WRF-fire model applied in Bulgaria

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Abstract

Wildland fires are dangerous phenomena that wipe out vast areas with forests every year and can cause loss of life. The final result is miles of burned area, some of which protected zones with rare species of the flora and fauna. The known methods are mostly focused on different aspects of fire propagation, with seldom incorporation of weather influence on the fire spread. The WRF-Fire model is giving the opportunity of combining the meteorological and environmental factors responsible for full description of the fire behavior. A wildland fire interacts with the atmosphere dynamics through fluxes of momentum, water vapor, and heat, as well as with the soil through moisture and heat retention. Data do not come as exact coefficients and initial and boundary conditions for the model variables. Instead, various quantities only indirectly linked to the model variables are measured at discrete points spread over time and space, and the data are burdened with errors.

Keywords: Environmental modeling, Wildland fires, WRF model, WRF-Fire module

Presenting Author's biography

Nina Dobrinkova is a PhD student in the Institute of Mathematics and Informatics and a researcher in the Institute of Information Technologies, Department Decision Support Systems, and both institutes are part from the Bulgarian Academy of Sciences. Nina is doing her research in the field of Environmental modeling with main focus on systems for early warning in case of natural hazards like forest fires, flood events and landslides.

Mariana Vassileva is an associate professor in the Institute of Information Technologies, where she is head of the Decision Support Systems Department. Her main field of investigation is systems with multicriterial analysis with affiliation to early warning systems with application in dissastermanagement.

1   Introduction

A computational model can capture only a fraction of the significant mechanisms in the wildland fire process. Even if a complete model existed, the data are not sufficient to make an accurate prediction possible. Also, one challenge of modeling is to estimate the accuracy of a forecast; a forecast has little value without additional information on what confidence level can be placed on it. Therefore, it is natural to consider statistics-based data assimilation methods. These methods include parameter and state estimation. Then the state of the model is the probability distribution of possible wildfire scenarios. The data are entered as the values of the measurements along with information about the probability distribution of measurement errors. The data assimilation methods proceed in analysis cycles. In each cycle, the model state is advanced in time, and then new data are injected at the end of the cycle by combining the probability distributions.

The evolution of fire is highly nonlinear, and the ignition is sharp or even discontinuous on the model scale. Statistical variability in additive corrections to the state may cause spurious ignitions, and additive corrections are not adequate for making changes to the location of the fire. The probability distribution of the fire state can be multimodal and centered around the burning and nonburning states at any given point in space. The overall fire state may concentrate around more than one distinct scenario, such as whether or not the fire jumps a road. Several models ranging from simple linear algorithms to complex computational fluid dynamics codes have been developed to simulate the propagation and behavior associated with wildland fire. All attempt in some way to incorporate the effect of the three environmental factors affecting fire behavior. These factors are fuel, weather, and topography. Some semi-empirically based fire spread algorithms such as BEHAVE and FARSITE have led to practical in-the-field tools that require simple point or two-dimensional surface values of meteorological fields such as wind as input.

While many challenging fire behavior research questions remain, many intriguing links between fire and other important issues remain to be explored, including fire impacts on air quality, water resources, and the carbon cycle. The research-quality tools capable of exploring these complex interactions are not widely available to the research community. The widely-used, established mesoscale models such as MM5 have recently begun to be applied through regional centers to provide more directed meteorological information to fire operations, also some centers are using Weather Research and Forecasting Model (WRF). However a better solution for wildland modeling is the coupled atmosphere-fire behavior module for WRF (WRF-Fire) based upon the NCAR coupled atmosphere-fire model, which is a nice tool either for research or operational system for fine calculations. In this paper we will focus on this new tool, which official release date will be in March 2010. [1][2][3][4]

2   General model description

2.1 Model description

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 $\vec{n} = \vec{n}(x, y, t)$. The spread rate S is a function of the components of the wind $\vec{v}$ and the terrain gradient ∇z given by the modified formula by Rothermel [5]:

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

where R_0 is the spread rate in the absence of wind, $\phi_W = a\left(\vec{v} \cdot \vec{n}\right)^b$ is the wind correction, $\phi_S = d\nabla z \cdot \vec{n}$ 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 [6]:

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

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

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

The coefficients R_0, $S_{\max}$, a, b, d, W, and A, which characterize the fuel, are encoded in a table of 13 fuel categories [7]. 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.

2.2 Coupling with WRF

The fire model is in the physics layer. In every time step, it takes as input the horizontal wind velocity $\vec{v}$,

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.

2.3 Fire line propagation

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 than given by the next equation $\Gamma(t) = \{(x, y) : \psi(x, y, t) < 0\}$. The level set function satisfies the differential equation [8]:

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

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 $[\Delta x, \Delta y]$. To advance the model in time the Runge-Kutta method of order 2 (Heun's method) is used,

$$\psi^{n+1/2} = \psi^n + \Delta t F(\psi^n) \qquad (5)$$

$$\psi^{n+1} = \psi^n + \frac{1}{2} \Delta t \left(F(\psi^n) + F(\psi^{n+1/2}) \right),$$

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

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

where $\overrightarrow{n} = \nabla\psi/\|\nabla\psi\|$ is computed by central differences and $\overline{\nabla}\psi = [\overline{\nabla}_x\psi, \overline{\nabla}_y\psi]$ is the upwinded finite difference approximation of $\nabla\psi$ by the Godunov method, where 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 ∇_x^+ 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.

2.4 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 $t + \Delta t$, that is $\psi(x, y, t) > 0$ and $\psi(x, y, t + \Delta t) \leq 0$. 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

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

2.5 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 $\psi_1, ..., \psi_4$ 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

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

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

2.6 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) ψ (x, y, t_1) and ψ (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 mesh sizes large. Multiple ignitions at the same time or at different times are possible.

3 Application of theWRF-Fire model in Bulgaria

The fire scheme in WRF model is very new feature and not investigated in dept. A team from Bulgarian Academy of Sciences - Institute of Information Technologies has dedicate time and research force on the fire scheme, because Bulgaria as south state in Europe suffer from forest fires very often, which can cause great damages in each aspect of live. A comparison between the results from game-method model [9] and the trivial cases in WRF-Fire gave the idea of our team to start investigating deeper in the fire scheme of WRF (so calledWRF-Fire).

We plan to collect real data for big Bulgarian fires from the last years and to implement the data into the WRF-Fire mesh. The normal resolution for Bulgaria has to be divided into smaller cells, because now the WRF-Fire support only kilometer by kilometer resolution, which is too big for the territory of Bulgaria.

4 Expected results

The modification of WRF-Fire model on smaller resolution will give to Bulgarian researchers a tool for simulation of forest fires with real data coming from the fire line coupling with weather forecast data, which will give better simulation results closer to the actual situation, when the simulated fire has began.

5 Acknowledgement

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