GENERAL DESCRIPTION OF WRF-FIRE MODEL, APPLICABLE TO BULGARIAN FOREST FIRE DATA

Nina Dobrinkova[1], **Mariana Vassileva**[1]

[1]Intitute of Information and Communication Technologies, Bulgarian Academy of Sciences,
1113 Sofia, Acad. G. Bonchev str. Bl.2, Bulgaria

ninabox2002@yahoo.com; nido@math.bas.bg (Nina Dobrinkova)

mvassileva@iinf.bas.bg (Mariana Vassileva)

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

Forest fires are problem in most of the south European countries, because of the dry climate during the summer and the year-round high temperatures. Statistics have been done among the south European EU member states and the results shows that after the year of 1995 the intensity of the fires has increased.

In this statistics Bulgaria and Romania haven't been included up to 2006, because both countries became member states in 2007. Bulgaria has done for its territory statistics for forest fires for the period 1994-2006. There is also data collected about the number of forest fires for every year between 1971 – 2006. This information is published by the National Fire Safety and Civil Protection Service, part of the Bulgarian Ministry of Interior.

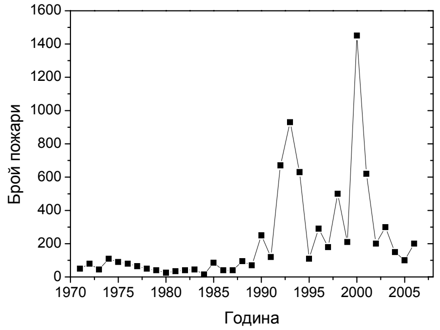

Figure 1: Total number of the forest fires per year in Bulgaria between 1971 and 2006

There is a considerable increase of the number of forest fires in Bulgaria after 1990 and especially in 1993 and 2000 when fire activity peaked and more than 1000 wildland fires devastated huge areas of forests in the lowlands as well as in the mountains. The number of fires and the average size of the fires have increased about 6 times in the recent years, however the total burned area and the percentage of vegetation burned during a year has increased dramatically - more than 30 times [1].

Even though the number of wildfires is increasing and the consequences are not only of environmental, but also of economical and social significance, proper solution haven't been found. At present most of the countries suffering from wildfires are dealing with the disaster in the moment of its occurrence. It would be much easier to avoid the long and very expensive period of handling with the fire if a working tool such as WRF-Fire can be applied to the areas with high risk of fires.

Bulgaria as country has accepted a policy that prevention of natural disasters has to be done well in advance and an Aero-Spatial Observation Center (ASOC) in Sofia, Bulgaria has been created.

It is the first aerospace center in Bulgaria. It's aimed to improve and streamline the process of early warning, prediction and monitoring of natural disasters and accidents on national scale. It allows discovering and following the dynamics of wildland and forest fires, floods, to estimate the loss of forest, control the conditions of the vegetation, soil humidity and erosion as well as air pollution.

There are four main sources of information received by the center:

- Satellite images from the Dartcom system. Information is received on every 40 min with resolution of 1 km and in five frequency ranges.
- Images from MODIS system once per day.
- Images from the DMC (Disaster Monitoring Constellation) with much higher resolution, namely 32m, received once on every two or three days depending on the satellites trajectory.
- System for aerospace monitoring via a radio navigated or human navigated airplane. Data are sent directly to the center by satellite connection.

The system operates on national level and is also used by other governmental organizations e.g. Ministry of Economy and Energy, Ministry of Environment and Water Supplies, Ministry of Agriculture and Forestry and others.

However ASOC still lacks a system for automated satellite images recognition and early detection of forest fires, floods and other natural or human-caused disasters. That is why our team from the Bulgarian Academy of Sciences has started its own research project dedicated to the forest fires models and tools for fire simulations. After a literature based analysis, we found that WRF-Fire is free Linux based model, which can simulate open area fires not only in US, but also in Bulgaria, when the needed set of data is carefully implemented into the run process.

1.1 General overview of the available forest fires tools

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. Challenging is also the modeling which has 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, usually is used statistics-based data assimilation method. 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 was in March 2010. [2][3][4][5]

2 General model description

2.1 Model description

The model bases are 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 Ω = Ω(t) with the boundary Γ = Γ(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 [6]:

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

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 [7]:

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

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 [8]. 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 Γ(t) = $\{(x,y) : \psi(x,y,t) < 0\}$. The level set function satisfies the differential equation [9]:

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

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 [Δx, Δy]. To advance the model in time the Runge-Kutta method of order 2 (Heun's method) is used,

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

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

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

where $\vec{n} = \nabla\psi / \|\nabla\psi\|$ 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 $\Delta\psi = \nabla_x^+\psi - \nabla_x^-\psi + \nabla_y^+\psi - \nabla_y^-\psi$ 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 + Δt, that is ψ (x, y, t) > 0 and ψ (x, y, t + Δt) ≤ 0. The ignition time $t_i = t_i$ (x, y) at the point (x, y) satisfies ψ(x, y, t_i) = 0. Approximating ψ linearly in t, we have

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

which gives

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

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

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

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

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

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 ψ (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. Our team from Bulgarian Academy of Sciences has dedicated 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 life. A comparison between the results from game-method model [10] and the trivial cases in WRF-Fire gave the idea of our team to start investigating deeper in the fire scheme of WRF.

We plan to collect real data from a big Bulgarian forest fire in the area of Harmanli. This mountain area is protected by Nature 2000. It is located in south-east Bulgaria and reaching it is very difficult because of the bad infrastructure and mountain terrain. That is why finding a tool to help the work of the fire brigades to simulate the fire behavior in the cases of its early allocation can be of much help on national and local levels.

Our work up to now has focused on collecting all relevant data necessary to be implemented into WRF-Fire model to work properly.

We have created an initial domain for the chosen area, which is covering area of 48 km^2 with resolution 300m (160x160). This domain is producing boundary and initial meteorological conditions for the inner domain and in this domain there are no fire simulations Fig.2. Than we did an inner domain located in the middle of the coarse domain. The resolution in D2 is 60m and the area covered is 9.6 km^2 (161x161). Meteorological conditions can have high impact on the fire propagation and the use of nested domain gives us much better meteorological background field for the studied area.

D2 is centred on the fire ignition line and it is covering the areas of villages Ivanovo, Leshnikovo and Cherna Mogila. This area is located in South-East Bulgaria close to the Bulgarian-Greece border.

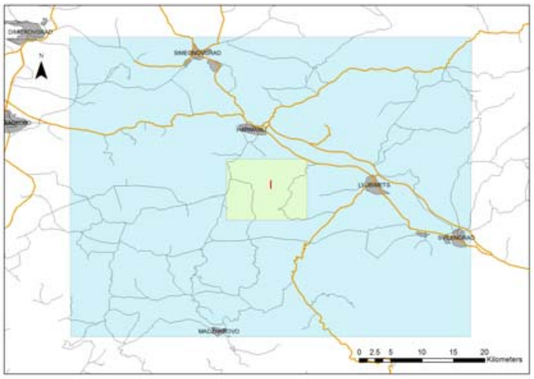

Figure 2: Map of domain 1 – blue, domain 2 – green, ignition – red line

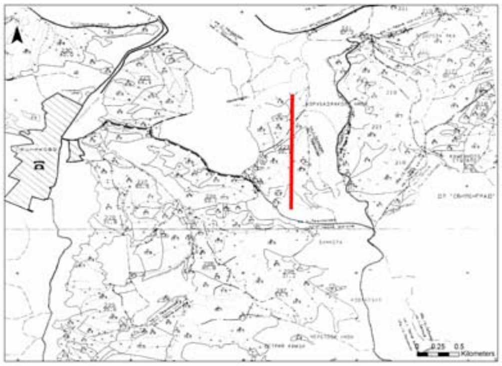

Figure 3: Plot of the ignition line in WRF-Fire, west from Leshnikovo village

We have implemented these domains into the WRF-Fire successfully, but still some meteorological data from the real fire is missing. This is the reason that we used ideal case meteo data, which gave us the way how we can incorporate the real data, when we have it.

From the experiments we concluded that WRF-Fire is a powerful tool and forest fires can be simulated by it.

4 Conclusion

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

This work is supported by the National Science Fund of the Bulgarian Ministry of Education, Youth and Science under Ideas Concourse Grant DID-02-29 "Modelling Processes with Fixed Development Rules (ModProFix)" and Young researchers Concourse

Grant DMU 02/14 “Collecting and Processing of Data Concerning Wild land Fires, Occurred On The Bulgarian Territory In The Recent Years By Using WEATHER RESEARCH AND FORECASTING MODEL-FIRE (WRF-FIRE)”

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