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Real-time wildland fire spread modeling using tabulated flame properties

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ABSTRACT

This paper is an extension of previous papers [1,2] on a raster-based fire spread model which combines a network model to represent vegetation distribution on land and a physical model of the heat transfer from burning to unburnt vegetation items, and takes into account local conditions of wind, topography, and vegetation. The physical model, still based on the unsteady energy conservation in every fuel element and detailed local and non-local heat transfer mechanisms (radiation from the flaming zone and embers, surface convection, and radiative cooling from the heated fuel element to the environment), now includes wind-driven convection through the fuel bed. To address the challenge of real-time fire spread simulations, the model is also extended in two ways. First, the Monte Carlo method is used in conjunction with a genetic algorithm to create a database of radiation view factors from the flame to the fuel surface for a wide variety of flame properties and environment conditions. Second, the front-tracking method, drafted in [2], is extended to polydisperse networks and implemented in the new version of the model, called SWIFFT. Finally, the SWIFFT model is validated against data from different fire scenarios, showing it is capable of capturing the trends observed in experiments in terms of rate of spread, and area and shape of the burn, with reduced computational resources.

1. Introduction

Currently there are two major approaches to model fire spread: the raster-based approach and the vector-based approach [3]. In the raster-based approach fire spread is treated as a series of cell-to-cell interactions, a set of rules defining the spread mechanism from a cell to its neighbors (see for example [4–9]). The vector-based approach assumes the propagation of the fire front as a continuously expanding polygon and is the basis of the most widely used fire spread models: FARSITE [10], PROMETHEUS [11], and SiroFire [12]. The strengths and weaknesses of both approaches are extensively discussed in [3,13]. One of the main advantages of the raster-based approach is that it is computationally less intensive and is much more suited to heterogeneous fuel and weather conditions [3]. These features led us to develop a fire spread model based on raster implementation [1,2]. The model combined a monodisperse network (i.e. one in which the fuel elements are close to a single size) to represent vegetation distribution on land with an unsteady physical model of the heat transfer from burning to unburnt fuel elements. The preheating energy-transfer mechanisms considered were: radiation from the flaming zone and embers; surface convection; and radiative cooling from the heated fuel element to the environment. At each time step, overhead flame radiation was calculated by coupling the solid flame model with the Monte Carlo method.

In the continuation of these studies, we present here the enhancements of the fire spread model that are now being included to improve the scope and validity of the model, and to reduce the computational resources needed to perform simulations. First, in order to improve model predictions of wind-driven fires through highly porous fuels, wind-driven convection inside the fuel bed is included in the model. The second enhancement concerns the calculation of flame radiation during fire spread. Although it provides high accuracy, this calculation requires a large amount of computational resources, which is incompatible with the operational needs of fire and land management services. In order to run real-time fire spread simulations, radiation calculation is thus performed using a precomputed database of view factors (VF) from the flame to the fuel surface for a wide variety of flame properties and environment conditions. Finally, the front-tracking method, used to track the fire-front interface by a moving separate grid of lower dimension than the fixed DEM grid [2], is extended to

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Nomenclature

a	fuel bed absorptivity
a,b,c	ellipse parameters (or genes) (m)
c_p	specific heat (J/kg/K)
d_{ij}	distance between cells i and j (m)
D	diameter (m)
E	emissive power (W/m²)
F	view factor
h	heat transfer coefficient (W/m^2/K)
H	height (m)
k	thermal conductivity (W/m/K)
L	length (m)
L_{vap}	latent heat of vaporization (J/kg)
m	mass
m''	mass per unit area (kg/m^2)
$\vec{n}$	unit normal vector
N	number of radiation quanta
N_{bc}	number of burning cells
Pr	Prandtl number
q	volumetric energy flux (W/m^3)
$\dot{Q}$	heat release rate (W)
S	surface area (m^2)
t	time (s)
T	temperature (K)
U	velocity (m/s)
V	volume (m^3)

Greek

α	volume fraction of fine fuel elements
δ	mean free path of radiation (m)
ε	emissivity
θ	flame angle (rd)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant (W/m^2/K^4) surface to volume ratio (m^{-1})
τ	flame residence time (s)
χ^r	radiant fraction of the heat release lost by the flame

Subscripts

i	burning cell
ij	from cell i to cell j
j	unburnt receptive cell
0	initial
∞	environment

Superscripts

c	convection
e	embers
f	flame
i	internal
ign	ignition
l	lost by radiation
m	radiation view factor
r	radiation
s	surface
"	per unit fuel element area
w	water

Acronyms

DFF	Dry Fine Fuel elements
DEM	Digital Elevation Model
FT	Front Tracking
MCM	Monte Carlo Method
noFT	no Front Tracking
RD	Radiation Database
VF	View Factor
WFF	Wet Fine Fuel elements

polydisperse networks (i.e. composed of fuel elements of different sizes) and implemented in the new version of the model, called SWIFFT.

2. Model overview

2.1. Governing equations and assumptions

Vegetation is here depicted as a monodisperse or polydisperse network of combustible fuel elements, or cells, that can be distributed on the soil surface either randomly or regularly depending on the coverage and spatial arrangement of vegetation, leading to either an amorphous or a crystalline network. As shown in Fig. 1, a receptive cell j may be exposed to overhead flame radiation q_{ij}^{rf}, ember radiation q_{ij}^{re}, surface and internal convection, q_{ij}^{cs} and q_{ij}^{ci}, from the burning cells (i = 1 to N_{bc}), while it may loss heat by radiation to the environment, q_j^{rl}. The fire spread model is based on the energy conservation equation assuming that:

H1. Each combustible cell j(e.g. a tree or a shrub) has a cylindrical shape with a height H_j and a diameter D_j. The elementary volume involved in preheating is a top layer of the fuel element with a thickness δ_j and a volume $V_j=\pi D_j^2\delta_j/4$. The thickness δ_j, which cannot exceed H_j, corresponds to the mean free path of radiation through the cell. It can be related to the surface-to-volume ratio of fine fuel elements, σ_j, and to the volume fraction of fine fuel elements, α_j, as $\delta_j=min(4/\sigma_j\alpha_j; H_j)$ [14,15]. This implies that for a travel distance greater than δ_j the medium does not interact with radiation.

H2. Wildfire spread is dominated by the fine, thermally-thin vegetative fuels (grass and foliage of shrubs and trees), while the thicker fuel elements, typically greater than 6 mm in diameter burn more slowly at the back of the fire front [16,17] and do not contribute to fire spread.

H3. As is commonly the case in fire models involving fine wildland fuels, the thermally thin assumption is adopted here, which means that there is no temperature difference in the control volume. This is assumed to apply if δ_j is small compared to flame length.

H4. The thermal response of wet fine fuel (WFF) matter to heating involves three successive paths [18]. First, wet fine fuel elements rise in

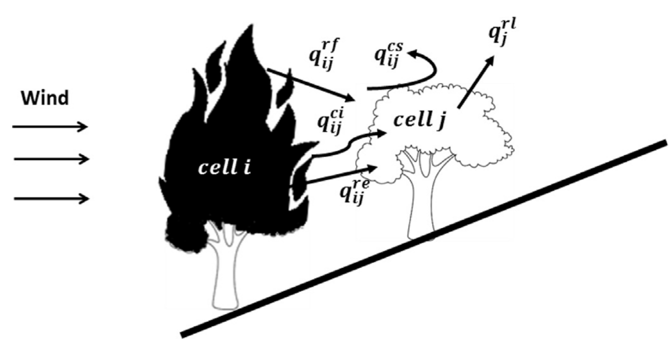

Fig. 1. Flame spread schematic, with energy-transfer mechanisms indicated.