire perimeter and the shading represents the vertical component of the vector (vortex) potential.

Simulating VLS using the near-field modelling approach (equation (3)), requires a method for converting the ambient horizontal vorticity that occurs when winds flow over a leeward slope into an appropriate vertical vorticity ω_p (representing that produced by the fire). Sharples and Hilton (2019) considered the schematic set up in Figure 5, and derived an expression for the pyrogenic vorticity as

$$\omega_p = k' \delta(|\mathbf{x} - \mathbf{x}'|) \delta(\phi) (\hat{\mathbf{n}} \cdot \mathbf{s}_{xy}).$$

where $k' = u_z k$, \mathbf{x}' is the nearest point on the line source to \mathbf{x} , ϕ is the distance from the fire perimeter, \mathbf{s}_{xy} is the ambient horizontal vorticity and $\hat{\mathbf{n}}$ is the outward normal of the fire perimeter. This gives rise to a source where $\nabla u_z \cdot \mathbf{s}_{xy} > 0$ and a sink where $\nabla u_z \cdot \mathbf{s}_{xy} < 0$ resulting in two counter-rotating vortices, as illustrated in Fig. 6.

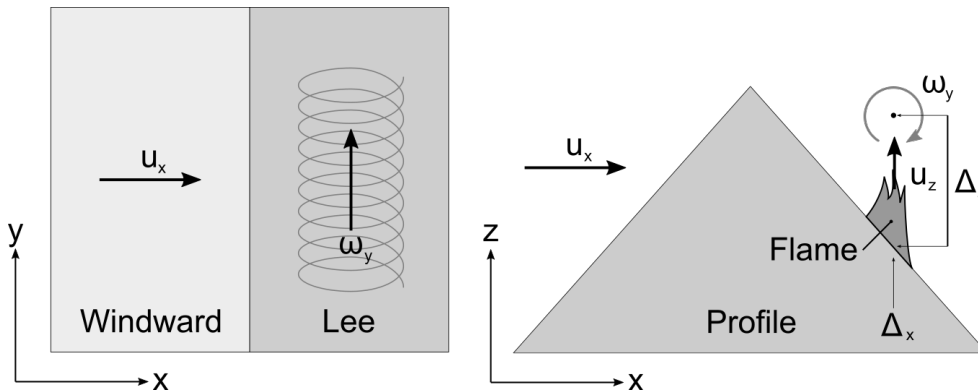


Figure 5: Schematic set-up of the near-field model for VLS simulation

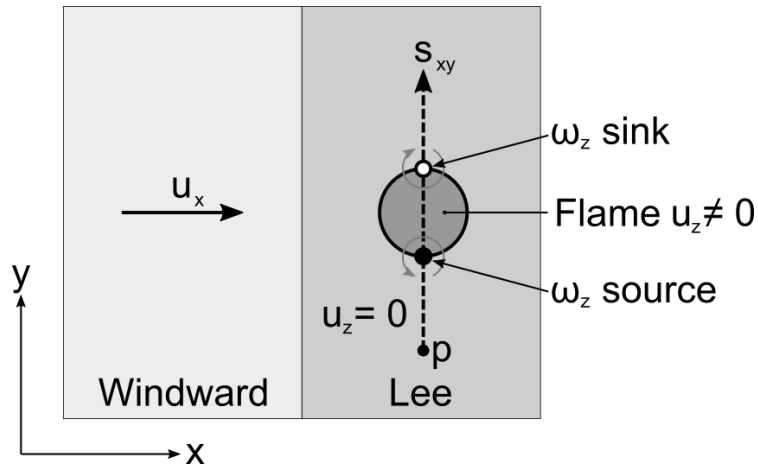


Figure 6: Resultant vorticity in the z direction and circulation in the xy plane from an idealised plume.

Figure 7 compares VLS simulation using a fully coupled fire-atmosphere model (approx. 10 hours simulation time) with that obtained using the 2D pyrogenic potential model (approx. 10 seconds simulation time). The simpler model is able to capture the key characteristics of VLS. Some differences remain on the leeward slopes, below the main region of lateral spread. These are likely due to flow turbulence in the coupled model, which is not accounted for in the pyrogenic potential model.

Nevertheless, the pyrogenic potential model offers a feasible operational approach to modelling dynamic modes of fire propagation. Ongoing research will refine the model and increase its suitability for use in operational environments.

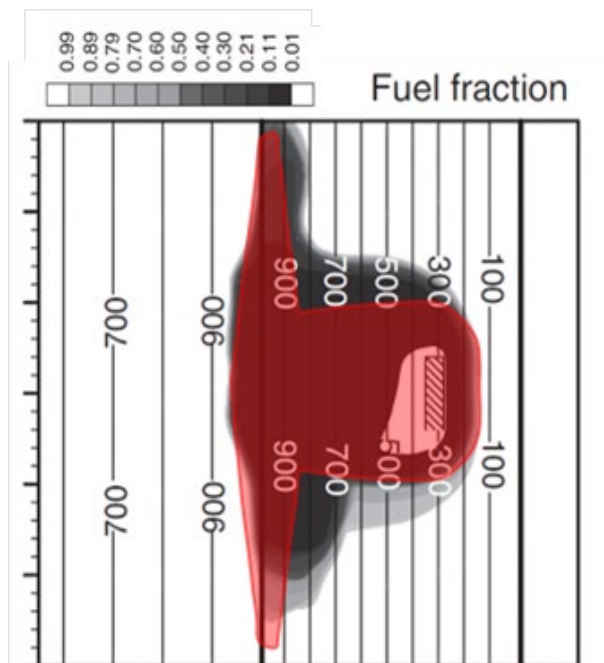


Figure 7: VLS simulated using a coupled fire-atmosphere model (grey scale), overlaid with corresponding output from the 2D pyrogenic potential model (red shading).



PRESENTATIONS

The project has delivered the following presentations and posters:

1. **MODELLING THE DYNAMIC EVOLUTION OF BUSHFIRES.** Presentation at the 2018 Australian Academy of Science – Science at the Shine Dome Symposium, Canberra, May 2018. Delivered by J. Sharples.
2. **PREDICTING FIRESTORM OCCURRENCE.** Presentation at the 2018 NSW Rural Fire Service Association Conference, Sydney, July 2018. Delivered by J. Sharples.
3. **DYNAMIC MODELLING OF EMBER STORMS.** Presentation at the 6th International Fire Behaviour and Fuels Conference, Sydney, May 2019. Delivered by J. Hilton.
4. **RAPID MODELLING TECHNIQUES FOR THE INCLUSION OF LOCAL WIND AND PRESSURE FIELDS IN WILDFIRES.** Presentation at the 6th International Fire Behaviour and Fuels Conference, Sydney, May 2019. Delivered by J. Hilton.
5. **A UNIVERSAL RATE OF SPREAD INDEX FOR AUSTRALIAN FUEL TYPES.** Presentation at the 6th International Fire Behaviour and Fuels Conference, Sydney, May 2019. Delivered by J. Sharples.
6. **EXTREME WILDFIRE DEVELOPMENT AND IMPLICATIONS FOR THE WILDLAND URBAN INTERFACE.** Presentation at the 6th International Fire Behaviour and Fuels Conference, Sydney, May 2019. Delivered by J. Sharples.
7. **FIRE-ATMOSPHERE INFLUENCES ON MEGAFIRES.** Presentation at the Science to Understand Megafire Interactions with the Atmosphere Workshop, Los Alamos, July 2019. Delivered by J. Sharples.

END-USER ENGAGEMENT

Members of the project team engaged with various end-users a number of times throughout the year. The main user engagement activities are included in the list of presentations provided above. Specifically these activities included:

- The 2018 AFAC/Bushfire and Natural Hazards CRC conference
- The 2018 Bushfire and Natural Hazards CRC Research Advisory Forum
- The 2019 Bushfire and Natural Hazards CRC Research Advisory Forum
- ACT Bushfire Council
- AFAC Predictive Services Group

PROGRESS OF THE PHD SCHOLAR

The PhD scholar (Chris Thomas) submitted his thesis, which has been examined. He is currently making minor corrections before resubmitting. Conferral of the degree is imminent.



PUBLICATIONS LIST

- Lahaye, S., Curt, T., Fréjaville, T., Sharples, J., Paradis, L., & Hély, C. (2018). What are the drivers of dangerous fires in Mediterranean France? *International Journal of Wildland Fire*, 27(3), 155-163.
- Lahaye, S., Sharples, J., Matthews, S., Heemstra, S., Price, O., & Badlan, R. (2018). How do weather and terrain contribute to firefighter entrapments in Australia? *International Journal of Wildland Fire*, 27(2), 85-98.
- Raposo, J. R., Viegas, D. X., Xie, X., Almeida, M., Figueiredo, A. R., Porto, L., & Sharples, J. (2018). Analysis of the physical processes associated with junction fires at laboratory and field scales. *International Journal of Wildland Fire*, 27(1), 52-68.
- Hilton, J. E., Sullivan, A. L., Swedosh, W., Sharples, J., & Thomas, C. (2018). Incorporating convective feedback in wildfire simulations using pyrogenic potential. *Environmental Modelling and Software*, 107, 12-24.
- Sullivan, A.L., Swedosh, W., Hurley, R.J., Sharples, J.J., Hilton, J.E. (2019). Investigation of the effects of interactions of intersecting oblique fire lines, with and without wind. *International Journal of Wildland Fire*. In press
- Thomas, C.M., Sharples, J.J., Evans, J.P. (2019). The terminal velocity assumption in simulations of long-range ember transport. *Mathematics and Computers in Simulation*. In press
- Sharples, J.J., Hilton, J.E., Sullivan, A.L. (2019). Pyroconvective interactions and spot fire dynamics. *Hazard Note*, BNHCRC, June 2019.
- Sharples, J.J., Hilton, J.E. (2019). Modelling vorticity-driven wildfire behaviour using near-field techniques. *Frontiers in Mechanical Engineering* (under review)
- Hilton, J.E., Garg, N., Sharples, J.J. (2019). Incorporating spotting in models of dynamic fire propagation. In 23rd International Congress on Modelling and Simulation. Canberra, Australia. (under review)
- Hilton, J.E., Sharples, J.J., Garg, N., Swedosh, W. (2019). Wind-terrain effects on firebrand dynamics. In 23rd International Congress on Modelling and Simulation. Canberra, Australia. (under review)
- Sutherland, D., Sharples, J.J., Moinuddin, K.A.M. (2019). The effect of ignition protocol on grassfire development. *International Journal of Wildland Fire*. (under review)



CURRENT TEAM MEMBERS

The research team is currently made up as follows:

A/Prof. Jason Sharples, UNSW

Dr James Hilton, CSIRO Data61

Dr Andrew Sullivan, CSIRO Land and Water

End-user/Advisory Committee – lead by Brad Davies, NSW Rural Fire Service.

ADDITIONAL TEAM MEMBERS

Mr Richard Hurley, CSIRO

Richard is a technical officer working at the CSIRO Pyrotron facility with Dr Sullivan. Richard is extensively involved in conducting the experimental program and as such is a crucial member of the project team.

Mr Will Swedosh, CSIRO Data61

Will is a graduate research officer working at CSIRO with Dr Hilton. Will is involved in implementing the level set models including pyrogenic potential and has been instrumental in analysing the Pyrotron experimental data. He has also contributed significantly to publications.

Additional assistance for experimental work in Phase 1 was provided by Dr Matt Plucinski and Mr Vijay Koul.



REFERENCES

- Bose, C., Bryce, R., Dueck, G. (2009) Untangling the Prometheus Nightmare. *Proceedings: 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009*
- Cruz, M.G., J.S. Gould, S. Kidnie, R. Bessell, D. Nicholls, and A. Slijepcevic (2015) Effects of curing on grassfires II. Effect of grass senescence on the rate of spread. *International Journal of Wildland Fire* 24, 838-848.
- Hilton, J.E. (2014) *Level set methods for fire fronts*. CSIRO Computational Informatics, Report No. EP141393.
- Hilton, J.E., Miller, C. Sharples, J.J., Sullivan, A.L. (2016) Curvature effects in the dynamic propagation of wildfires. *International Journal of Wildland Fire*, 25(12) 1238-1251.
- Linn, R., Reisner, J., Colman, J.J., Winterkamp, J. (2002) Studying wildfire behavior using FIRETEC. *International Journal of Wildland Fire*, 11(4), pp.233-246.
- McArthur, A.G. (1967) *Fire behaviour in eucalypt forests*. Commonwealth Department of National Development. Forestry and Timber Bureau, Leaflet 107, Canberra, ACT. 23 pp
- Mell, W., Jenkins, M.A., Gould, J., Cheney, P. (2007) A physics-based approach to modelling grassland fires. *International Journal of Wildland Fire*, 16(1), pp.1-22.
- Sethian, J.A. (1999) *Level Set Methods and Fast Marching Methods: Evolving Interfaces in Computational Geometry, Fluid Mechanics, Computer Vision, and Materials Science* (2 ed.). New York: Cambridge University Press.
- Sharples, J. J., I. N. Towers, G. Wheeler, V.-M. Wheeler, and J.A. McCoy (2013). Modelling fire line merging using plane curvature flow. *Proceedings: 20th International Congress on Modelling and Simulation*, pp. 297–303.
- Sullivan, A.L. (2009) Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models. *International Journal of Wildland Fire*, 18(4), pp.349-368.
- Sullivan, A.L., Knight, I.K., Hurley, R.J., Webber, C. (2013) A contractionless, low-turbulence wind tunnel for the study of free-burning fires. *Experimental Thermal and Fluid Science* 44, 264–274.
- C.S. Tarifa, P.P. del Notario, (1962) *Open Fires and Transport of Firebrands*, Technical Report, Instituto Nacional de Tecnica Aeronautica, Madrid,
- Thomas, C., Sharples, J.J., Evans, J.P. (2017) Modelling the dynamic behaviour of junction fires with a coupled atmosphere-fire model. *International Journal of Wildland Fire*, 26(4) 331-344.
- Viegas, D. X., Raposo, J.R., Davim, D.A., Rossa, C.G. (2012). Study of the jump fire produced by the interaction of two oblique fire fronts. Part 1. Analytical model and validation with no-slope laboratory experiments. *International Journal of Wildland Fire* 21, 843–856.