A ‘complete’ physical model of forest fire behaviour as a tool to manage the forest fuel on WUI

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Abstract

The management of wildland/urban interfaces (WUI) is one of the basic key-point of wildland fire prevention policy and land management in Mediterranean regions. Managers faced to fire prevention on WUI lack methods and tools to assess the wildland fire hazards to interfaces of given intrinsic characteristics (wildland fuel, urban structures and constructions), and to test the consequences of wildland fuel reduction on wildland fire behaviour and effects. In the frame of the FireStar(*) research programme, a forest fire behaviour model, named “complete” physical and multiphase model, is developed to deal with such requirements arising from managers. This model is briefly presented. Some results of numerical simulations of the model are shown for shrub land fires. Then it is shown how the model is a powerful tool to help the management of fuel on fuel breaks or on a WUI. The main limits of the model itself and of the use of such a complex model are also reminded.

(*) Fire Star: A decision support system for fuel management and fire hazard reduction in Mediterranean wildland - urban interfaces. Funded by the European Union. Contract: EVG1-CT-2001-00041.

Introduction

The management of wildland/urban interfaces (WUI) is one of the basic key-point of wildland fire prevention policy and land management in Mediterranean regions. We consider that an interface is commonly composed of three zones: (i) zone 1: either woodland or shrubland in which no specific treatments for wildland fire prevention have been applied; (ii) zone 2: wildland area in which specific treatments like thinning and tree pruning, and/or shrubs, herbaceous and litter suppression, have been applied to create a fuel break; (iii) zone 3: the immediate environment of the structures, the structures themselves and the exposed persons (inhabitants and fire-fighters). Managers faced to fire prevention on WUI lack methods and tools to assess the wildland fire

Close this chapter

hazards to interfaces of given intrinsic characteristics (wildland fuel, urban structures and constructions), and to test the consequences of wildland fuel reduction (zone 2) on wildland fire behaviour and effects.

In the frame of the Fire Star (*) research programme, we chose to develop a forest fire behaviour model, named "complete" physical and multiphase model that enables to deal with such requirements arising from managers. A brief presentation of this model is given in the first section. Some results of numerical simulations of fire propagation in shrub lands are reported in the second section in order to show some typical outputs of the model. Finally, the third section illustrates the use of the model as a tool to manage the fuel on the WUI.

The multiphase "complete" physical model.

The development of a sophisticated physics-based model was initiated six years ago. Larini *et al*. (1998) presented a first multiphase formulation of a complete physical model and some results of a 1-Dimensional solution of the equations. At the same time, two simplified models were developed from this approach (Giroud 1997, Dupuy and Larini 1999). A 2-Dimensional numerical solution of the « complete » model was then obtained and we ran it on laboratory fuel beds to compare the predictions to observed fires, with a reasonable success (Morvan and Dupuy 2001). First simulations of fires propagating in a realistic natural vegetation (*Quercus coccifera* guarrigue) were run in 2001 and the main results are reported in Morvan and Dupuy (2003). Now we are performing the first simulations of the model at the full scale of forest stands.

In the multiphase approach, we regard the vegetation as a set of fuel particles distributed in the ambient air (Figure 1). Particles that have similar properties are grouped into families or solid phases. Examples of families are leaves, or twigs, or branches, of a same plant species. To describe the vegetation, we define the volume fraction of each family, which is the fraction of space volume actually occupied by the particles of a solid phase at a given point of the vegetation layer. Important properties of the particles of course are their surface-to-volume ratio and their moisture content.

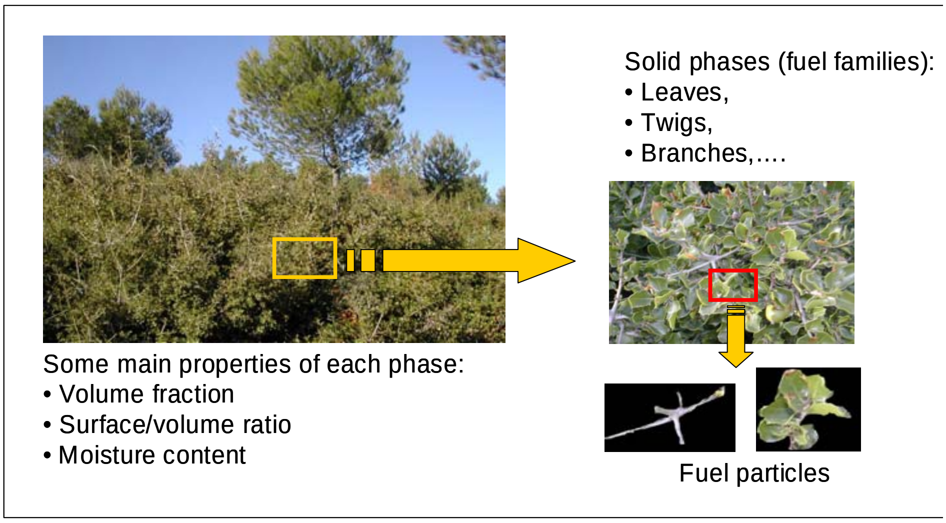

Figure 1: Multiphase description of the vegetation

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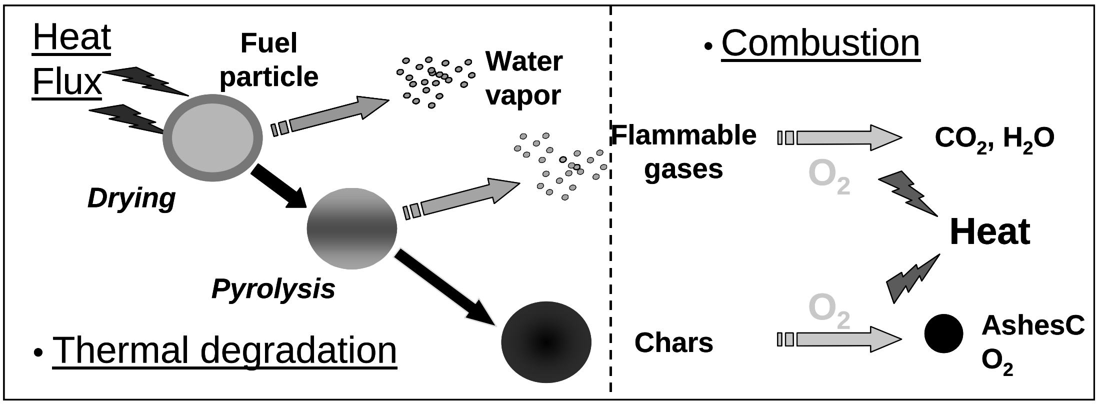

Figure 2: Basic mechanisms of fire propagation

Figure 2 provides a scheme of the basic mechanisms of fire propagation. It is well known that the fire propagates through a fuel layer due to the heat transfer from heat sources, flame and embers, to the fuel particles located ahead of the fire. Heat is mainly transferred by radiation and convection. These fluxes make the temperature of fuel particles increase and then, the thermal degradation of the fuel starts. First, the drying releases water vapour and at higher temperatures, the pyrolysis process releases flammable gases and produces chars. Both flammable gases and chars react with oxygen, and this combustion releases heat that in turn will be transferred to the unburned fuel.
In order to describe these mechanisms through a mathematical model, we have to establish and solve a set of partial differential equations based on conservation principles. The equations are derived from the multiphase approach that consists in applying a method of volume averaging. Usual transport equations for the gas phase, including turbulent terms, and in addition the radiation transfer equation, are obtained. For solid phases, usual balance equation for mass, mass of chemical species and energy are obtained. Gas phase equations and solid phases equations are coupled through interaction terms that appear when the volume averaging is applied to point equations.
The main sub-models, which describe the physics for each phase and interaction terms, are listed in Figure 3. We notice that soot are an essential component of the radiation balance and also that soot must be taken into account to deal with smoke problems.

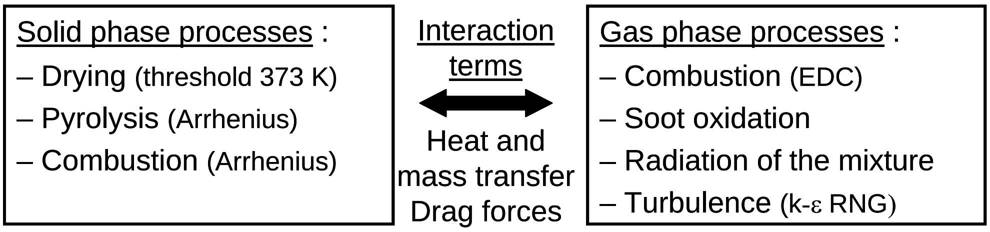

Figure 3: Sub-models for physical and chemical processes

Up to now we solved the problem in the vertical plane (x, z) (propagation of a fire line) using a finite volume method. An adaptive mesh is used to solve the conservation equations of the gas phase in order to reduce the computational cost of the simulations. This cost however remains a limiting factor for the use of the model (half a day to one day to run a simulation in a real forest stand of 200 meters length on a PC Pentium 4 2GHz).

Close this chapter

Some results of numerical simulations in shrub lands

The model predicts all the physical variables of interest to describe the phenomena, temperature, densities, gas velocity, radiant intensity, and so on. Figure 4 shows the fields of gas temperature and gas velocities predicted at a given time for different wind speeds. These simulations were performed using fuel parameters representing a typical shrub land of the south of France composed of a layer of *Quercus coccifera* of 0.5 m height and a layer of grasses. The ambient wind speed is described by a given value of wind speed U_H at a reference height (here 2 m) and by a given profile of wind velocity. These input data are used as boundary conditions of the model (left side of the resolved domain). Figure 4 illustrates three different regimes that were identified through a set of numerical simulations performed in varied conditions of wind U_H and fuel layer height. Figure 5 shows the ratio of the rate of spread to the wind speed as a function of a Froude number for the above set of simulations. The rate of spread of simulated fires is deduced from the evolution of the position of isotherms (here isotherm 500 K was used). An interesting feature is the comparison to a rule of thumb used by fire fighters, which states that the fire spreads at a rate equal to 3% of the wind speed (Valabre model).

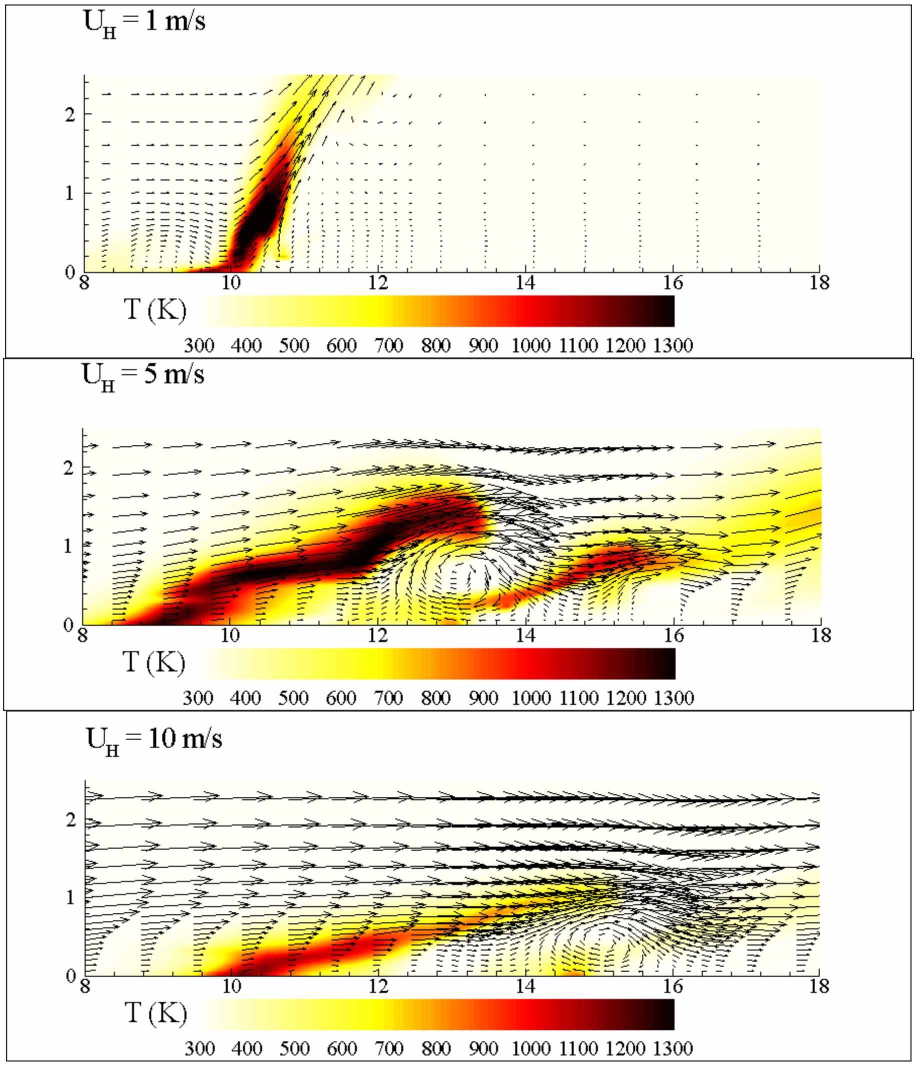

Figure 4: Fields of gas temperature and gas velocity obtained at three different wind speeds (*Quercus coccifera* garrigue).

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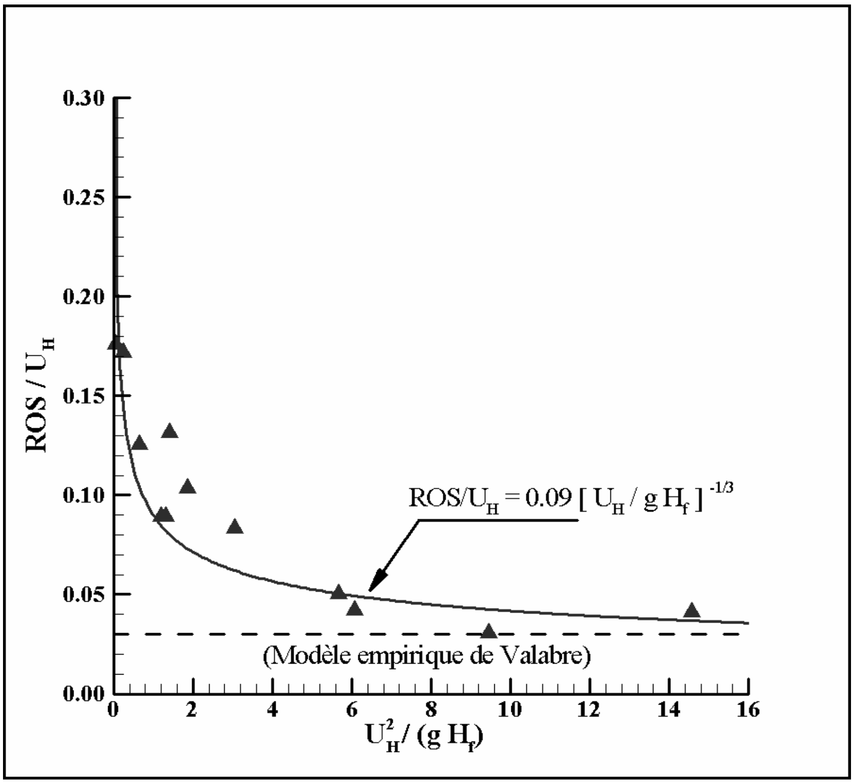

Figure 5: Ratio of the rate of spread to the wind speed as a function of a Froude number based on wind speed U_H *and flame height* H_f *(*Quercus coccifera *garrigue).*

Effects of fuel reduction on crown fires

The first simulations of crown fires and of the effects of fuel reduction on crown fires have been performed in the frame of the FireStar programme. Numerical simulations of the model through the zones 1 and 2 of the WUI enable to test the consequences on fire behaviour of different prescriptions of wildland fuel reduction applied to zone 2.

Figure 6 shows a sketch of the simulated situation. We considered a wild forest stand, on the left, and a fuel break that results from some fuel treatment on the right. Figure 7 shows the vertical structure of the vegetation of the wild forest stand (no treatment in zone 2) and of the fuel break (two different treatments in zone 2). The wild forest stand is represented as a layer of shrubs of 1 m height and a layer of tree crowns – here a Mediterranean pine – of 8 m height. The first fuel treatment consists in clearing the shrubs above 25 cm height. The second treatment consists in both clearing the shrubs and pruning the trees up to 4 m height.

We ran the simulations of the three cases with a given wind speed of 11 m/s at 10 m height above a bare ground, corresponding to 40 km/h of ambient wind speed. Fire behaviour may be observed thanks to animated images of the fields of temperature (gas and solid phases) and of the amount of remaining fuel (volume fraction of solid phases). When no treatment was applied to the vegetation in zone 2, the fire spread in both the shrub layer and the tree crowns all over the domain. We observed in particular that hot gas pockets ignited the top of the tree crowns several tens of meters ahead of the main fire front. Clearly, fire fighters could not fight such a fire on zone 2.

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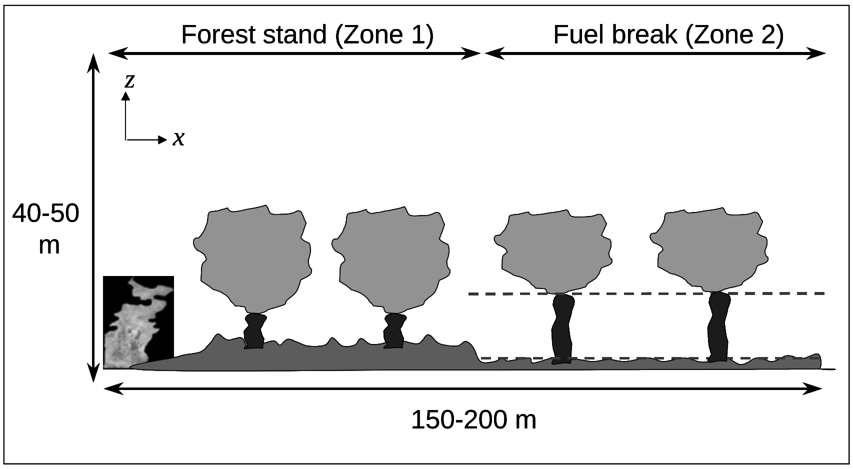

Figure 6: Sketch of the simulated situation

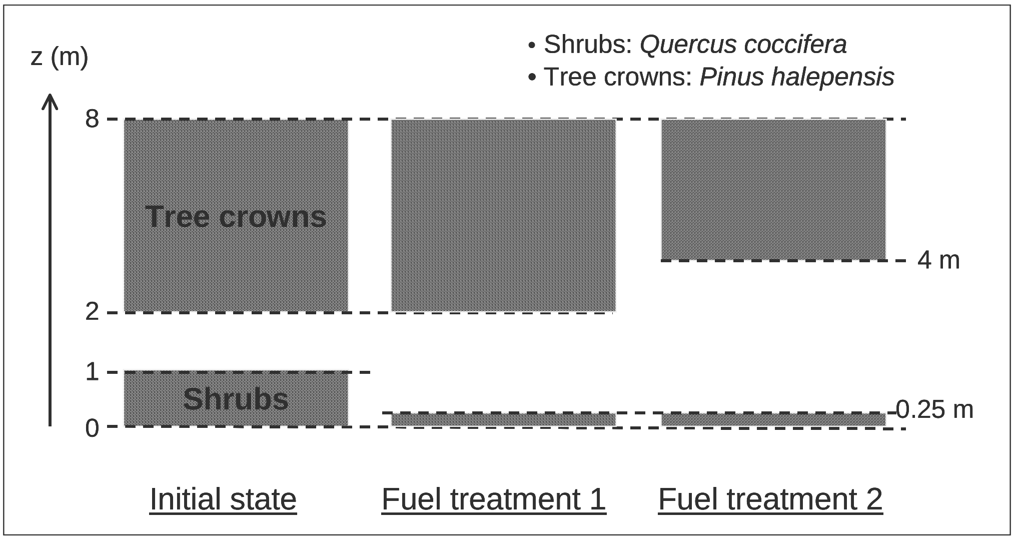

Figure 7: Vertical structure of the vegetation on zone 2

When the treatment 1 was applied to the vegetation, we observed that the fire intensity was reduced in the zone 2 as a result of fuel reduction, but the fire continued to propagate through tree crowns and we can state that the fuel treatment 1 is not efficient. When the fuel treatment 2 was applied to the vegetation, the fire stopped to propagate through tree crowns; a low-intensity surface fire however continues to propagate in the shrub layer. Hence, according to the model predictions, firemen would have to fight a surface fire propagating in shrubs instead of a crown fire and we can state that the fuel treatment 2 is efficient.

As an illustration of the above results, Figure 8 shows the gas temperature fields obtained with treatments 1 and 2 when the fire reached the distance 90 m at ground level. A localized ignition of tree crowns is still visible for treatment 2 (bottom field), almost 20 meters ahead of the fuel break. The next images of temperature fields would show that the fire no longer affects the tree crowns ahead of the point x=100 m.

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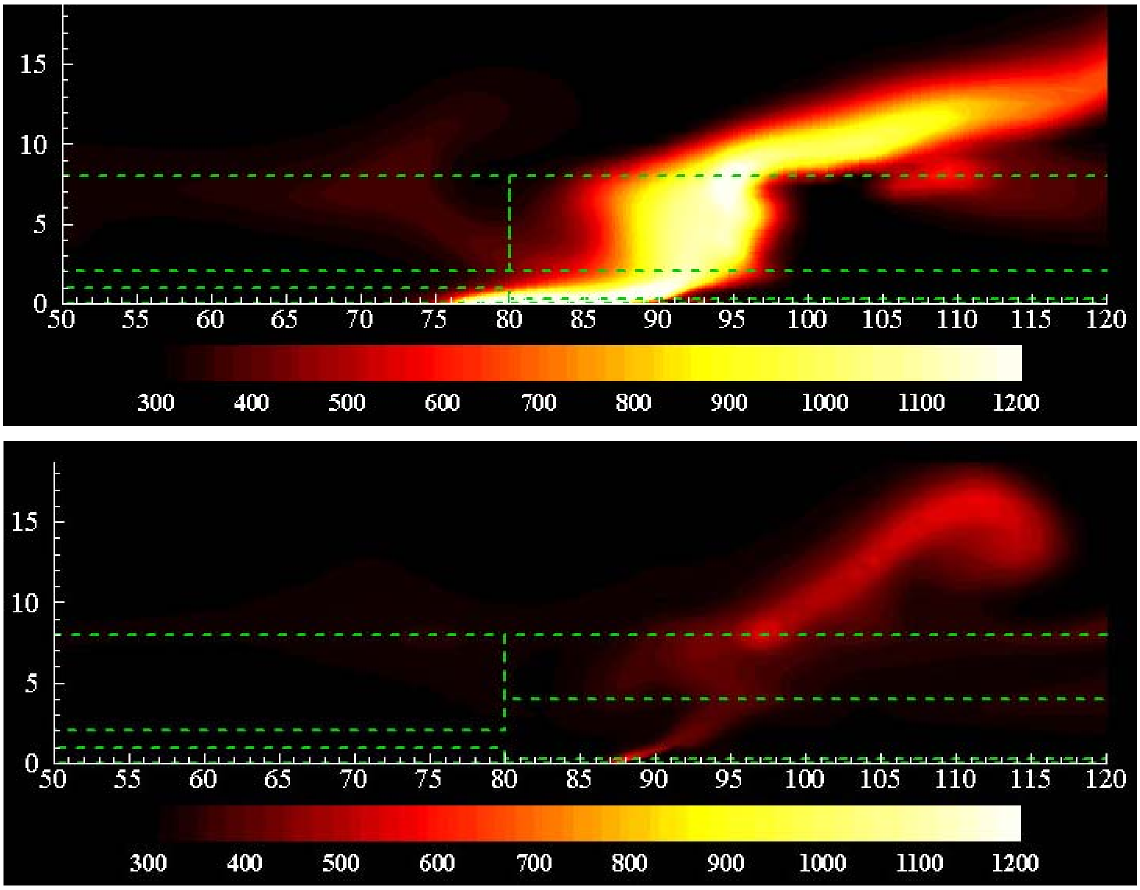

Figure 8: Gas temperature (K) fields (Top: Treatment 1; Bottom: treatment 2).

Conclusions

The outputs of the "complete" physical model enable to calculate fire characteristics like the type of fire (surface fire, surface fire with local crowning, or crown fire), the fire line rate of spread and intensity, the energy flux to a given point of the resolved domain, the amount of smoke,... Hence, this model is a powerful tool for the assessment of the danger for fire fighters, and as a consequence of this, of the efficiency of the fuel break regarded as an area where fire fighting is possible in satisfactory safety conditions. An effort is being pursued in the FireStar programme to provide user-friendly procedures and guidelines to extend the use of the model and to train non-specialist users. In addition, a catalogue of well-documented simulations in varied situations will be made available for end-users.

According to our modelling approach, we assume that to describe the essential physics of the phenomenon allows being confident in the model predictions. But if we account for a lot of physical processes, we also use a lot of approximations to describe these processes. This is the reason why model testing against experiments is a complementary and crucial activity, which has to be led jointly with model development. The FireStar programme also includes this activity.

Numerical simulations of the model provide useful information from the scale of a branch to the scale of a forest stand and describe in details the fire behaviour. When questions are addressed at such scales, the vegetation thus has to be described in details, with a high resolution. We are developing a method to go from a reasonable field description of the vegetation to the input of the fire model – i.e. the volume fraction of each fuel family at each point of the vegetation layer [see the complementary paper of Cohen *et al*. in the proceedings of the workshop].

Of course, it would be more realistic to describe the fuel and the fire behaviour in three dimensions. This would extend the predictive ability of the model to a wide range of fuel structures. The development of a 3D version of the model is a major perspective for the near future, which however is mainly restrained by the computational cost of the numerical simulations.

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