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PYROCONVECTIVE INTERACTIONS AND DYNAMIC FIRE PROPAGATION

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ABSTRACT

Pyroconvective interactions and dynamic fire propagation

Modelling the dynamic propagation of wildfires remains a significant challenge. Pyroconvective interactions between the fire and the atmosphere, or between different parts of the fire itself, can produce distinctly non-steady modes of fire propagation that cannot be accounted for using current operational models.

While sophisticated three-dimensional models (e.g. computational fluid dynamics (CFD) models or coupled fire-atmosphere models) have been successfully applied to wildfires, their computational requirements render them impractical for operational usage.

Here we discuss a computationally efficient two-dimensional propagation model, which can accurately replicate dynamic features of fire spread that cannot be simulated using existing two-dimensional models. These features include the development of a wind-driven fire line into a parabolic shape, attraction between nearby fires and the observed closing behaviour of junction fires. The model is compared to experimental results with good agreement.

The model incorporates a simple sub-model to account for the inflow of air generated by a fire, which allows the model to run orders of magnitude faster than full physical models, while still capturing many of the essential features of dynamic fire propagation. We argue that such a model could lead to significant improvements in operational wildfire prediction.

In addition, we will highlight some recent insights in to how the geometry of a fire line and the flaming zone influences development of the pyroconvective plume above a fire. In particular, we present evidence that the geometry of the burning region can affect plume development in a way that is comparable to the effect of total energy release.

INTRODUCTION

Computer modelling of wildfire behaviour is needed and used for a number of purposes. These range from risk management and operational predictions of a potential or actual wildfire in progress, to complex physics-based models investigating the complex processes and dynamics of wildfires. Currently, many operational prediction systems use rapid two-dimensional perimeter propagation models, which are based on empirical rate-of-spread models for various fuel types. Perimeter propagation models use a range of different computational algorithms such as cellular automata, front-tracking techniques and level set methods [1]. Generally, these methods track or model the fire perimeter and advance the perimeter based on local fuel, weather and topographic information to provide a prediction of the wildfire's extent at future times. Although very fast (taking on the order of seconds to minutes to complete a prediction of several simulated hours) they are limited by the nature of the perimeter propagation algorithm. In contrast, three-dimensional physics-based wildfire models can model the entire combustion and air flow dynamics around a wildfire to a high degree of accuracy as they are based on discretisation and solution of the fluid and thermo-dynamic equations [2]. Currently, however, these models are too slow to be used in operational predictions (taking on the order of hours to days to complete a prediction on a supercomputer).

MODELLING WITH NEAR-FIELD TECHNIQUES

We introduce a two-dimensional perimeter propagation model that incorporates aspects of a full three-dimensional physics-based model using near-field approximations to fire-induced flows. Specifically, the model comprises a two-dimensional perimeter propagation approach with an additional physics-based component allowing new types of fire behaviour to be predicted rapidly enough for operational usage. The additional component is a nearfield approximation to the ground-level fire-induced flow $\boldsymbol{u}$, which is represented using a Helmholtz decomposition in terms of a local scalar potential, ψ, and a vector potential, $\boldsymbol{\chi}$ (see Eq. (1)). The scalar potential is, essentially, the ground-level pressure field in the presence of any fires and the vector potential arises from any large-scale sources of vorticity present around the fire

$$\boldsymbol{u} = \nabla\psi + \nabla \times \boldsymbol{\chi}. \tag{1}$$

This new near-field model requires two additional computational steps in comparison to a standard perimeter propagation model. The first is the calculation of the source terms for the near-field and the second is the calculation of the field itself requiring the solution of a two-dimensional Poisson equation for the scalar potential and a solution of set of two-dimensional Poisson equations for the vector potential:

$$\nabla^2\psi = -\partial_z w, \quad \nabla^2\boldsymbol{\chi} = \boldsymbol{\omega}, \tag{2}$$

where w is the vertical air flow and $\boldsymbol{\omega}$ is a specified vorticity. From comparison and investigation to experimental fires the vector potential appears to be negligible in most cases, although may be important in certain situations where wind interacts with topography to form lateral vortices.

Once the set of Poisson equations, Eq. (2), are solved, the local wind field due to near-field effects can be calculated using Eq. (1) and added to the global (ambient) wind field. In this work, all simulations were carried out in the Spark framework [5], a level set based perimeter propagation solver. The Poisson equations, Eq. (2), were solved using a multigrid technique.

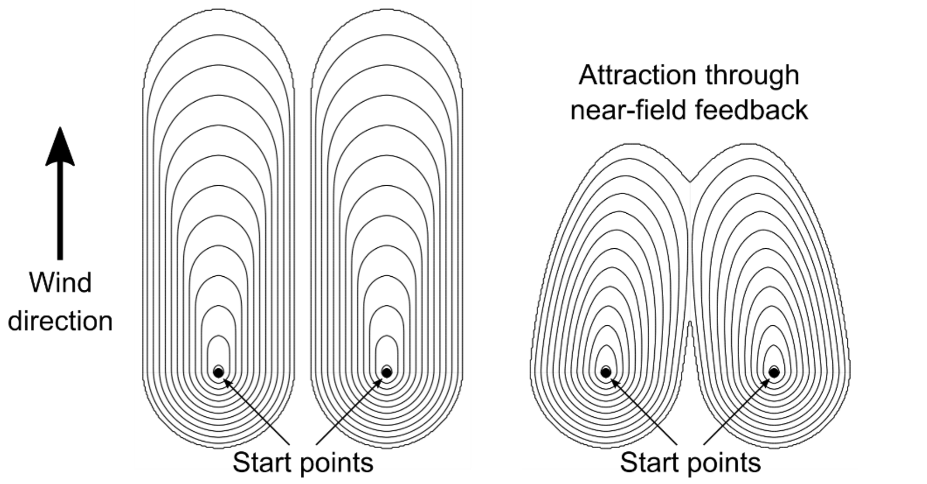


FIGURE 1 – ISOCHRONES FROM TWO FIRES SIDE-BY-SIDE WITHOUT NEAR-FIELD COUPLING (LEFT) AND WITH NEAR-FIELD COUPLING (RIGHT). THE NEAR-FIELD COUPLING THE TWO FIRES TO ATTRACT, AS IS OBSERVED IN EXPERIMENTS.

The use of near-field techniques permits modelling of aspects of fire behaviour that were previously difficult, or impossible, to simulate in two-dimensional perimeter propagation approaches. This includes the attraction between nearby fires, as shown in Fig. 1, which has been observed in experimental fires.

A second behaviour is the parabolic rounding exhibited by a wind-driven fire line. Fig. 2 shows an example of the progression of a fire line lit in uniform wind conditions and a comparison to the near-field model. There is an excellent match between the simulation and experimental results, and the parabolic rounding arises naturally when using the near-field approach.

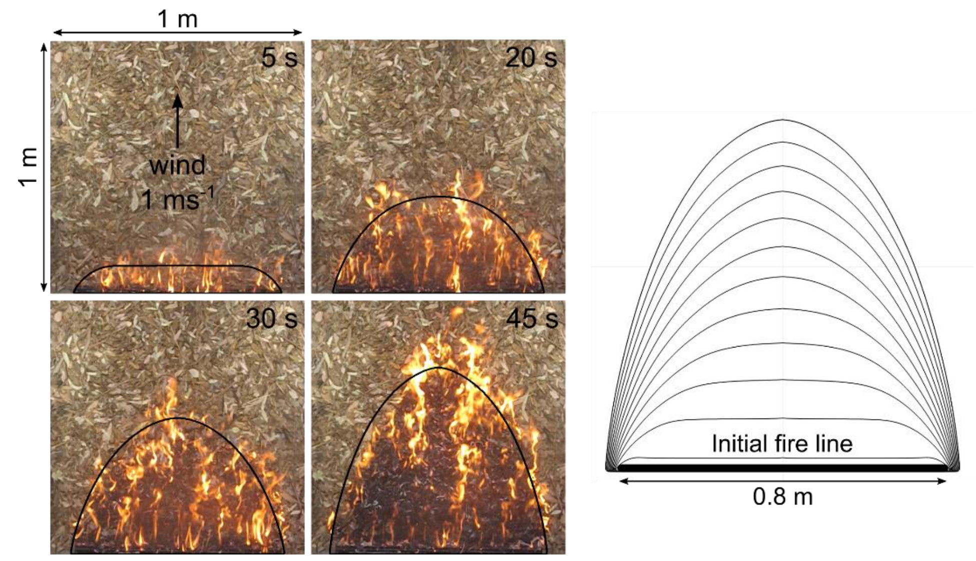
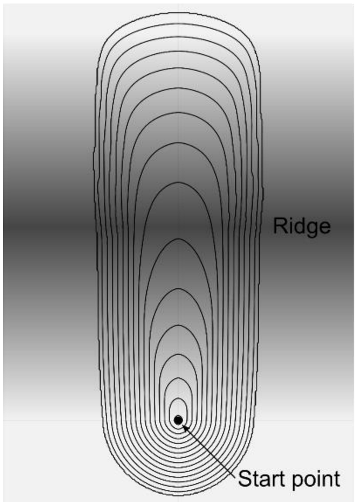


FIGURE 2 – COMPARISON OF NEAR-FIELD MODEL TO EXPERIMENTAL RESULTS (LEFT) AND SIMULATION ISOCHRONES SHOWING PARABOLIC ROUNDING ARISING NATURALLY FROM THE MODEL (RIGHT). FIGURE ADAPTED FROM [3].

The expression for the source term in Eq. (2) is dependent on a vertical displacement of air from the fire. This is mathematically identical to a forcing term from lifting of air over terrain, and this can easily be incorporated into the model (Fig. 3, left) resulting in a mass-correcting wind behaviour with minimal additional computational overhead. The simulated fire in this example is started downwind of a ridge (elevation is shown as shaded grey in the image, with black high elevation) and can be seen to accelerate on the windward slope and decelerate on the lee slope of the ridge. Vorticity terms (if present) can easily be incorporated into the model (Fig. 3, right). This image shows an example of a vortex source in the ground plane (a single component of $\boldsymbol{\omega}$, representing circulation in the ground plane), where the vertical component of the vector potential is shown in greyscale.



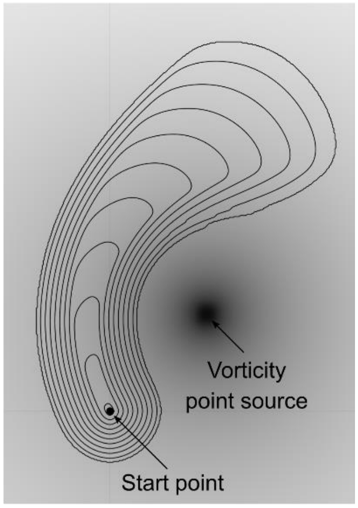


FIGURE 3 – INCORPORATION OF TERRAIN INTO THE NEAR-FIELD MODEL AS A SOURCE TERM FOR THE SCALAR POTENTIAL (LEFT). EXAMPLE OF FIRE PROPAGATION IN THE PRESENCE OF A VORTEX POINT SOURCE (RIGHT).

The method potentially allows fire line interaction, wind and terrain effects, fire shape development and vortex sources to be incorporated in perimeter propagation using a single computational approach. In particular, it could accommodate dynamic modes of fire propagation such as vorticity-driven lateral spread [5] within two-dimensional fire simulators.

Although the near-field model has been implemented here using a level set solver, the process could be applied to other perimeter propagation methods. The near-field approach may improve the accuracy of rapid computational models with low additional overhead suitable for operation usage.

FIRE COALESCENCE AND DEEP FLAMING

When multiple spot fires form ahead of the main fire front in reasonably close proximity, they can coalesce in such a way that expansive zones of active flame are formed. Such instances have been referred to as 'deep flaming' events.

Deep flaming has been hypothesised as being a necessary part of firestorm development – the core of the convective plume above a deep flaming event is quasi-isolated from the entrainment of ambient air that occurs on the plume boundary. As a consequence, deep flaming is more likely to result in plumes that penetrate deeper into the atmosphere. This means that the common notion that pyroconvective potential is driven by the total energy release of a fire is in error, and that the geometry and spatial expanse of the flaming zone are additional factors that must be considered.

Effect on pyroconvective plume development

In research funded by the Australian Research Council, the effect of the spatial expanse of a surface heat source was investigated using the Weather Research and Forecasting (WRF) model. Specifically, WRF simulations using idealised surface heat fluxes were used to examine how the maximum plume height was affected by the spatial configuration of the surface heating.

Figure 4 shows the results for plumes emanating from a circular heat source, a broad rectangular heat source and a thin rectangular heat source. The thin rectangular heat source is more representative of a normal linear fire front, whereas the circular source is more like a deep flaming event. As can be seen, despite each heat source having exactly the same total energy release, the plume emanating from the circular heat source penetrates above the tropopause at 12 km, while the thin rectangular heat source only reaches a height of about 6-7 km.

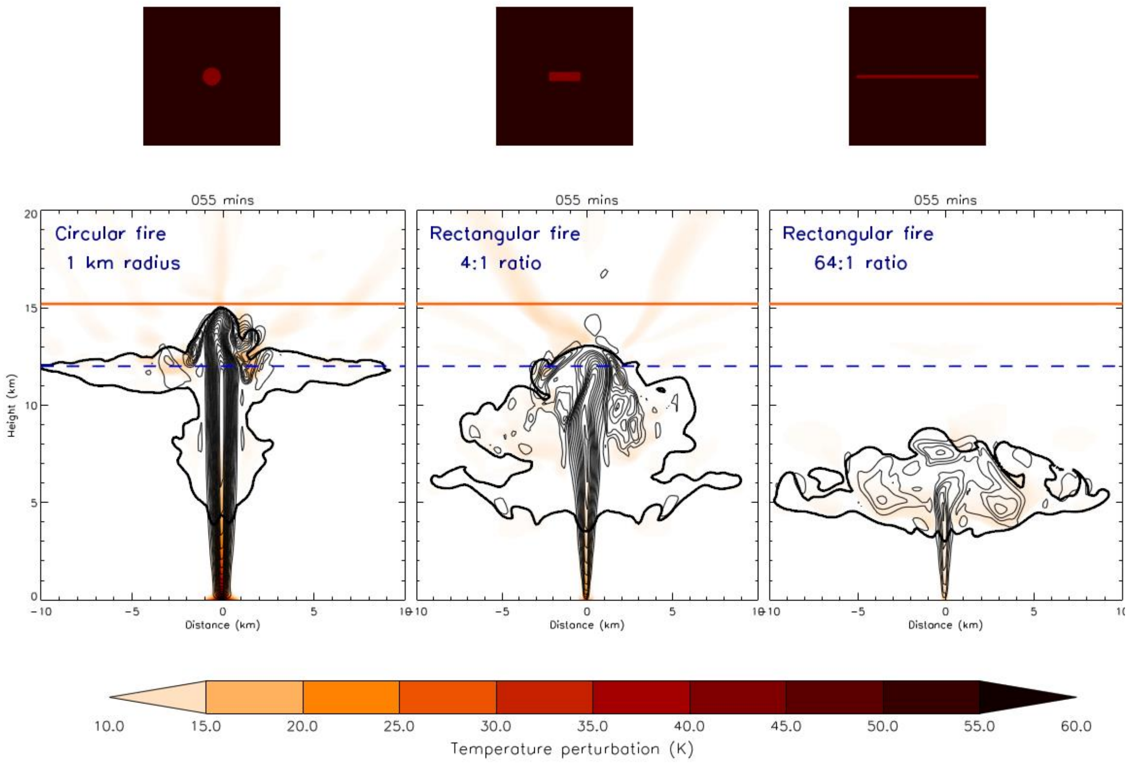


FIGURE 4 – THE EFECT OF THE SPATIAL CONFIGURATION OF SURFACE HEAT FLUX ON PYROCONVECTIVE PLUME DEVELOPMENT. THE FIGURES IN THE TOP ROW SHOW THE GEOMETRY OF THE HEAT FLUX. THE TOTAL ENERGY RELEASE IS THE SAME IN EACH CASE.

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