FINDINGS

Two-dimensional fire simulators have been extended to model vorticity-driven lateral spread and incorporate spotting processes.

Incorporating firebrands and spot fires into vorticity-driven wildfire behaviour models

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Complex modes of fire behaviour resulting from fire-atmosphere coupling are a significant challenge for operational wildfire spread simulations. While three-dimensional fully coupled fire-atmosphere models are able to account for many types of fire behaviour, their computational demands are prohibitive in an operational context. We investigated extending computationally efficient two-dimensional fire spread simulations to model coupled effects resulting from wind flow over a ridge that can result in a number of non-intuitive modes of fire behaviour, such as vorticity-driven lateral spread (VLS). Furthermore we developed extensions of these two-dimensional models to incorporate three-dimensional firebrand transport and showed that enhanced downwind spot fire formation can result under certain VLS conditions.

Introduction

Fire spread simulators play an essential part in wildfire risk assessment and management, but their effectiveness is limited in a number of ways. In particular, when the spread of a wildfire is dominated by dynamic modes of fire propagation, which arise due to fire-atmosphere interaction. VLS is a mode of dynamic fire behaviour that has been shown to be critical in the development of extreme wildfires. VLS is characterised by rapid lateral propagation of a fire across the top of lee-facing slopes, but its influence on extreme wildfire development can be mostly attributed to the secondary generation of firebrands, massive ember attack and spot fire coalescence downwind of the lateral spread zones. Modelling these important aspects of fire behaviour are currently beyond the capability of operational fire spread simulators.

Methods

Hilton et al. (2018) detailed a two-dimensional fire spread model that uses a potential flow formulation to partially account for local fire-atmosphere interactions. This model has been implemented as part of the Spark fire simulation framework, which is based on the level-set method. Sharples & Hilton (2020) extended the model to simulate vorticity-driven effects. Here the model is extended further to incorporate firebrand generation and spot fire formation.

Firebrands were incorporated into the simulation using a Lagrangian particle model implemented in the Spark framework. The motion of each firebrand was given by:

$$m\frac{\partial \mathbf{v}}{\partial t} = \frac{1}{2} c_D \rho A \|\mathbf{u} - \mathbf{v}\|(\mathbf{u} - \mathbf{v})\mathbf{g}'$$

where m is the mass of the firebrand, $\mathbf{v}$ is the firebrand velocity vector, ρ is the air density (kg m^{-3}), c_D the coefficient of drag for the firebrand and A (m^2) is the cross-sectional area of the firebrand perpendicular to the flow. The reduced gravity vector $\mathbf{g}'$ accounts for buoyancy effects and is given by $\mathbf{g}' = (0, 0, (b-1)g)$, where g = 9:8 m s^{-2} and b is a dimensionless buoyancy parameter.

Results

In the absence of definitive research to inform the choice of parameter value, the buoyancy parameter was treated as a free parameter. To account for cooling effects within the plume, we assumed a simple exponential cooling model, where the buoyancy parameter reduces over time according to $b = b_0 \exp(-kt)$, where k is a decay parameter.

Simulations of fire spread in the lee of a ridge are shown in Fig. 1. The domain was a ridge 1 km high with a slope of 20° on the windward side and 35° on the lee slope. The ignition was initiated as a line 300 m in length and 50 m in width perpendicular to the ridge at a distance of 950 m from the ridge line. The simulation resolution was 10 m and the simulation was run for a period of 2 hours. The fire rate-of-spread was estimated using the Rothermel model with a fuel moisture content of 8%, a fuel load of 13.024 tonnes acre^{-1} and a surface-to-volume ratio of 1159 ft^{-1}. Simulations took approximately 10 seconds on a K6000 GPU without firebrands and 110 seconds when firebrands were used.

The wind direction was set to be perpendicular to the ridge with a speed of 10m s^{-1} on the windward slope and re-circulation over the leeward slope was prescribed by setting the wind speed to -1m s^{-1} on the lee slope. This imposed wind field was then modified by the pyrogenic potential model to account for vertical vorticity effects in the ground plane.

Discussion

The combined VLS and firebrand models appear to qualitatively replicate the fire behaviour shown in real fires, despite the range of simplifications used for the models. There are a number of assumptions and unknowns in the model which require calibration and further research. These include the firebrand rate of production and the plume decay constants b_0 and k. However, simulations using these models could provide information on counter-intuitive modes of fire behaviour for management and risk assessment. Future studies will investigate the applicability of the models to more complex scenarios and compare the results of the model to real-world data.

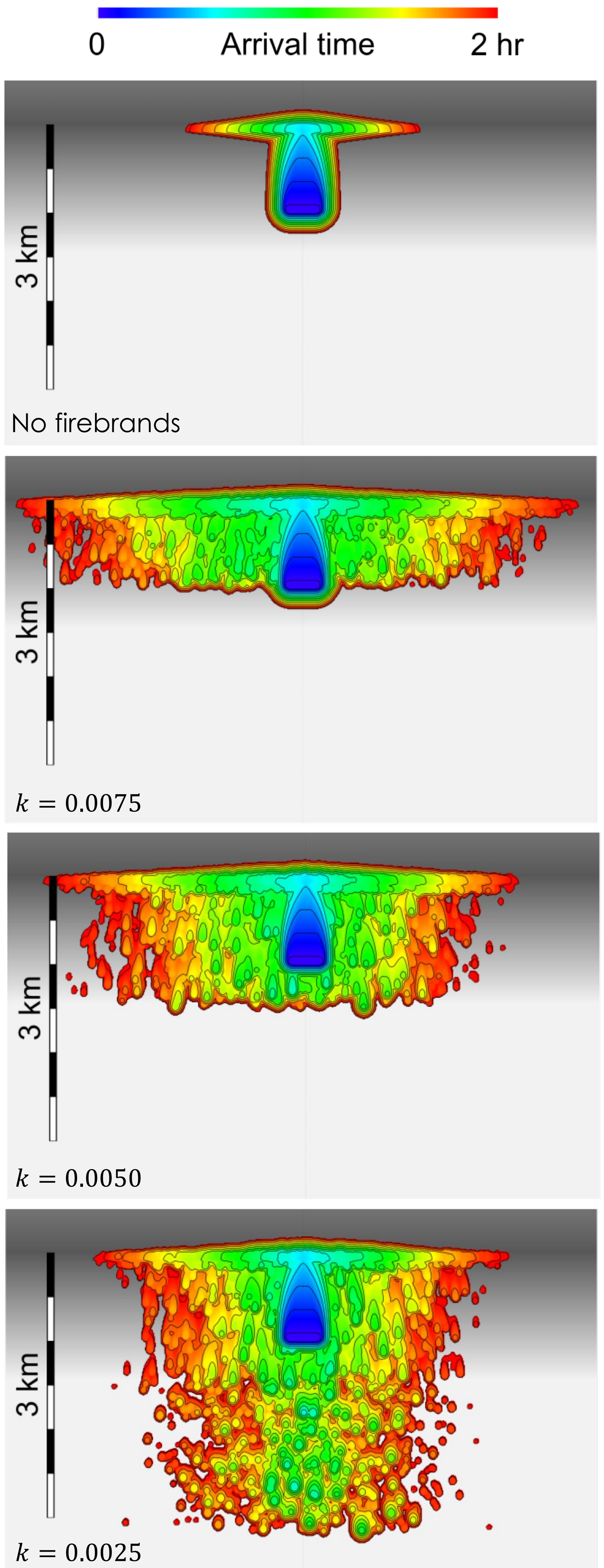

Figure1: Dynamic fire spread simulator demonstrating capability to emulate VLS and spotting behaviour. Each panel shows the results for a different decay parameter, as indicated. The elevation is shown in grayscale and the colour scale represents the fire arrival time at each point. Ten-minute isochrones are overlaid as solid black lines.

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References:
Hilton et al. (2018) *Environmental Modelling and Software*, 107.
Rothermel (1972) Research Paper INT-115.
Sharples & Hilton (2020) *Frontiers in Mechanical Engineering*, 5.

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