SIMULATION BY A PHYSICAL MODEL OF FIRE SPREAD WITHIN A RELATIVELY LARGE SCALE DOMAIN WITH COMPLEX GEOMETRY

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Abstract
A numerical code, based on a physical model, is used to perform simulations of a fire developing over a relatively large real terrain. The paper shows how a physics based model can be efficiently used to study the behaviour of a fire propagating over a large area with a real surface configuration. In particular, the code provides information about fire front shape profiles and terrain area burned in time. The proposed method of employment of the simulation software is compared with data, available in the literature, concerning a piloted fire accident occurred in central Portugal in 2001. The comparison between the experimental and the modelled results shows a good agreement and may suggest that this model may serve as the basis for an on going prediction method.

1. Introduction

The scientific observation of fires in natural conditions is a difficult task. As for many environmental phenomena, fire modelling is a way to reduce the amount of observations necessary for understanding and predicting fire behaviour. Modelling approaches can be reduced to two types: empirical and physical.

Fire behaviour empirical models are derived on the basis of a reasonable number of fire observations. They predict the temporal evolution of rate of spread or the flame size of a fire [1]. Usually, simple equations give the rate of fire spread as a function of a certain number of parameters such as wind speed, fuel characteristics, fuel moisture, and slope.

Physical models, instead, are based on the conservation laws of the physics and on the principles of combustion [2] and numerical codes solve the model equations over time on a spatial grid. They are able to provide information about spread of fire and its basic parameters, such as temperature, air velocity, heat release rate, smoke transfer, and in some cases they enable to test strategy and effectiveness of fire suppression which may be useful for fire suppression staff [7]. However, due to their computational requirements, it is unlikely that in the near future they, at least in their present form, will replace present day operational models and approaches (e.g., [3, 4, 5, 6]). However, with respect to empirical models they have the potential, in the near term, to provide reliable and detailed predictions of the behaviour and effects of fire over a much wider range of conditions. Examples of

near term research orientated applications include assessing the effect of fire on vegetation during prescribed burns, the response of a fire to a given fire break or thinning strategy and understanding of the behaviour and spread of fires through the intermix of structural and vegetative fuels that characterize wildland-urban interfaces (WUI).
Besides the mentioned limits these models, enabling three-dimensional simulations of fire spread, are, generally, used only for small area domains or for laboratory scale experiments. In the first case in order to limit the computational costs, and in the second case because, when used for validation purposes, the small scale is simpler to control. Currently, for large scale (>10 km^2) fire GIS-based fire simulators are adopted, which work in conjunction with a GIS platform able to provide information about the heterogeneity of the terrain and of the vegetation fuel. All this makes the computational load heavier.
This work try to satisfy the need for the use of a physics based code at a medium scale domain without the use of specific GIS software. This task was accomplished using a free software to convert free available elevation data of a domain [8] into the format recognized by the main fire computational code.

2. Mathematical model and simulation conditions

The fire simulations were performed by means of the WFDS [9] software: it is a free, physics-based code developed by NIST (National Institute of Standard and Technology) and the US Forest Service as an extension of an already existing software for the simulation of fire propagation in enclosures (FDS [10]). The main reference for this code is from Mell, *et al.* [11].
The calculation domain was derived from a real terrain with the configuration of the canyon shown in Figure 1. Its conversion into the format recognized by the computational code was first performed by turning the domain into a xyz table, using the free software SURGE [12], then the matrix representing the height (z) of the surface in correspondence of each point (x,y) of the plane was converted in the final format recognized by WFDS using common editing programs (Microsoft Word and Excel).
Figure 1 reports also the plot of the coordinates extracted by the aerial view of the real terrain. It represents one of the plots in which the area of Lousã, located in central Portugal, was divided from 1998 to 2002 in order to perform fire tests in open field [13, 14]. Those experiments were designed to generate input data to be used in fire behaviour models and to support the development of new models and their validation. All the cited experiments were made in good weather conditions with wind below a certain threshold that would have made unsafe the experiments. For this reason simulations were carried out in the absence of wind.

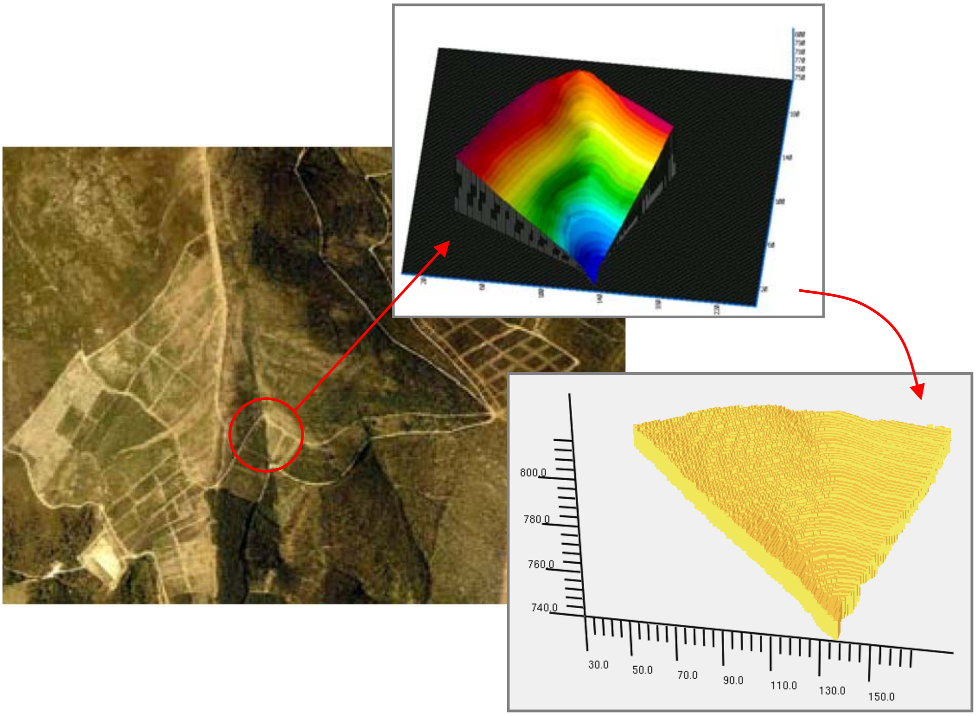

Figure 1. Aerial view of the Lousã area (left), its visualization in SURGE software (top) and its conversion in WFDS code (right).

The computational domain is 145 m long (x), 162 m wide (y) and 92 m tall (z) and has a surface area of about 25.2 ha. The whole computational domain was divided into 23 computational meshes: to limit the calculation load, the back side of the canyon, where no event occurs, was kept out of the simulation. Each computational mesh had the resolution of 1 m in the x and y direction and 0.8 m in the z axis. Simulation was performed on a single CPU core and was completed in about 30 h on an Intel Xeon E5630 at 2.53 GHz CPU with 6 GB ram.
The vegetative fuel was assumed to cover uniformly the domain and was represented by three shrubs species, *Erica umbellata*, *Erica australis* and *Chamaespartium tridentatum* with an average height of 1.0 m and a fuel load of 3.7 kg/m^2. However, in the real domain such a vegetative species corresponded to the 85% of the total cover with some heterogeneity in the respect to the shrub height as well. In general, near the top of the hill, the shrubs are lower and more disperse and some fuel breaks exist. The vegetation gets more dense and very high near the bottom where shrubs 2 m high could be found.
The physical characteristics of the fuel, implemented in the computational code,

were taken from the literature [15]. Shrubs were ignited at three points near the water line at the base of the canyon. The maximum heat flux release rate, associated with the ignition source, was set equal to 12000 kW/m^2. As said, simulations were run in the absence of wind.

3. Results

Results, reported in Figure 2, show the time profiles of the fire front during its propagation along the canyon. The fire contour at each time step was evaluated as the isotherm at 100°C. Under the assumption of no external factors (i.e., no wind field, uniform fuel density, etc.) a fire front on a flat surface would propagate at the same rate in all directions, creating concentric fronts; on the contrary, in this case the fire propagates following the surface irregularities and, then, the fire front moves slower in the canyon water line than along its flanks (Fig. 2) [16].

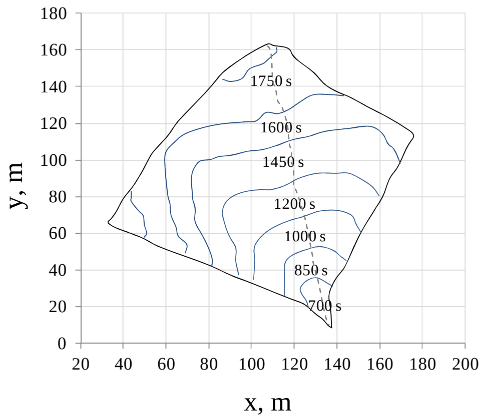

Figure 2. Time shape profiles. Dashed line: canyon water line

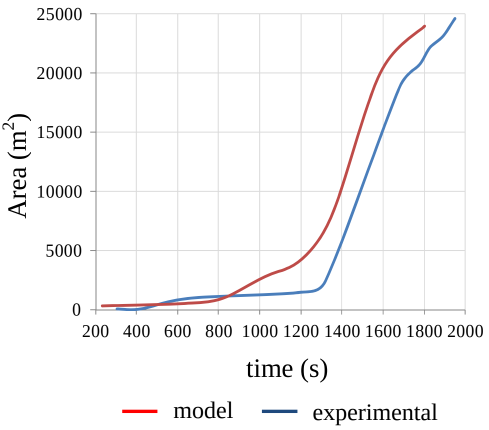

Figure 3. Area growth in the field experiment compared with the modelled results

Figure 3 reports the comparison between the calculated and the experimental values of the cumulative area spanned by the fire as a function of time. Such a figure shows that a) the canyon surface becomes completely burned in about 1800 s; b) initially, the area spanned by the fire increases in time at a relatively low rate but after about 1200 s from the fire start there is a strong acceleration and such a rate becomes more than 10 times higher; c) the experimental and the calculated values of the spanned area in time have similar trends although the calculated values resulted shifted upward of about 100 s with respect to the experimental results; d) toward the end of the test the rate of increase of the cumulative burned

area decreases because of both a lower amount of fuel available and a slight reduction in the inclination in the canyon [17].
The feature described under the point b) above is typical for this kind of domains (canyons). Indeed, the concave shape of the terrain is able to generate, even in the absence of wind, a sudden change of the fire behaviour (eruptive fire) because it favours the pre-heating of the fuel located ahead of the fire front and promotes the continuous intake of fresh air at the base of the canyon (chimney effect) [13].
The minor discrepancy between experimental and calculated data, underlined under the point c), could be due to incorrect assumptions (power and or position) of the ignition source in the numerical model, which could give rise to an anticipated fuel ignition with respect to the real case. Indeed, detailed information about the ignition source used in the experiments were not available. This aspect needs to be further investigated.

5. Conclusions

Results showed that the use of the physics-based model, WFDS, specifically designed to simulate forest fire, is effective in studying the way fire spreads across a real domain with a complex configuration. Results confirm the strong dependency of the terrain heterogeneity on the time profiles of the fire front.
At the level of resolution adopted, WFDS was not able to directly resolve the fire behaviour details in the grass fuel bed, but the fire/domain interactions that occur over scales on the order of a few meters could be resolved. This level of resolution of the fire physics was sufficient to capture the dynamics of the fire perimeter and also to highlight the role of the domain geometry (canyon) in generating an eruptive fire behaviour. Results of the cumulative area spanned in time by the fire also showed a good agreement between experimental and calculated values, while minor differences between results are probably due to an over estimation of the ignition source power or to an incorrect position of it. Results provide a basis to carry out a risk analysis of fire spreading taking into account specific terrain features and vegetative characteristics of a given geographic area.

6. References

[1] Sullivan A.L.:"Wildland surface fire spread modelling, 1990–2007. 2: Empirical and quasi-empirical models". *Int. J.of Wildland Fire*, 18: 369–386 (2009).
[2] Sullivan A.L.: "Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models". *Int. J. of Wildland Fire* 18: 349–368 (2009).
[3] Andrews, P.L.: “BEHAVE: Fire behavior prediction and modeling system -- BURN subsystem part 1,” *USDAFor. Serv. Gen. Tech. Rep. INT-194.* See also http://www.fire.org (1986).

[4] Finney, M.A.: “FARSITE: Fire Area Simulator-Model, Development and Evaluation,” *USDA Forest Service, Rocky Mountain Research Station Paper, RMRS-RP-4*, (1998).

[5] Hirsch, K.G.: “Canadian forest fire behavior prediction (FBP) system: user's guide”, Canadian Forest Service, Special Report 7, Northwest Region, Northern Forestry Centre.(1996).

[6] Nobel, I.R., Bary, G.A.V. and Gill, A.M.: “McArthur's fire-danger meters expressed as equations” *AustralianJ. of Ecology*, **5**: 210-203 (1980).

[7] Huo Ran, Jin xu-hui, Liang Wen: "Simulation analysis for people’s escape in large public building fire". *Fire Safety Sci.* 8, 2: 8-14 (1999).

[8] i.e. http://maps.google.it/, terrain mode

[9] http://www2.bfrl.nist.gov/userpages/wmell/nist_wui_models.html

[10] McGrattan, K. B., Hostikka, S., Floyd, Fire Dynamics Simulator. Users Guide. National Institute of Standards and Technology Special Publication 1019-5, Gaithersburg, Maryland, USA (2009).

[11] Mell W.E., Marenghides A., McDermott R., Manzello S.: "Numerical simulation and experiments of burning Douglas fir trees". *Combustion and flame*, 156: 2023-2041 (2009).

[12] http://surgeweb.sweb.cz/surgemain.htm

[13] Viegas, D.X.: "Fire spread in canyons". *Int. J.Wildland Fires*, 13: 253-274 (2004).

[14] Viegas D.X., Cruz M.G., Ribeiro L.M., Silva A.J., Ollero A., *et al*.: Gestosa fire spread experiments. In 'Proceedings of the IV International Conference on Forest Fire Research and Wildland Fire Safety', Luso, Portugal, 18–23 November (2002).

[15] Barboutis J.A., Philippou J.L.: "Evergreen Mediterranean hardwoods as particle board raw material" *Building and Environment*, 42(3) 1183–1187 (2007).

[16] Malangone L., Russo P., Vaccaro S.: "Fire behaviour in canyons due to symmetric and asymmetric ignitions". International Congress *Fire Computer Modeling* October 18-19 Santander (Spain) (2012).

[17] Malangone L., Russo P., Vaccaro S.: "The role of the terrain geometry on the flames propagation through a vegetative fuel bed", *MCS 7* Chia Laguna, Cagliari, Sardinia, Italy, September 11-15 (2011).

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