Validation of a physics-based fire spread model and simulation method on a large wildfire accident

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Abstract
An operational wildland fire model need to be robust and accurate. In this study, a physical model of fire spread is presented and used to perform simulation with an asynchronous method. The aim of this work is to provide an efficient simulation method capable of providing resutls in less than a minute and a resolution of a few meters using a physical model. The proposed simulation software is validated on a reanalysis of a fire accident occurred in south of France in 2005. The use of a physical model enables to build a confidence interval for the simulation results based on the uncertainity on a physical parameter. The proposed simulation method and fire spread model performs well in obtaining these results in a very quick simulation time, while still performing high resolution calculation necessary to take into account precisely roads, non uniform wind and elevation data.

Keywords:
fire spread, asynchronous, simulation, discrete events, flame, forest, wildland, fire model.

Introduction

For decades, the scientific community has been trying to predict forest fire propagation with the aim to support decisions of fire fighting and prevention. A valuable tool for assisting these decisions is a fire spread simulation software that, from a limited set of inputs (vegetation, humidity, slope, wind, and ignition points), can quickly and explicitly provides the fire evolution.

A few of these fire spread simulators are already frequently used by professionals (such as BEHAVE or FARSITE (Finney and Andrews 1994) many based on the model presented by Rothermel (1972). Although those software packages prove to be very useful and generate accurate results, they are not fully satisfying in many ways.

They are based on a model that is mostly empirical; therefore, a limited set of experiments can be reproduced by those simulators. Another objection for those models is that they are taking into account wind and slope separately to deduce the fire spread speed, which cannot be theoretically justified. Those models also have evolved in time to take into account more and more situations, often resulting in the addition of many sub-models and parameters that must be set empirically to generate sensible results. The added complexity of those empirical models renders it difficult to find sensible parameter on which to built confidence intervals.

Moreover, even with those simplified models, calculation time is typically of several minutes for the entire simulation of a medium sized wildfire and for a sensible resolution (about ten meters or the width of a road). Such calculation time can be limiting for the operator that wants to try many scenarios.

The aim of this work is to propose a new model that can be more physical than empirical, generic enough to take into account most situations with a relative confidence and a simulator that can provide results in less than a minute with a sensible resolution.

The first part of the paper presents briefly the simulation method, based on front tracking, which is used to simulate the advance of the fire front. The actual physical model used to calculate the speed of the fire front is presented in the second part.

The third part of the paper shows the application of the software in a reanalysis of a real fire accident that occurred in Lançon de Provence in July 2005.

Efficient asynchronous simulation of fire front evolution

Most work done in the field of numerical methods of fire spread has been done with models that prognoses Rate of Spread (RoS) to reconstruct an evolving fire front. RoS for every portion of the front is used to reconstruct the shape of the fire over time from an initial solution. Among reconstruction methods, the most commonly used is the method of ellipses where ellipses the size of a fire advance for a given time step are drawn around an initial front to reconstruct the front one step forward (Finney and Andrews 1994). Ellipses is not the only method that can be used to reconstruct the very fire front, as one can use level set (Mallet et al, 2007), volume of fluid (Hirt and Nichols, 1981), or markers (Lallemand *et al*. 2007). This family of methods is usually referred as front tracking methods.

Front tracking

Front tracking method (Risebro and Tveito 1992) is the general denomination for any numerical scheme that integrates the behavior of the very interface between two phases of a system (burnt/unburnt, water/oil, etc…). In more general front tracking method, the propagation operator does not have to be an ellipse but in fact, any function that can provide a propagation speed for a specific direction of the front, set of state and local topology (such as local curvature).

The method proposed in this paper derives from the markers method that proves to be relatively quick and accurate (Lallemand *et al*. 2007). Interface is discretized by a set of points or markers; at each step markers are moved according to the speed function in the direction of the front normal at this point (displacement vector). The application of the front tracking method to fire front is presented in Figure 1.

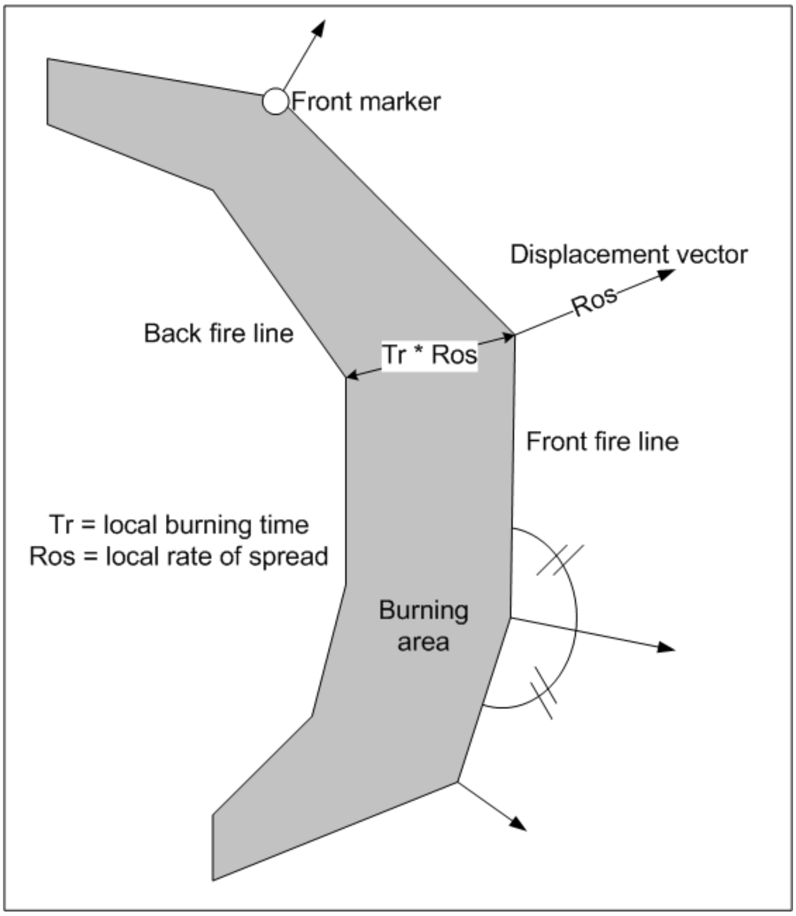

Fig. 1. Front tracking markers method.

Nevertheless, the main problem of this method is that collision or intersection must be checked each time a marker is moved to take care of intersections between fronts.

If all markers are moved synchronously using an explicit time step, there will be as many topological checks as there are markers at every step, event if the marker has moved by a few centimetre due to its relative low speed. The originality of the proposed front tracking markers method is to move markers asynchronously, with no global time step, by using Discrete Event Simulation (DES).

In time driven simulation, all state changes must be performed synchronously at each time step. Because the time step is a spatially uniform time interval, it is conditioned by the smallest detail that needs to be taken into account in the simulation: the Courant-Friedrichs-Levy (CFL) condition $\Delta t < \Delta x / V$ where V is the fastest speed in the whole domain, and Δx the size of the smallest detail, or se size of an unitary cell in a mesh.

Specifically in markers method, the time step will be constrained by the fastest marker at each step (such as in FARSITE). In forest fire, speed for the same front can range from a few cm.s-1 (back fire) to a few m.s-1 (head fire), in such configuration markers are re-calculated regardless of the actual distance covered resulting in many unnecessary computations (at each time step the slower markers will be moved by a very small distance while the faster markers will be moved by the maximum acceptable distance given by the CFL).

In DES, the local state change of a system is triggered by an event. Each event has an occurrence time which does not have to be spatially uniform. During simulation events with occurrence time are created, scheduled in an event list sorted by this occurrence time, and processed asynchronously with the most imminent event processed first. By using DES it is possible to move every marker independently, calculating the marker advance only when it has covered a significant distance, thus removing the constraint of the CFL condition.

Simulation algorithms

As for every discrete event simulation, markers are reacting to events that are triggering their advance in space and time. There are two key concepts that form the base of the simulation as they are generating the driving events:

- Quantum distance: noted Δq, defines (in meters) the maximum distance that is allowed to be covered by a marker advance. The actual resolution of the simulation is limited by this quantum distance and details that are smaller than this quantum distance may not be taken into account.
- Collision: A collision is happening when a marker is moving into a different area (from bushes to a fuel break, or from an un-burnt area to an already burnt area). Collisions also occur if a marker and its neighbour marker are separated by less than a minimum distance allowed during simulation: the quantum distance. Each collision will trigger a dynamic modification of the shape, by adding or deleting markers.

All motion and all events are generated by either a collision or by the marker planning an advance in space and time. Collisions trigger the resolution of the overall shape modification. While markers are actually moving by self-activation until they stop.

Unlike conventional Lagrange method for the computation of a particle advance in a flow, in DES resolution of a marker advance has to resolve the inverse problem, fixing a quantum distance instead of fixing a time step. Activation time for markers is given by time advance (t_a) that is computed by calculating how long it will take for the marker to travel Δq.

Calculation of t_a function is performed explicitely with $t_a = \frac{\Delta q}{\mathbf{v}_o}$. Activation event are schedueled to reactivate the market at time $t_n = t_o + t_a$, move it to the next position, check for collision for this marker and schedule next advance.

The marker advance is integrated by a simple Euler approximation with the marker direction and speed dependant of the velocity function *R*. Local slope angle and wind speed for *R* at the very location of a marker is approximated by bi-cubic interpolation if the elevation and wind data are in grid format. At the local scale, quantum distance is driving the numerical integration of a marker path; behaviour of the overall front is handled by the reaction to collision events.

Shape behaviour

Each structural state change occurs anytime a collision happens between the interface and the environment, or the interface with itself. An internal collision, when there is an intersection of the shape with itself or another shape, it triggers a front recomposition (Figure 3). And a self collision occurs if part of the interface has moved by a certain distance, it triggers a self-decomposition that refines the shape (Figure 4).

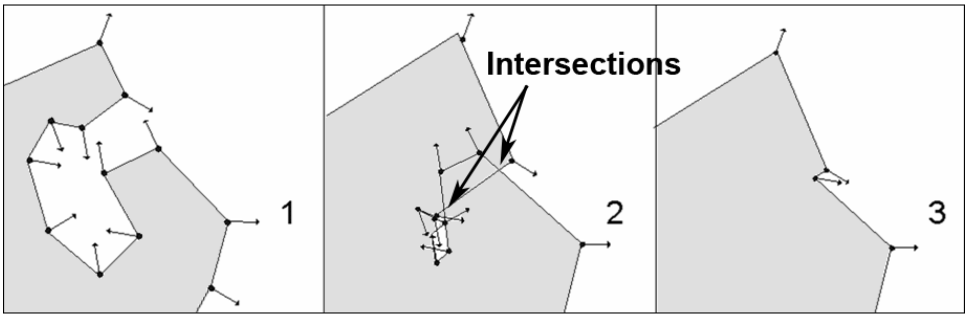

Fig. 2. Recomposition after internal intersections are found, (1) before intersection, (2) intersections detected, (3) after recomposition.

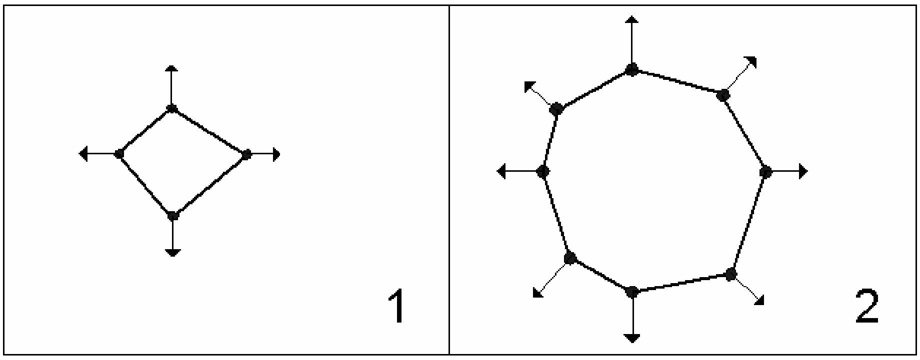

Fig. 3. Self-decomposition (refinement) after a critical size is reached, (1) before decomposition, (2) refined shape

If the simulation was synchronous, geometrical checks for collisions have to be done for every marker at every step, so that the complexity of the check is N^2 with N = the number of markers. Asynchronous simulation is reducing those checks to the very marker that has moved, so that there is N check at each marker advance.

Finally, what drives the marker is a fire spread model, the *R* function. At any given point of space and time, a marker must be able to compute its speed giving its direction. For that, we developed a physical based model. An overview of this model is presented in the next chapter.

Physical fire spread model

This model derives from a formulation presented in Balbi *et al.* (2007). This physical based model has been developped to provide an analytical formulation of the propagation speed given a slope angle, wind speed, and fuel parameters. The model is based on the main hypothesis that the fire front is acting as a radiation panel that is heating the vegetation in front of it, such as shown in figure 4.
It is based on the following hypothesis :

- The heat transfer is due to the radiation, of the front fire, assimilated to its tangent plane.
- The radiation factor decreases with the surface/volume ratio of the flame.
- The speed in the flame is the vectorial sum of the wind speed with vertical speed due to buoyancy**.**

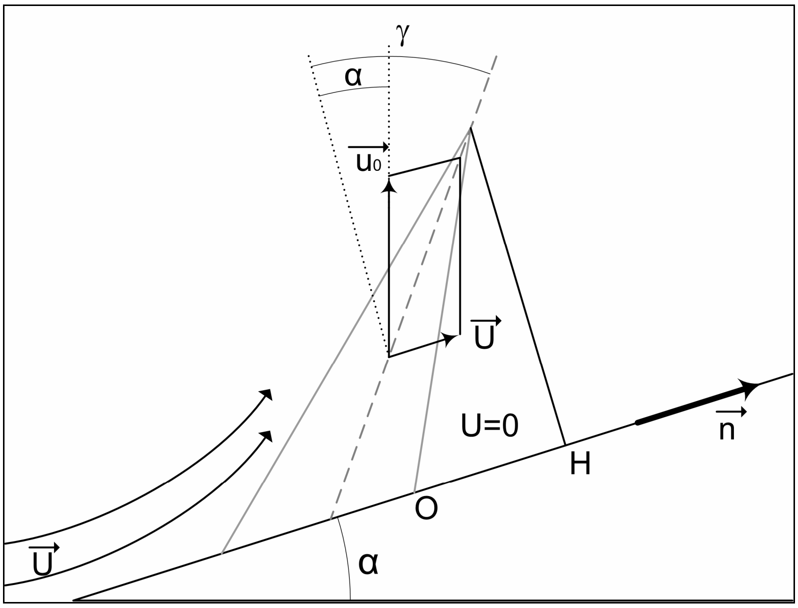

Fig. 4. Calculation of the flame angle

These hypotheses leads to a simple expression of the physical laws: mass, species, momentum, energy balances in the flame and in the fuel, providing the following model:

$$\tan\gamma = \tan\alpha + \frac{U}{u_0}$$

$$R = R_0 + A\frac{R(1+\sin\gamma - \cos\gamma)}{1+\frac{R}{r_0}\cos\gamma}$$

Where the model outputs are:

γ Flame tilt angle in degrees,

R Rate of spread in $m.s^{-1}$.

The input variable are:

α Local slope angle in degrees,

U Normal wind velocity in $m.s^{-1}$.

The model parameters that characterize the fuel are:

A Ratio of radiated energy over ignition energy (in $J.J^{-1}$) ,

r_0 Speed parameter due to radiation in $m.s^{-1}$,

R_0 Rate of spread without wind and spread in $m.s^{-1}$,

u_0 Vertical velocity in the flame without wind and slope in $m.s^{-1}$.

The model output is directly a rate of spread given any direction of the front normal; a natural representation of the model output is a speed polar diagram as shown in figure 5. The polar diagram shows that the model is providing results that can be quite different of the ellipse that is commonly used to derive speed in most fire simulation models (see Finney and Andrews (1994)). Therefore it can be considered as a non-elliptical fire growth model.

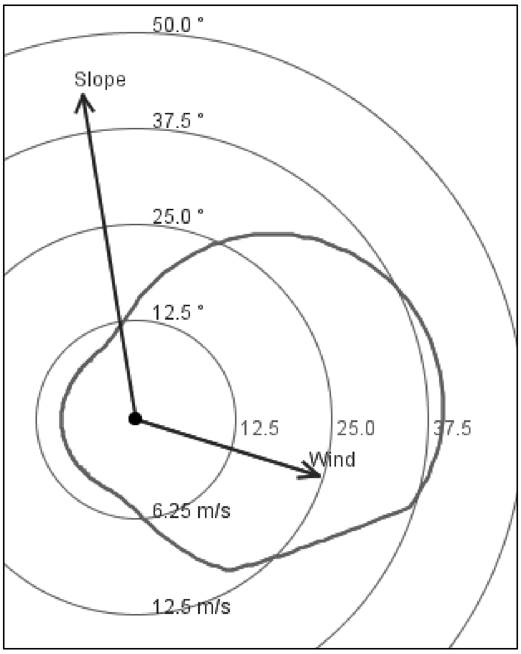

Fig. 5. Speed polar diagram of the model output for a given wind and slope vector and a given set of parameters, the black ovoid line represents the polar view of propagation speed in all direction and the two arrows the wind and slope direction and intensity**.**

In order to calculate the propagation speed at any given point, the four fuel parameters have to be setted. The following example presents an use case of this model and simulation method over a real fire accident.

Validation on Lançon accident.

To verify the robustness and speed of the method in propagating 2D fire fronts, we ran the model to simulate a fire based on a real scenario. We selected the 2005 Lançon fire that took place in the south of France and burnt about 800 Ha of shrubs and forest. On the day a North Westerly wind of 50Kmh was blowing, providing extreme condition of propagation, fire started at 9h40 AM and last until 16h30.

This accident is particularly well documented, as a vegetation map is available, as well as roads, ignition points and 3 contours of the fire front evolution at 12h, 14h30 and 16h30.

Nevertheless, it is known that fire-fighters have made numerous attacks on the fire in order to protect the urban area of "Val de Sibourg" and to constrain the fire on its right flank. As there is no precise data available for these attacks, we ran the simulation without taking into account the effect of the fire-fighters.

The wind map has been calculated as a stationary solution using mainstream computational fluid dynamics software (Fluent), resolution of the wind map is the same as the digital elevation model: 50m*50m. Figure 6 presents the actual situation of the Lançon area on the day of the fire.

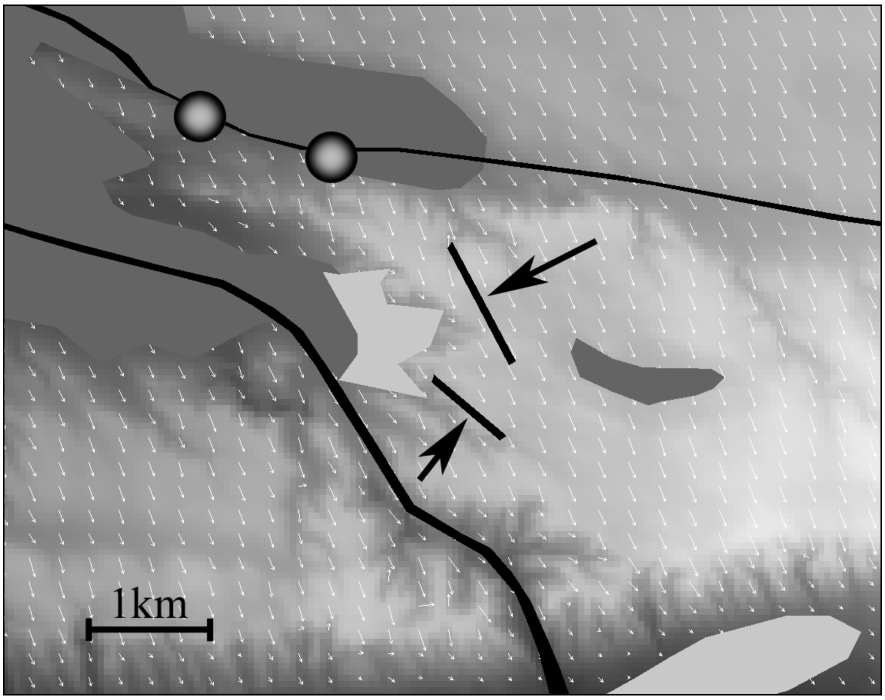

Fig. 6. Map of the Lançon area. Areas in dark and light grey correspond to crops and urban areas and considered non burnable. Shades of grey in the background represent the elevation ranging from 50m for plain black to 300m for plain white. Black lines correspond to large roads and big dots to the ignition points that started the fire at 9h40. The two arrows are pointing to the main estimated areas of fire fighting. Thin white lines shows the wind vector as simulated.

Simulation parameters

The simulation has been run with a quantum distance of ten meters, as it is discrete events based, there is no time step. Because the vegetation is quite homogeneous, the simulation is driven by far by self-decomposition (the most events are generated because marker moves over the quantum distance). While every detail less than ten meters are taken into account, simulation time using this quantum distance is under 30 seconds on a 2.5 GHz single core processor with 1 GB of RAM. The interested reader can rerun the simulation directly using a java applet online http://spe.univ-corse.fr/filippiweb/simulation/.

Determination of fuel parameters

The fire propagation model needs four parameters (A, r_0, R_0, u_0) to be settled in order to characterize the fuel. Identification of the class of vegetation available thanks to the IGN data collected before the accident. Because the vegetation is approximately known, it is possible to guess a possible interval for those parameters thanks to experimental data collected with the same class of vegetation.

In the case of the Lançon accident, most of the burn vegetation consisted of shrubs, we will use two sets of parameters, one for shrubs, and one for all area that cannot burn (with zero propagation speed), consisting of large roads, urban area and crops.

This kind of shrubs is very typical in the Mediterranean region, so the parameters can be guessed from an instrumentation of a prescribed burning from a previous study (Santoni *et al.* 2006) also conducted during the same season and with same vegetation class.

In this study, lowest values for Ros (with no wind) correspond to parameter R_0, during the prescribed burning it ranged from $0.02 m.s^{-1}$ to $0.75 m.s^{-1}$, with an average value of $0.05 m.s^{-1}$.
In the case of Lançon as well, the average propagation speed deduced from the advance of the back fire of the first contour (at 12h) from the provided ignition point at 9h30 corresponds to a speed of $0.05 m.s^{-1}$.
The three other parameters (u_0, A, r_0) are assumed to be relatively independent of the inter-seasonal variability of the fuel for a dry day (in terms of relative humidity and fuel depth). In order to obtain the values for those parameters, R_0 is fixed to the average value of $0.05\ m.s^{-1}$, A and u_0 are set to 1 and r_0 is fitted so that the model first matches the propagation speed observed in case of low wind (typically $0.15 m.s^{-1}$ for a $3 m.s^{-1}$ wind in the prescribed burn). Then u_0 is fitted so that the model matches the observed propagation speed in stronger winds (typically $0.4 m.s^{-1}$ for a $5.5 m.s^{-1}$ wind). After fitting those two parameters with A set to 1, the value for shrubs for parameter u_0 is $5\ m.s^{-1}$ and $0.15\ m.s^{-1}$ for r_0. Once we have fitted u_0 for strong wind, A is readjusted so the model both matches the observed propagation speed in case of low and high winds; in this case A is readjusted to $1.5\ J.J^{-1}$.
In case of badly known vegetation those three measurements, propagation speed in no winds, low winds and high winds are always needed to fit those parameters; they are easily observed as the propagation speed at the back, the flank and the head fire.

Simulation with optimal fuel parameters

Simulation results and observations are presented in Figure 7,8 and 9. The simulation was started at 9h40 at the exact same points as the estimated ignition points, and stopped at 16h30 (last known contour). Although no adjustments have been made on the parameters during the simulation run, the simulated contours and times is in good accordance with the observed front. Nevertheless, the simulation results show a strong development on the right front that is not observed in the actual fire. This diference is probably due to the attack of the fire fighters that prevented the fire to develop on the right flank.
Also, on the backfire, we can observe that simulated contour is larger than the real fire, we believe that this phenomenun is due to a wind cooling effect on the backfire. This effect is not taken into account in the model but is the subject of further improvement.

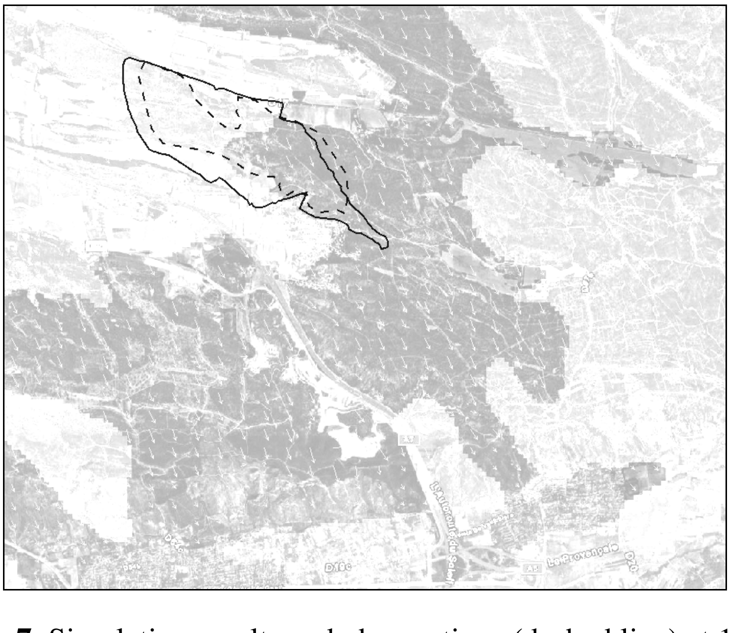

Fig. 7. Simulation results and observations (dashed line) at 12h.

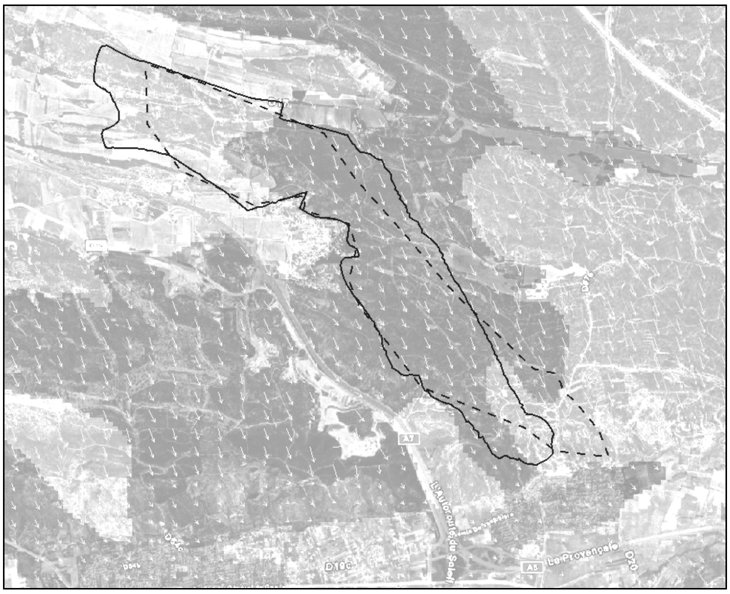

Fig. 8. Simulation results and observations (dashed line) at 14h30.

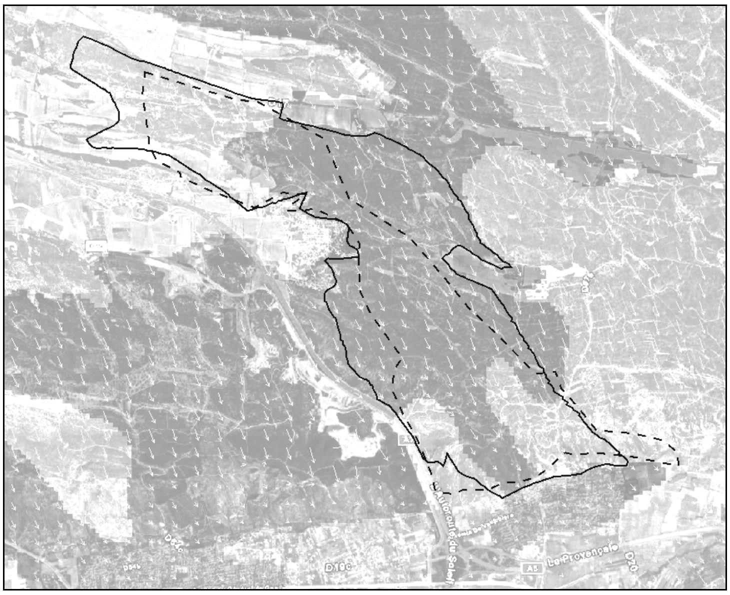

Fig. 9. Simulation results and observations (dashed line) at 16h30**.**

Such are obtained with the optimal value for the parameter R_0, to validate the robustness of the simulation it is necessary to perform simulation with minimum and maximum possible values of this parameter.

Sensitivity analysis

Parameter R0 is mainly dependant on the packing ratio of the vegetation, which can range greatly between similar vegetation classes and between areas. In order to represent this range of incertitude the following simulation we will use a value of 50% of the optimal R0 for an “optimistic” simulation, and 150% of the optimal R0 for the “pessimistic” simulation. The range of variation of 50% to 150% corresponds to the range in measurements in the prescribed burning used to fit the parameters (Santoni *et al*. 2006).

In figure 10, 11 and 12, the simulated contours correspond to the optimistic and pessimistic

value for R0. For most portions of the fire, the observed front is well within the area between the pessimistic and optimistic simulated contours.
Moreover the simulation results are relatively stable considering the high range of variations that is applied to R_0, illustrating the robustness of the model.

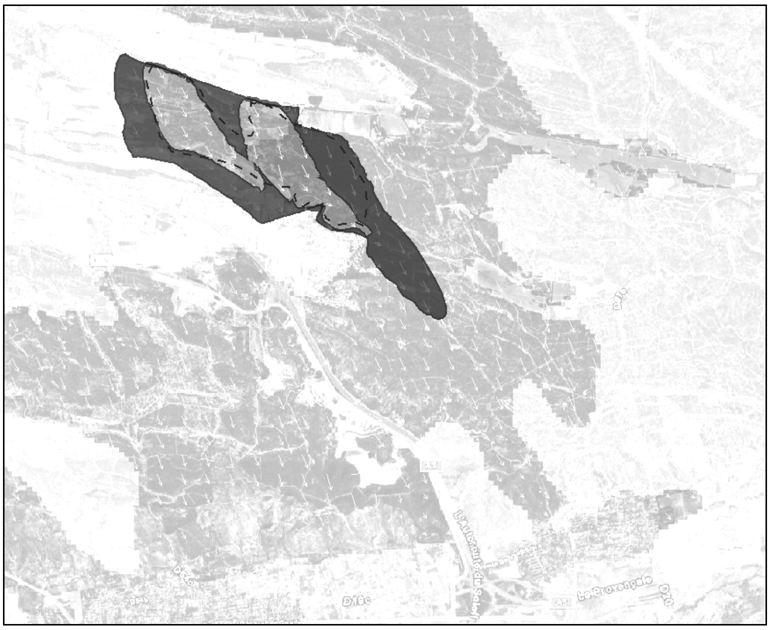

Fig. 10. Pessimistic(dark), Optimistic (light) simulation results and observations (dashed line) at 12h.

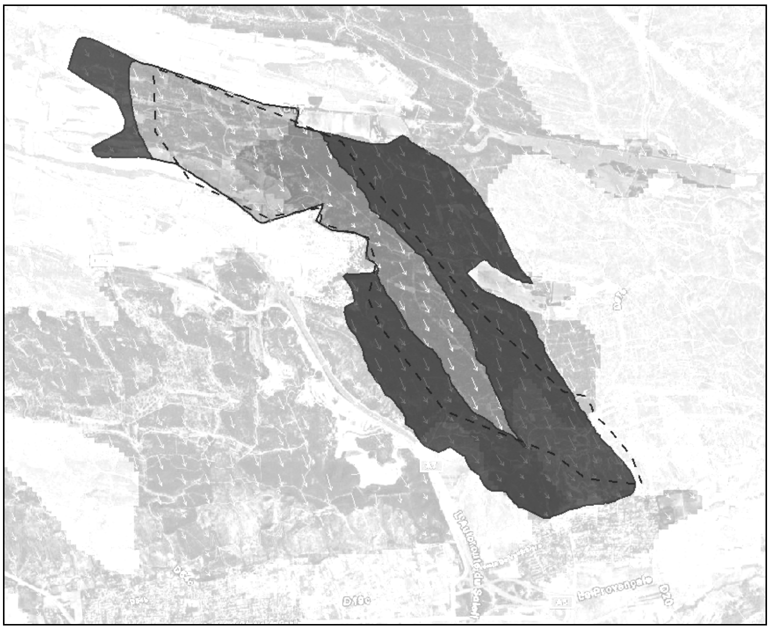

Fig.11. Pessimistic(dark), Optimistic (light) simulation results and observations (dashed line) at 14h30.

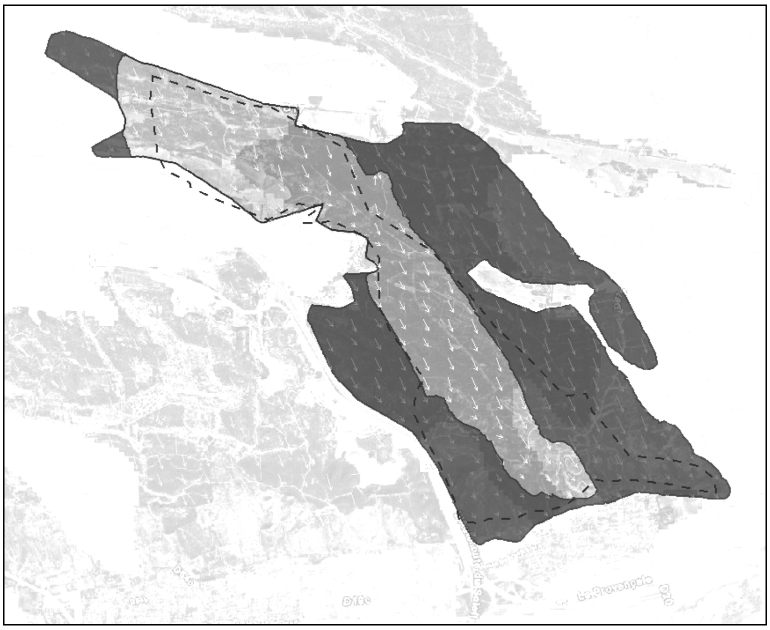

Fig. 12. Pessimistic(dark), Optimistic (light) simulation results and observations (dashed line) at 16h30**.**

Conclusion

This paper presented a physical model of fire spread coupled with an original simulation method. Results show that the software is well suited to simulate the behaviour of front propagation in a real case scenario. Only four simple parameters have to be fixed to obtain a sensible result, and it is possible to obtain a confidence interval that is physically justified.

The asynchronous front tracking method developed for the simulation permits to have very accurate and fast simulation time with a simulation of a real case taking under half a minute for a ten meters resolution. Such simulation times opens the way for new practices in wildfire simulation where many fighting scenarios can be tested in a short amount of time and many virtual fires can be started from a large number of possible ignition point.

Further enhancements to the simulation systems are planned to take into account the wind cooling effect on the back fire as well as more test on real fire scenarios.

Acknowledgements

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