Environmental Modelling and Software 107 (2018) 12–24

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Incorporating convective feedback in wildfire simulations using pyrogenic potential

J.E. Hilton[a,*], A.L. Sullivan[b], W. Swedosh[a], J. Sharples[c], C. Thomas[c]

[a] CSIRO, Clayton, VIC 3168, Australia
[b] CSIRO, Canberra, ACT 2601, Australia
[c] UNSW, Canberra, ACT 2610, Australia

ARTICLE INFO

Keywords:
Wildfire modelling
Laboratory experiments
Wildland fire
Fire behaviour
Fire spread

ABSTRACT

Modelling the dynamics of wildfires is very computationally challenging. Although three-dimensional computational fluid dynamics (CFD) models have been successfully applied to wildfires, the computational time required makes them currently impractical for operational usage. In this study, we develop a two-dimensional propagation model coupled to a 'pyrogenic' potential flow formulation representing the inflow of air generated by the fire. This model can accurately replicate features of fires previously unable to be simulated using current two-dimensional models, including development of a fire line into a parabolic shape, attraction between nearby fires and the observed closing behaviour of 'V' shaped fires. The model is compared to experimental results with good agreement. The pyrogenic potential model is orders of magnitude faster than a full CFD model, and could be used for improved operational wildfire prediction.

1. Introduction

Wildfires are driven by a complex set of physical and chemical processes that interact both between themselves and with the surrounding environment (Morvan, 2010). These processes include thermal degradation, pyrolysis and charring reactions of complex carbohydrate fuels, the gas and solid phase oxidation reactions of thermal degradation products (Sullivan and Ball, 2012; Sullivan, 2017a) and the transfer of heat liberated from these processes to adjacent fuels through advection of hot gases, thermal radiation, and transport of burning material (Sullivan, 2017b). The bulk behaviour and spread of a wildland fire can be reasonably successfully modelled using a variety of modelling approaches (Sullivan, 2009a; b; c). These range in a continuum from fully physical numerical models (Simeoni et al., 2011; Peace et al., 2015; Canfield et al., 2014) through statistically-based empirical models of the pseudo-steady or median rate of forward spread of a fire (Cheney et al., 2012; Anderson et al., 2015; Cruz et al., 2015a) to mathematical analogue models (Hilton et al., 2016b; Encinas et al., 2007). However, modelling of fine temporal and spatial scale fire behaviour (in the order of seconds and metres) has generally been less successful (Cruz and Alexander, 2013).

Of particular interest from both a fire science modelling perspective, as well as for fire management and suppression, is the ability to predict the behaviour and propagation of the fire perimeter. This perimeter is defined by the boundary between the burning and un-burnt regions of fuel. Central to this is understanding how the behaviour of the fire perimeter interacts with local physical processes (namely thermal radiation and convection) dominating the transfer of heat liberated during combustion in the flame zone to adjacent fuel. The interaction of these processes along with the ambient environment can play a significant role in determining the non-local behaviour of a wildland fire (Canfield et al., 2014).

As an example of the interaction of local heat transfer processes, Fig. 1 shows an overhead view of a small-scale laboratory fire burning in a reconstructed fuel bed. Two intersecting lines of fire are lit at a 90° angle. The lines are 0.8 m long and burn in uniform dry eucalypt forest litter (leaves, twigs and bark < 6 mm in diameter) with a uniform background wind speed of $1.0\,\mathrm{m\,s^{-1}}$ shown as the vertical arrow in Fig. 1a (a detailed description of these experiments is given in Section 2.3). Rather than spreading just in the direction of the wind, the fire lines appear to move towards each other, filling in the centre of the 'V' (approximate local spread directions are indicated with small arrows). After 20 s the fire has filled in the centre of the 'V' and appears to follow this inward spread direction even at the tips of the ignition region (Fig. 1c, dashed lines). Subsequently the fire spreads forward in the direction of the wind.

Such effects represent important aspects of fire behaviour that must be incorporated into predictive models. However, the role and relative

* Corresponding author.
E-mail address: James.Hilton@csiro.au (J.E. Hilton).

https://doi.org/10.1016/j.envsoft.2018.05.009
Received 10 September 2017; Received in revised form 11 March 2018; Accepted 21 May 2018

Software availability

Software name Spark wildfire modelling toolkit
Developers Spark development team
Contact information spark@csiro.au
Software and hardware required Windows, Linux or Mac device with OpenCL GPU drivers
Program languages C, C++
Availability Graphical-user interface and batch mode server version free to download from https://research.csiro.au/spark. Research toolkit freely available for non-commercial use on request

strengths of convectively-induced pressure effects (convergence of hot gases from the flame zones towards the convective centre) and radiative effects (from the increased flame view factor of the fuel at the centre) in the dynamics of fire propagation are unclear. A number of dedicated studies have investigated the relative strength of each of these effects (Anderson, 1969; Wolff et al., 1991; Morandini et al., 2001), with no clear verdict on which is dominant in wildfires (Hilton et al., 2016a). Some experimental studies have concluded that radiation is the primary mechanism for fire spread (Silvani and Morandini, 2009), particularly in the absence of wind (Albini, 1985; Anderson, 1964), whereas others have reported convection as the mechanism of fire spread (Pitts, 1991; Anderson et al., 2010), or a mixture of the two depending on fire conditions (Frankman et al., 2010, 2013; Finney et al., 2015).

Previously, we investigated the use of perimeter curvature as a proxy for such local small-scale fire spread effects (Hilton et al., 2016a). In this earlier study, the propagation of the fire perimeter was modelled using a extra term based on local curvature of the fire perimeter in addition to bulk effects of wind and fuel. This extra term imposed an additional rate of spread inversely proportional to the fire perimeter curvature. Negative curvature (a concavity) positively affected fire spread, whereas positive curvature (a convexity) negatively affected fire spread. This effect of curvature has been observed both in our experiments and detected in large-scale fires using remote sensing methods (Ononye et al., 2007). While this method showed a good fit to field-scale experimental fires, it had significant limitations as it could not model observed interactions between fire lines that were separated. The study also left open the question of whether this local scale behaviour was the result of radiative or convective effects. Furthermore, the application of curvature was found not to correctly account for behaviour of fires of certain geometries in large-scale coupled wind-fire models (Thomas et al., 2017). Finally, the implementation of curvature based method required a semi-implicit method for stability, which was numerically intensive and therefore reasonably slow to compute.

In this study we show that a two-dimensional model based on the air flow around a fire provides a more robust match than the curvature model to wildfire experiments over a parameter space with length scales ranging from metres up to tens of metres. The model is based on a potential flow formulation in the near-ground plane around a fire and is essentially a corrective pressure gradient accounting for effect of the updraught of the fire plume on the heat flux from the flame zone to adjacent fuel. The model considers two-dimensional flow in the near-ground plane rather than modelling the full three-dimensional inflow dynamics (Smith et al., 1975; Raupach, 1990; Potter, 2012). To our knowledge no similar two-dimensional models have been proposed for wildfire modelling, although a Laplacian pressure forcing term as input to a coupled meteorological interface model has been presented by Achtemeier (2013) as part of a unique ‘rabbit hopping’ wildfire model. Although the model presented here is a considerable simplification of the pressure field around a wildfire, it shows remarkable performance in predicting the propagation of small scale fires. Additionally, the model also provides a physical explanation for the curvature-based model and can account for interaction effects between separated fire lines.

The pyrogenic potential model is very straightforward to implement and works in two dimensions, making it more computationally efficient (taking on the order of seconds to run) than a fully three-dimensional model which can take several days to run on high-end supercomputers (Linn et al., 2002; Mell et al., 2007; Sullivan, 2009a). This relative efficiency may make the model suitable for improving operational fire prediction models. The model is implemented in the level set-based fire perimeter propagation framework called ‘Spark’ (Hilton et al., 2015). The details of the model and comparison to experimental fires are detailed in the following sections.

2. Methodology

2.1. Level set method

The growth of the fire perimeter was modelled using the level set method (Sethian, 2001) using the Spark fire propagation framework (Hilton et al., 2015; Miller et al., 2015). The level set method is a general purpose model for moving and merging interfaces. Rather than representing the interface directly, the method updates the distance from the interface across a grid, naturally handling complex topological changes such as breaking and merging. The ability to handle merging interfaces makes the method well suited to fire propagation simulations, where the interface represents the division between burnt and unburnt regions defining the fire perimeter.

The level set equation is:

$$\frac{\partial \phi}{\partial t} = -s\left|\nabla \phi\right| \tag{1}$$

where ϕ is the distance to the nearest interface and s is the outward speed of the interface. For wildfire simulations, this is the speed of propagation of the fire expressed as the fire rate of spread in a given direction. The distance ϕ is signed such that it is negative within the interface and positive outside. The speed can vary at each point on the interface, which is a further advantage in fire propagation modelling as different rates of spread in different fuel types, topography or orientations with the wind can easily be incorporated in the one perimeter. In

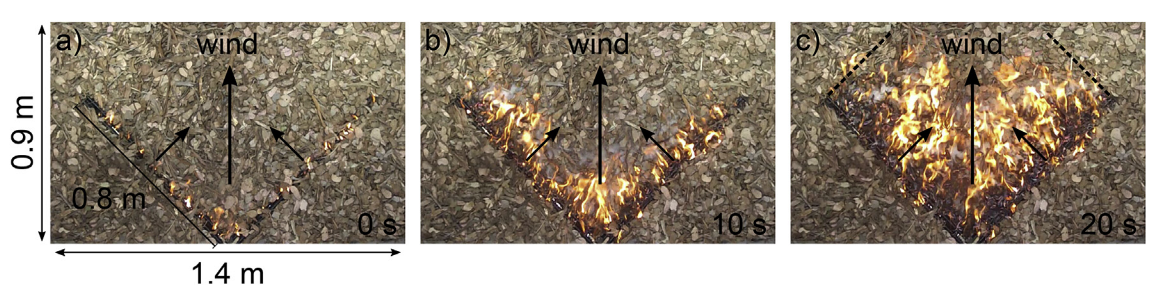

Fig. 1. Plan view of fire line interaction in a ‘V’ ignition line set-up in a homogeneous fuel bed with uniform wind. The fire is shown at a) ignition, b) 5 s after ignition and c) 10 s after ignition.