A coupled atmosphere-fire forest model based on cellular automata

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1 Introduction

Forest fires have been the cause of numerous and irreversible damages with deep ecological and socio-economic impacts. Entire ecosystems thriving with –also rare-animal and plant life have been wiped off while rural properties, villages and civil infrastructures lying along the verge of forests have also suffered from the ravages of wildfires which quite often result in the loss of human lives. What happened during the last days of August of 2007 in Peloponnesus was the worst damage of the last 100 years in Greece: a total of 2 thousand square kilometers of forest and agricultural areas.

It is easily understood that the need for designing and developing effective ways of dealing with forest wildfires is constantly increasing as such phenomena appear ever more often. The fire suppression policies can be generally categorized into preventive and operational ones. For both policies the numerical simulations are crucial. A model for predicting a wildfire spread would have to take into account external environmental factors like meteorological conditions as well as specific characteristics of the terrain. According to [1], the most important factors that affect the rate of spread and shape of a forest fire front are the fuel type (type of vegetation) and humidity, wind speed and direction, forest topography (slope and natural barriers), fuel continuity (vegetation thickness), and spotting which is a phenomenon where burning material is transferred by the wind or other reasons such as the fling of flaming pinecones to areas that are not adjacent to the fire front.

Building a mathematical model that could predict the spread of a wildfire, taking into account all the aforementioned factors is not an easy task as between them there are complex interactions, often poorly understood. The subject has been tackled very often in the literature, where a lot of interesting models have been proposed. One of the most important among them is the pioneering work of

Rothermel [2] who based on laboratory experiments has identified the dynamic equations that characterize the maximum fire spread rate. Rothermel's equations have subsequently been applied in a variety of approaches which in terms of spatial representation can be categorized in two types. The first type consists of models based on continuous planes [3], where it is assumed that the fire-front travels on a continuous landscape, advancing in an elliptical shape. Solutions to these models are usually obtained by solving a system of partial differential equations which can be rather computationally demanding. The second type, which is simpler and computationally faster, consists of the models that are based on a grid [4]. Among them, models based on the Cellular Automata (CA) methodology appear very promising especially for real time computation [5]. More specifically a finite grid is applied to the macroscopic scale splitting it to a large number of cells. Each cell is usually described by several variables whose states, being usually discrete, evolve in discrete time, according to a set of rules and the states of the neighboring cells. CA have proven to be powerful in predicting emergent complex macroscopic dynamics from simple rules defining the physics at the microscopic-atomistic scale [6]. This property, together with the fact that CA can easily be combined with digital data from Geographical Information Systems (GIS) or other sources makes them attractive candidates for modeling the complex behavior of wildfire spread.

Not surprisingly, many researchers have proposed CA-based approaches for modeling the spread of forest wildfires: [7-11]. However, all the previous studies do not consider the influence of the fluidodynamics of the wind on fire evolution and propagation.

This work presents an enhanced methodology for predicting the spread of a wildfire that is based on the CA framework. In particular, we aim to build a coupled atmosphere-fire model which is able to predict in real time the evolution of a forest fire over complex, large-scale and heterogeneous environments. Such coupling is, indeed, still missing in the literature. The fluidodinamic model which is implemented to numerically compute the wind field is based on the Navier-Stokes equations in the RANS formulation and the main assumptions are those of the Atmospheric boundary layer *(*ABL).

2 Cellular automata model for the fire propagation

The model uses a two dimensional grid splitting the terrain to a number of cells. Each cell represents a small patch of land and its shape has been chosen to be square, thus offering eight possible directions of fire spreading.

Each cell is characterized by a finite number of states which evolve in discrete time. The possible states are the following:

The state of a cell is one, when there is no forest fuel. This state may describe the cells that contain sea, parts of the city with no vegetation, rural areas with no vegetation etc. The state of a cell is two, when the cell contains forest fuel that has not ignited. The state of a cell is three, when the cell contains forest fuel that is burning. The state of a cell becomes four, when the contained fuel has been burned down.

In summary, at each discrete time step t of the simulation, the following rules are applied to the elements i, j of the grid:

Rule #1: IF state(i, j, t) = 1 THEN state(i, j, t+1) = 1

This rule implies that the state of a cell with no forest fuel (empty cell) remains in the same state and thus it cannot catch fire.

Rule #2: IF state(i, j, t) = 4 THEN state(i, j, t+1) = 4

This rule implies that the state of an empty cell that has been burned down in the previous step stays in the same state.

Rule #3: IF state(i, j, t) = 3 THEN state(i, j, t+1) = 4

This rule implies that a burning cell at the current time step will be burned down at the next time step.

Rule #4: IF state(i, j, t) = 3 THEN state(i±1, j±1, t+1) = 3 with a probability p_{burn}

This rule implies that when a cell catches fire at the current time step, the fire can be propagated to the neighboring cells at the next time step with a probability p_{burn}. This probability is a function of various parameters and it is calculated using the flowing formula:

$$p_{burn} = p_h (1 + p_{veg})(1 + p_{den}) p_w p_s \qquad (1)$$

where p_h denotes the constant probability that a adjacent to a burning cell containing a given type of vegetation and density will catch fire at the next time step under no wind and flat landscapes; p_{den}, p_{veg}, p_w, p_s are the fire propagation probabilities that depend on the density of vegetation, the type of vegetation, the wind speed and the slope respectively. Notice that these probabilities are multiplied by the constant probability p_h to give the corrected probability that takes into account all the aforementioned factors (for a detailed discussion about the above parameters, please refer to [11]). Differently from the previous papers, the parameter p_w will now be computed from the following relations:

$$p_w = \boldsymbol{exp}(c_1 V) f_t ,\; f_t = \boldsymbol{exp}(V c_2 (\cos(\theta) - 1)) \qquad (2)$$

where c_1, c_2 are constants to be determined and θ is the angle between the direction of the fire propagation and the direction of the wind. The velocity of the wind V is calculated from the following fluido-dynamic model.

3 Fluidodynamic model

The fluidodinamic model which is implemented to numerically compute the wind field is based on main assumption that the gas is incompressible. Such hypothesis will be removed later for the development of a more detailed model. The Coriolis forces due to the earth rotation are also neglected, as we are interested only to the atmosphere within the boundary layer.

The model is based on the Navier-Stokes equations in the RANS formulation. Decomposing the variables in the average value and fluctuation respect to the average value, the equations appear as:

$$\frac{\partial \overline{\rho}}{\partial t} + \nabla \cdot \overline{\rho} \mathbf{U} = 0$$

$$\frac{\partial}{\partial t} \overline{\rho} \mathbf{U} + \nabla \cdot (\overline{\rho} \mathbf{U} \mathbf{U}) = -\nabla \overline{p} + \nabla \cdot \overline{\sigma} - \nabla \cdot \overline{\rho} \mathbf{U}'' \mathbf{U}''$$

where

$$\sigma = 2\mu(T)\mathbf{S} - \frac{2}{3} \mu Tr(\mathbf{S}) \mathbf{I}$$

and S is the deformation tensor.

The height of the atmosphere boundary layer depends on the average altitude of the ground, on the position as well as on the meteorological conditions. The model of the atmospheric boundary layer implemented in the code is the one reported by [12]. This requires the determination of the roughness leghnt, z_0, for the different surfaces. These values are reported in Tab.1 [13].

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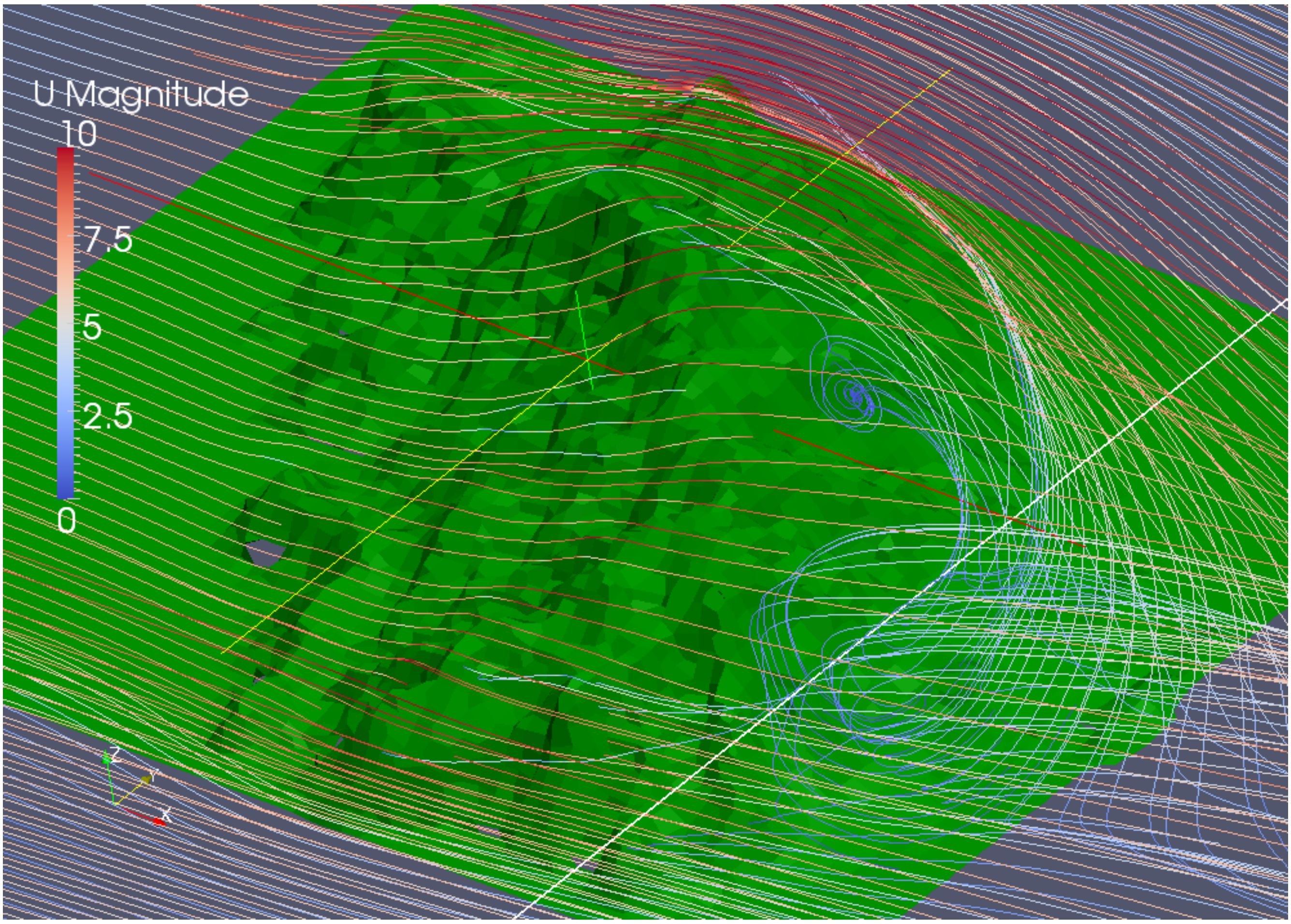

Figure 1. Streamlines traced from the front of hill injection position at z=20 m and rear of hill injection position at z = 50 m and z=150 m. Streamlines are coloured by wind velocity magnitude.

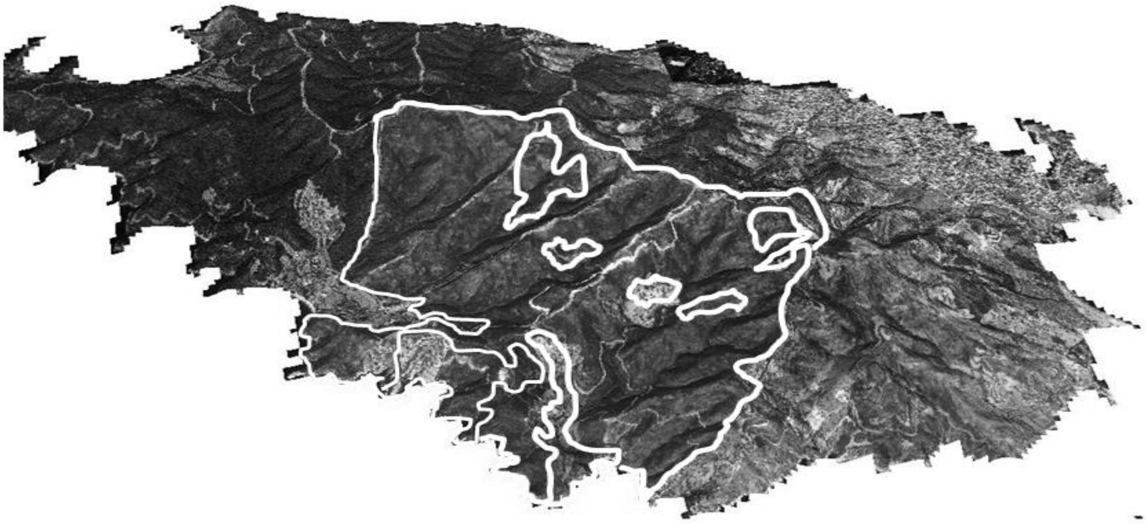

Figure 2. Stereoscopic map of the Spetses island after the fire took place; the burned area is also marked by the white contours.

Table 1: Roughness length values from various surface types

Roughness Type	Z_0 (m)
Sea, sand, snow	0.0002
Concrete, desert, flat tides	0.0002-0.0005
Flat snow field	0.0001-0.0007
Rough ice field	0.001-0.012
Fallow ground	0.001-0.004
Short grass	0.008-0.03
Long grass, heather	0.02-0.06
Low crops	0.04-0.09
High crops	0.12-0.18
Pine forest	0.8-1.6
Town	0.7-1.5

As we are interested to test the proposed methodology for the prediction of the spread of a wildfire that swept through Spetses island on August 1, 1990 in Greece (Fig. 2), we compute the wind field considering as computational domain the relief map of the island. Some results of the computed wind field are reported in Fig.1, where are reported some streamlines at different heights. The ongoing work is now focus on the linking between the cellular automata model reported in section 2 and the fluid-dynamic model reported here. The coupling is realized trough the equation (2) and we will finally compare the obtained results with the real accident happened in Spetses island of Greece.

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