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Short communication

Modeling wildland fire propagation using a semi-physical network model

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ABSTRACT

In this paper we present a surface wildfire model which can be used to develop and test new firefighting strategies and land use planning practices. This model is simple, easy to implement and can predict the rate of fire spread, the fire contour and both burning and burned areas. It also incorporates weather conditions and land topography. The predictive capability of the model is partially assessed by comparison with data from laboratory-scale and prescribed burning experiments. A sensitivity analysis is conducted to identify the most influential input model parameters controlling fire propagation.

1. Introduction

With global warming and ever-increasing urban-interface areas, forest fires have become a major issue in terms of human casualties, economic losses, and environmental damage. Fire modeling is used to understand and to predict possible fire behavior. Fire propagation models belong to different types depending on the approach they use. They are divided into stochastic and deterministic models, the latter being either empirical or based on the laws of physics. The model developed by Porterie et al. [1,2] combines the features of a stochastic network model with those of a semi-physical model of the interaction between the fire front and the vegetative fuel. As stated in [3], it has the advantage of taking into account physical effects well beyond the nearest neighbors of a burning site, such as flame-induced radiative effects or firebrand impact. This model combines the solid flame model and the Monte Carlo method to calculate radiation. However, this model does not take into account heat transfer by convection [3], which plays an important role in wind-driven surface fires. Indeed, as shown in [4,5], on a wide range of scales for relatively low fuel loads, fire spread is mainly governed by convective heat transfer. To take into account this important mechanism of heat transfer, the above-mentioned radiation-driven fire model is coupled with the thermal model of Koo et al. [6], in which vegetation is considered as a porous fuel layer through which the fire spreads by convection and radiation.

This paper is organized as follows. First, the one-dimensional thermal model is extended to two dimensions where vegetation is depicted as a regular network of combustible cells. Second, we compare model results with data from

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laboratory-scale and prescribed burning experiments. Third, a sensitivity analysis is conducted to identify the most influential input model parameters controlling fire propagation. Finally, in the last section conclusions are drawn and recommendations are made for future work.

2. The model

The present model is built from a two-dimensional regular network of equal-size square cells, with a density p of combustible cells (*i.e.* a cell which contains forest fuel), the $1-p$ remaining cells being either empty or filled with non-combustible elements (Fig. 1). Combustible cells can be distributed either randomly (for statistical purposes) or deterministically using a vegetation map of the study area. It is assumed that each combustible cell j has a cylindrical shape with a height H_j and a diameter D_j. A combustible cell j is said to be healthy when its temperature T_j is equal to the ambient temperature T_∞. The energy absorbed by the combustible cell when it is exposed to the fire front is used to raise the temperature of wet fine fuel elements to the boiling temperature of water, 373 K, evaporate the moisture, and raise the temperature of dry fine fuel elements to the ignition temperature. The combustible cell then continues to burn with a flame for a duration t_c (flame residence time), while transferring heat to the neighboring cells by means of convection and radiation. In the solid flame model, the visible flame is regarded as a uniformly radiating solid body with a cylindrical shape and with thermal radiation emitted from its surface.

The temperature of a cell is determined using the equation of energy conservation [6,7].

Let us consider a combustible cell j located at a distance d_{ij} from the burning cell i (Fig. 1). The total heat flux q_{ij} emitted from the burning cell i which is received by cell j is given by [6]:

$$q_{ij} = \underbrace{q_{ij}^{sr}}_{\substack{\text{surface}\\ \text{radiation}}} + \underbrace{q_{ij}^{ir}}_{\substack{\text{internal}\\ \text{radiation}}} + \underbrace{q_{ij}^{sc}}_{\substack{\text{surface}\\ \text{convection}}} + \underbrace{q_{ij}^{ic}}_{\substack{\text{internal}\\ \text{convection}}} + \underbrace{q_{ij}^{rl}}_{\substack{\text{radiative}\\ \text{loss}}} \tag{1}$$

The right-hand side of Eq. (1) is the sum of all possible heat transfer mechanisms: radiation on the top surface of cell j, internal radiation from the ember zone, convection on the top surface of cell j, internal convection inside the fuel bed, and radiation loss to the ambient at the top surface of cell j. For most nonzero ambient flow velocities, as is the case in the present study, the other energy-transfer mechanisms of preheating, such as turbulent diffusion, solid- and gas-phase conduction, convective cooling, as well as the energy absorbed by pyrolysis prior to ignition, may be disregarded [7]. Each term in Eq. (1) is examined below.

Only fine thermally thin vegetative fuels (*e.g.*, grass and foliage of shrubs and trees) are considered since they are responsible for the spread of fire, with thicker fuel elements burning more slowly at the back of the fire front. Fine fuels are defined as organic material less than 6 mm in diameter [8].

The energy q_{ij} absorbed by cell j is used on the one hand to raise the temperature of fine fuel elements and on the other hand to evaporate moisture at the boiling temperature of water,

$$q_{ij} = \begin{cases} \rho_j C_{pj} \phi_j \dfrac{dT_j}{dt}, & \text{for } T_j \neq 373\ \text{K} \\ -\rho_j h_{vap} \phi_j \dfrac{dW_j}{dt}, & \text{for } T_j = 373\ \text{K} \end{cases} \tag{2}$$

where T_j and W_j are respectively the mean temperature and the mass fraction of water of cell j, *i.e.* the mass of water per unit of initial wet fuel bed mass. In Eq. (2) ρ_j is the fuel particle density, C_{pj} is the specific heat capacity, h_{vap} is the specific enthalpy change of water to vapor at 373 K, and ϕ_j is the packing ratio, *i.e.* the fraction of the fuel bed volume filled with fine fuel elements. Their packing ratio may be deduced from the formula $\phi_j = M_j/H_j\rho_j$ where M_j is the initial mass of fine fuels per unit area and H_j the height of the vegetative cell j.

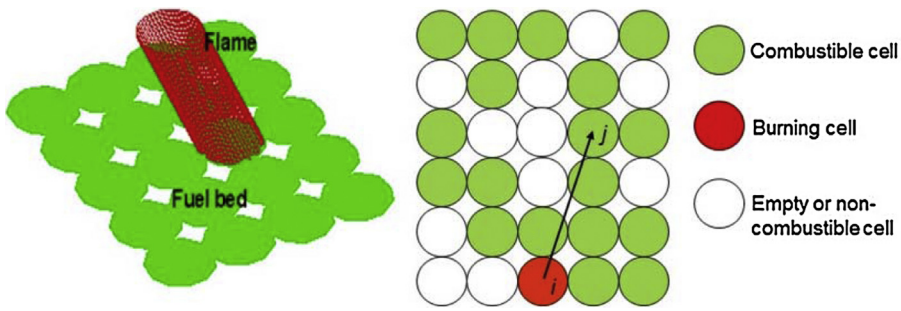

Fig. 1. Solid flame model (left) and schematic of the network showing the interaction between a burning cell i and a healthy cell j (right).