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Effects of spatial and temporal variation in environmental conditions on simulation of wildfire spread

J.E. Hilton [a, *], C. Miller [a], A.L. Sullivan [b], C. Rucinski [a]

[a] CSIRO Digital Productivity Flagship, Clayton South, VIC 3169, Australia
[b] CSIRO Land and Water Flagship, Black Mountain, ACT 2601, Australia

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ABSTRACT

Environmental conditions, such as fuel load and moisture levels, can influence the behaviour of wildfires. These factors are subject to natural small-scale variation which is usually spatially or temporally averaged for modelling fire propagation. The effect of including this variation in propagation models has not previously been fully examined or quantified. We investigate the effects of incorporating three types of variation on the shape and rate of propagation of a fire perimeter: variation in combustion conditions, wind direction and wind speed. We find that increasing the variation of combustion condition decreases the overall rate of propagation. An analytical model, based on the harmonic mean, is presented to explain this behaviour. Variation in wind direction is found to cause the development of rounded flanks due to cumulative chance of outward fluctuations at the sides of the perimeter. Our findings may be used to develop improved models for fire spread prediction.

1. Introduction

Accurately predicting the arrival time of a fire front at a specific location is crucial for effective fire suppression, as well as the co-ordination of safe evacuation operations. Accurate determination of the likely extent and severity of potential wildfires can enable reliable risk assessments to be performed for vulnerable regions. Wildfires are, however, extremely complex systems and modelling their behaviour, even for the most simple scenarios, can be very challenging. The nature of the generally disparate and heterogenous environmental conditions (i.e. vegetation, weather and topography) in which wildfires spread further complicates the task of accurately predicting the behaviour and spread of wildfires.

The physical processes governing a wildfire take place over a wide range of temporal and spatial scales (Sullivan, 2009a) from the combustion chemistry at the molecular scale (Sullivan and Ball, 2012), through to atmospheric interactions with the fire on the scale of kilometres (Sun et al., 2009). At spatial scales on the order of centimetres to tens of meters lie local factors governing the behaviour of the fire. These include the distribution of fuel type/composition and conditions such as moisture content and availability (Anderson and Rothermel, 1965; Catchpole et al., 1989, 1993; Viegas et al., 2013). Atmospheric effects on the order of centimetres to tens of meters also influence fire behaviour, such as surface level wind turbulence (Luke and McArthur, 1978; Albini, 1982; Sullivan et al., 2012). The local topographic slope, and wind interaction with the slope, also plays a large role in fire propagation (Viegas, 2004; Sharples, 2008; Sullivan et al., 2014).

The rate of spread of a wildfire is one of the most important parameters for operational purposes, as it can be used to predict arrival times. Other important parameters include the shape and intensity of the flame front as well as the propensity and behaviour of embers lofted into the air stream (fire spotting) which can lead to breakdown of suppression efforts (Ellis, 2011; Sullivan et al., 2012). The dispersal of smoke is also of interest from an environmental perspective (Goodrick et al., 2012).

Due to the importance of predicting the arrival time of a fire front, many empirical expressions have been developed to give the one-dimensional rate of spread of the head of a wildfire, the fastest moving part of the perimeter. The Rothermel model (Rothermel, 1972) is one of the earliest examples of such empirical models still in widespread operational use as part of the US BEHAVE system (Andrews, 1986) which continues to be revised and expanded (Scott and Burgan, 2005; Andrews, 2014). In the time since Rothermel's work, a number of more complex empirical models have been introduced, often for specific vegetation types. Recent

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

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examples include the Australian Dry Eucalypt Forest Fire Model (Cheney et al., 2012) and the CSIRO Grassland Fire Spread Model (Cheney et al., 1998; Sullivan, 2010).

Dynamic spatial fire spread simulation has generally taken two approaches. The first is computational fluid dynamic (CFD) models, which attempt to replicate fire behaviour based on the fundamental combustion and heat transfer processes. The second is perimeter propagation models, which generally apply empirical rate of spread rules, such as the Rothermel expression, to simulate the propagation of the fire perimeter. CFD models are most often based on the compressible Navier–Stokes equations with associated auxiliary relationships for factors such as chemical reactions and turbulence. Such models are less reliant upon extensive experimental relations for robustness but are very computationally expensive, can currently still only model a fraction of the complex processes occurring within wildfires, and are unsuited to operational use due to long computation times (Sullivan, 2009a).

Perimeter propagation models attempt to model the large-scale propagation of fire across a landscape rather than directly solve the underlying physical relations governing the fire (Sullivan, 2009c). As such, they can be based on simplified versions of more complex physical models, use empirical relationships measured in the field, or be based on a mathematical rule set. The fire perimeter in these models is the interface between regions which are burnt or burning, and unburnt. These models are usually applied on the scale of tens to hundreds of kilometres. These models can be subdivided into front-tracking methods or cellular methods. In both types, the fire perimeter is represented as a two-dimensional interface, giving a considerable saving in computational cost over three-dimensional CFD models.

In the front-tracking approach, the fire perimeter is described as a discretised set of line segments that expand according to a given rate of spread rule set. Each point on the fire perimeter is assumed to be a point source for future fire propagation (Knight and Coleman, 1993; Finney, 1994; Richards and Bryce, 1995; Coleman and Sullivan, 1996). The fire shape from these point sources is usually assumed to be elliptical, as ellipses have been found to provide a good approximation to fire perimeters in long-burning wildfires (Anderson et al., 1982; Richards, 1990). The geometry of the ellipse is determined using a one dimensional rate of spread from an empirical model, an empirical relation for the length-to-breadth ratio of the ellipse, and the duration of the simulation time step. The orientation of the ellipse is usually determined from the direction of the wind. The fire perimeter is updated as the maximum extent of all contributing fire ellipses for the time step.

Although these models are very fast, limitations arise from the use of only one type of front shape. While elliptical templates provide a close match to many fire propagation scenarios, other template shapes can provide a better match under certain circumstances (Green et al., 1983). For example, different fuels can produce oval or tear-drop shaped fronts (Peet, 1967). Other limitations in such models include the assumption of static conditions at each point on the perimeter for the period of the time step, and the assumption of instantaneous steady-state motion of the fire perimeter from a point source ignition. A large number of topology-dependent rules are often required in these models to resolve overlapping, twisting or colliding fronts (Knight and Coleman, 1993; Filippi et al., 2010; Bose et al., 2009). Models using this approach include SiroFire (Coleman and Sullivan, 1995, 1996), Phoenix RapidFire (Tolhurst et al., 2008), Prometheus (Tymstra et al., 2010), Aurora (Johnston et al., 2008) and FARSITE (Finney, 1998, 2004).

Cellular methods discretise the domain into an underlying grid over which all input data is prescribed and all calculations are performed. Rule sets based on empirical or physical formula are used to update the state of the grid over time. Such models include static raster implementations (Green et al., 1990), cellular automata models (Encinas et al., 2007; Achtemeier, 2013) and complex irregular stencil-based models (Trunfio et al., 2011). Examples of models using elliptical stencils include FireStation (Lopes et al., 2002), FIREMAP (Vasconcelos and Guertin, 1992), and PYROCART (Perry et al., 1999).

A more recent approach, which is used in this study, is perimeter-growth based on the level set method (Sethian, 2001). In this method a local rate of spread can be applied at any point on the fire perimeter. Topological changes, such as breaking and merging of perimeters, are handled without the need for any specialised rule sets to handle colliding interfaces. The method is also not reliant on the application of any pre-defined templates, such as ellipses. Implementations of such methods appear to be in the early stages of development compared to cellular and front-tracking methods. Rehm and McDermott (2009) showed that level set simulation of ignition points on flat homogeneous terrain evolved naturally into an elliptical form, highlighting the potential of the method for realistic fire perimeter simulation.

WRF-Fire, a coupled atmosphere-fire model (Mandel et al., 2011a; Coen et al., 2013), combines the Weather Research and Forecasting (WRF) atmospheric model (Skamarock et al., 2008; Kochanski et al., 2013a) with SFIRE (Mandel et al., 2011b), a fire spread sub-model that uses a level set approach employing the empirical rate of spread model of Rothermel (Rothermel, 1972). WRF-Fire utilises a subset of the physical processes for the coupling of fire with the atmosphere from the Coupled Atmosphere-Wildland Fire Environment Model (CAWFE) (Coen, 2005). WRF-Fire allows the interaction between the fire and local atmospheric effects caused by the fire to be directly modelled. Application of the model was found to compare well in both fire propagation behaviour and extent with recorded wildfire events (Jordanov et al., 2011; Kochanski et al., 2013b). However, no studies have systematically examined the effect of variation in the resolved wind component on the evolution of the fire perimeter.

Spatial and temporal variation in environmental conditions has long been understood to influence the behaviour and spread of wildfires (Frandsen and Andrews, 1979; Cruz and Alexander, 2013). The primary advantage of simulation techniques such as those described above is that they can easily incorporate such variations (primarily fuel and weather), at least on a scale commensurate with the computational limitations of the method employed (e.g. Green et al. (1990); Hargrove et al. (2000); Pimont et al. (2006)). However, little research has been presented on the understanding of the effects of such variations, particularly at smaller scales (i.e. order of metres), on rate of spread outside of simulation results. Fujioka (1985) undertook analytical analysis of the effect of non-uniform fuel attributes on the Rothermel fire spread model considering three averaging techniques; arithmetic mean of spread rates, spread rate based on mean fuel conditions, and harmonic mean of spread rates. Their findings suggested that harmonic mean of spread rates was the most appropriate estimator of spread rate in non-uniform fuel.

In this study we use a level set method to examine the effect of small-scale spatial variation in combustion conditions (fuel state and combustibility) and temporal variation in wind (magnitude and direction) on the evolution of a two-dimensional fire perimeter. The flexibility of the level set method approach allows these local small-scale spatial and temporal variations to be directly handled by the model. A brief description of the implementation of the level set method is provided, which is then applied to fire spread simulation using our codebase, called ‘Spark’. The effects of variation in environmental conditions (combustion and wind) on fire perimeter shape and rate of spread are then investigated and discussed.