Description of the fire scheme in WRF

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1 Introduction

The wildland fire model in WRF is an implementation of the semi-empirical fire propagation model developed in Coen (2005) and Clark et al. (2004). Not all features from Coen (2005) are implemented here yet. The WRF – fire interface is based on Patton and Coen (2004). The fire model runs as a WRF physics package on a surface mesh, which is a refinement of the innermost atmospheric domain mesh. WRF-Fire is included in WRF 3.2 and this document is meant to eventually become a part of the WRF Technical Note (Skamarock et al., 2008). The latest version of WRF-Fire is also available from the developers at `http://github.com/jbeezley/wrf-fire`, and further information can be found on `http://openwfm.org`. For more details on the implementation and a discussion of the numerical methods, see Mandel et al. (2009), which contains currently the only published description of the code.

2 Model equations

The model postulates the fire propagation speed normal to the fireline as a function of wind and terrain slope, and an exponential decay of fuel from the time of ignition. Consider the fire area $\Omega = \Omega(t)$ with the boundary $\Gamma = \Gamma(t)$, called the fireline. The fireline evolves with a given spread rate $S = S(x, y, t)$ in the normal direction $\overrightarrow{n} = \overrightarrow{n}(x, y, t)$. The spread rate S is a function of the components of the wind $\overrightarrow{v}$ and the terrain gradient ∇z given by the modified formula by Rothermel (1972)

$$S = \begin{cases} 0, & \text{if } \widetilde{S} < 0, \\ S_{\max}, & \text{if } \widetilde{S} > S_{\max}, \\ \widetilde{S}, & \text{otherwise,} \end{cases} \qquad \widetilde{S} = \min\{B_0, R_0 + \phi_W + \phi_S\}, \tag{1}$$

where R_0 is the spread rate in the absence of wind, $\phi_W = a(\overrightarrow{v} \cdot \overrightarrow{n})^b$is the wind correction, $\phi_S = d\nabla z \cdot \overrightarrow{n}$ is the terrain correction, a, b, and d are constants, and B_0 is the backing rate, that is, the minimal fire spread rate even against the wind. A small backing rate of

spread must be specified, since fires are known to creep upwind on their upwind edge due to radiation.

The fuel state is maintained as the ignition time t_i. In the burning area, the fuel fraction decreases exponentially from the ignition time and is given by the BURNUP formula (Albini, 1994),

$$F(x,y,t) = \begin{cases} e^{-\frac{t-t_i(x,y)}{W(x,y)}}, & \text{if } (x,y) \in \Omega\,(t), \\ 1, & \text{otherwise,} \end{cases} \tag{2}$$

where $W\,(x,y)$ is the $1/e$ time constant of the fuel. The heat flux from the fire to the atmosphere is determined from the amount of fuel burned by

$$H = -A\,(x,y)\,\frac{\partial}{\partial t} F\,(x,y,t)\,. \tag{3}$$

The coefficients R_0, $S_{\max}$, a, b, d, W, and A, which characterize the fuel, are encoded in a table of 13 Anderson (1982) fuel categories. The fire model input data consists of the fuel category array, which is integrated in the WRF input data and can be alternatively set from the namelist for testing.

3 Coupling with WRF

The fire model is in the physics layer. In every timestep, it takes as input the horizontal wind velocity $\overrightarrow{v}$, and it outputs the heat flux H, given by (3). Since the fire mesh is generally finer than the atmospheric mesh, the wind is interpolated to the nodes of the fire mesh, and the heat flux is aggregated over the cells of the fire mesh that make up one cell of the atmospheric mesh.

At the beginning of an atmospheric time step, the wind is interpolated from the atmospheric mesh to the nodes of the fire mesh. The fire model is then advanced one or more internal time steps to the end of the atmospheric time step. The maximum time step in the fire model is limited by the stability restriction of the numerical scheme. However, the time step for the atmospheric model has been so far short enough for the fire model, and thus only one time step of the fire model is performed. After advancing the fire model, the total heat flux H generated over the atmospheric time step is inserted in the atmospheric model. The heat flux is split into sensible heat flux (a transfer of heat between the surface and air due to the difference in temperature between them) and latent heat flux (the transfer of heat due to the phase change of water between liquid and gas) in the proportion given by the fuel type and its moisture. The heat fluxes are inserted by modifying the temperature and water vapor concentration over a given number cells, with exponential decay away from the boundary. This decay mimics the distribution of temperature and water vapor fields arising from the vertical flux divergence, which is supported by infrared observations of the dynamics of crown fires in Coen et al. (2004).

4 Fireline propagation by the level set method

Fire region is represented using a level set function $\psi = \psi(x, y, t)$, such that the burning area is $\Omega(t) = \{(x, y) : \psi(x, y, t) < 0\}$. The fireline is then given by $\Gamma(t) = \{(x, y) : \psi(x, y, t) < 0\}$. The level set function satisfies the differential equation (Osher and Fedkiw, 2003)

$$\frac{\partial \psi}{\partial t} + S \|\nabla \psi\| = 0, \tag{4}$$

which is solved numerically on the fire grid. The state of the fire model consists of the level set function ψ and the ignition time t_i, given as their values at the centers of the fire grid cells. The ignition time at a node is defined as the time when the level set function becomes negative at that node.

One time step of the fire model consists of one Runge-Kutta step to advance the level set function in time, followed by the computation of ignition time for all newly ignited nodes and computation of the fuel fraction left at the end of the time step.

The level set equation is discretized on a rectangular grid rectangular mesh with spacing $[\triangle x, \triangle y]$. To advance the model in time, the Runge-Kutta method of order 2 (Heun's method) is used, that is,

$$\begin{aligned} \psi^{n+1/2} &= \psi^n + \Delta t F(\psi^n) \\ \psi^{n+1} &= \psi^n + \frac{1}{2}\Delta t \left(F(\psi^n) + F\left(\psi^{n+1/2}\right)\right), \end{aligned} \tag{5}$$

The right-hand side F is a discretization of the term $-S\|\nabla\psi\|$ with upwinding and artificial viscosity,

$$F(\psi) = -S(\overrightarrow{v} \cdot \overrightarrow{n}, \nabla z \cdot \overrightarrow{n}) \left\|\overline{\nabla}\psi\right\| + \varepsilon \triangle \psi$$

where $\overrightarrow{n} = \nabla\psi / \|\nabla\psi\|$ is computed by central differences and $\overline{\nabla}\psi = \left[\overline{\nabla}_x\psi, \overline{\nabla}_y\psi\right]$ is the upwinded finite difference approximation of $\nabla\psi$ by the Godunov method (Osher and Fedkiw, 2003, p. 58), ε is the scale-free artificial viscosity, and $\triangle\psi = \nabla_x^+\psi - \nabla_x^-\psi + \nabla_y^+\psi - \nabla_y^-\psi$ is the scaled five-point Laplacian of ψ with $\nabla_x^+, \ldots$ being numerical derivatives by one-sided finite differences.

To compute the finite difference up to the boundary, the level set function is extrapolated to one layer of nodes beyond the boundary. However, the extrapolation is not allowed to decrease the value of the level set function under the value at the boundary. For example, when (n, k) is the last node in the domain in the direction x, the extrapolation

$$\psi_{n+1,k} = \max\{\psi_{nk} + (\psi_{nk} - \psi_{n-1,k}), \psi_{nk}, \psi_{n-1,k}\},$$

is used, and similarly in other cases. This is needed to avoid numerical instabilities at the boundary.

5 Updating ignition time

After the time step for the level set function has been completed, the ignition time t_i is set for all newly ignited nodes by linear interpolation using the level set function. Suppose that the

point (x, y) is not burning at time t but is burning at time $t + \triangle t$, that is, $\psi(x, y, t) > 0$ and $\psi(x, y, t + \triangle t) \leq 0$. The ignition time $t_i = t_i(x, y)$ at the point (x, y) satisfies $\psi(x, y, t_i) = 0$. Approximating ψ linearly in t, we have

$$\frac{\psi(x, y, t) - \overbrace{\psi(x, y, t_i)}^{=0}}{t - t_i} \approx \frac{\psi(x, y, t + \triangle t) - \overbrace{\psi(x, y, t_i)}^{=0}}{t + \triangle t - t_i(x, y)},$$

which gives

$$t_i(x, y) \approx t + \frac{\psi(x, y, t) \triangle t}{\psi(x, y, t) - \psi(x, y, t + \triangle t)}.$$

6 Computation of fuel burned

The fuel burned and thus the heat generated are then computed by numerical quadrature over each fire mesh cell from the postulated exponential fuel decay (2). Each fire cells is split to four subcells and the level set function ψ and the ignition time t_i are interpolated from the cell centers to the corners of the subcells. The fraction of a subcell C that is burning at time t is approximated by

$$\frac{\text{area}\{(x, y) \in C : \psi(x, y, t) \leq 0\}}{\text{area}(C)} \approx \beta = \frac{1}{2}\left(1 - \frac{\sum_{k=1}^{4} \psi_k}{\sum_{k=1}^{4} |\psi_k|}\right),$$

where $\psi_1, \ldots, \psi_4$ are the values of the level set function at the corners of the subcell. The time from ignition on the subcell corners is replaced by zero whenever the level set function is positive (and thus the corner cannot be on fire), and the fraction of the fuel burned since ignition is approximated as

$$\frac{1}{\text{area}(C)} \iint\limits_{\substack{(x,y)\in C \\ \psi(x,y,t)\leq 0}} \left(1 - e^{-\frac{t - t_i(x,y)}{W(x,y)}}\right) dxdy \approx \beta\left(1 - e^{-t_a/W}\right)$$

where t_a is the average of the modified time from ignition on the subcell corners.

7 Ignition

The model is initialized with no fire by choosing the level set function $\psi(x, y, t_0) = 1$. The ignition is specified in the namelist. If a given ignition time $t_1 > t_0$ falls within the time step, then at the beginning of the time step, ignition within radius r of a line L is implemented by replacing the level set function by the minimum of $(d((x, y), L) - r)\psi(x, y, t_1)$ and $\psi(x, y, t_1)$, where $d((x, y), L)$ is the distance of the point (x, y) from L. The ignition time on all newly ignited nodes is set to t_1. Point ignition is achieved by having both endpoints of the line the same. The ignition radius must be several fire mesh sizes large. Multiple ignitions at the same time or at different times are possible.

8 Parallel implementation

Each timestep of Heun's method (5), $\psi^{n+1/2}$ is computed on one layer of cells beyond the patch boundary. Thus, halo of width two on the level set function ψ^n and halo of width one is called on the interpolated winds is called before each time step, and halo of width one is called on the fuel coefficients as a part of initialization.

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