Simulation of coupled fire/atmosphere interaction with the MesoNH-ForeFire models

Jean Baptiste Filippi, Frédéric Bosseur, Xavier Pialat, Susanna Strada

Simulation of coupled fire/atmosphere interaction with the MesoNH-ForeFire models.

Jean Baptiste Filippi
Frédéric Bosseur
Xavier Pialat
SPE – CNRS UMR 6134, Campus Grossetti, BP52, 20250 Corte
Suzanna Stradda
LA – CNRS UMR 5560, OMP, 14 Avenue Edouard Belin, 31400 Toulouse

---

Abstract

Fire behaviour is dependent of many physical processes and modelling interaction between all these processes requires a highly detailed and computationally intensive model. In this paper we propose an approach that couples a fire area simulator to a mesoscale weather numerical model in order to simulate local fire/atmosphere interaction. Five idealized simulation cases are analysed showing strong interaction between topography and the fire front induced wind, interactions that could not be simulated in non-coupled simulations. The same approach applied to a real case scenario also shows results that are qualitatively comparable to the observed case. All of these results were obtained in less than a day of calculation on a dual processor computer, leaving room for improvement in grid resolution that is currently limited to fifty meter.

Keywords: Fire spread, wildland, fire, coupled atmosphere-fire numerical model

1. Introduction

Fire behaviour is dependent of many physical processes; modelling interaction between all these processes would require a highly detailed and computationally intensive model. Moreover, it is rarely possible to gather sufficient data to initiate a simulation at the level of detail required for such simulations. Nevertheless, fire area simulator, such as FARSITE, are of a prime interest to the people who fight wildfires, and taking into account more of these coupled physical effects may permit to enhance the accuracy of such models. The proposed approach has been developed to add local fire/atmosphere interaction to the family of fire area simulators. Numerical coupling of a fire model with an atmospheric model has already been the subject of numerous studies, starting from the work (with static fire) of Heilman and Fast (1992) to the more recent work of Clark *et al.* (2004), that proposes a simplified model of fire spread tailored for a Canadian forest (Rothermel, 1972), coupled with the WRF meso-scale model (Skamarock and Klemp, 2007). While these efforts are effective at simulating the coupled effects at the scale of a large fire (several square kilometres) with a high degree of fire front precision, the use of Rothermel model may be subject to caution as effects of wind and slope on the rate of spread is expressed through coefficients that are experimentally fitted to wind values. Wind predictions are then to be issued *as if the fire was not there* and no local heterogeneous change in the fire/atmosphere coupling can be taken into account.

Other studies are more focused on combustion processes with a detailed physical formulation of the fire front. With WFDS, Mell *et al.* (2006) obtained a good numerical correspondence with real prescribed burning experiment of Australian grassland (Cheney and Gould, 1995).

HIGRAD/FIRETEC, Linn *et al.* (2002) is able to perform several numerical investigations with different topography and wind conditions. These efforts are necessary to understand the mechanisms driving the fire spread and to evaluate fire suppression practices. Nevertheless the real-time tracking analysis of large fires would require access to large computing facilities and detailed ground data, which are difficult to gather because of the scales on which the simulation would be run.

In an effort to tackle these problems, Meso-NH and ForeFire have been developed to serve research purposes for operational models. In an approach similar to Clark *et al.* (2004), this meso-scale atmospheric model and the reduced physical front tracking wildfire model are coupled to investigate the differences induced by the atmospheric feedback in terms of propagation speed and behaviour. The main originalities of this combination resides in the fact that Meso-NH is run in a Large Eddy Simulation (LES) configuration and that the rate of spread model used in ForeFire provides a physical formulation to take into account effect of wind and slope.

2. Numerical models and coupling method

The coupled code is decomposed into three model components and a coupling component. The atmospheric model is responding to energy fluxes from the fire front. The fire rate of spread model and the front tracking method are used to simulate the fire front at a higher resolution than the atmospheric model. The coupling component performs the simulation synchronisation, the data transformation and interpolation.

Fire propagation model

The fire rate of spread (ROS) model is based on the assumption that the flame is acting lake a radiant tilted panel that is heating the vegetation in front of it (see Balbi *et al.*, 2009). It has been developed to provide an analytical formulation of the propagation speed given slope, wind speed, and fuel parameters.

A front tracking method is used for the simulation of the fire area evolution. The fire front line is decomposed into a set of connected points, or markers. Each marker has a specific propagation direction and speed, such as shown in figure 1. The velocity of each marker is given by the rate of spread model and the direction that coincides with the normal to the fire front at the location of the marker. This method has been selected due to its computational efficiency, and the ability to simulate the propagation of an interface at high resolution (a few meters) needed to take into account different vegetations, roads, houses and fire breaks over a large area typical of a wildfire accident (hundreds of square kilometres).

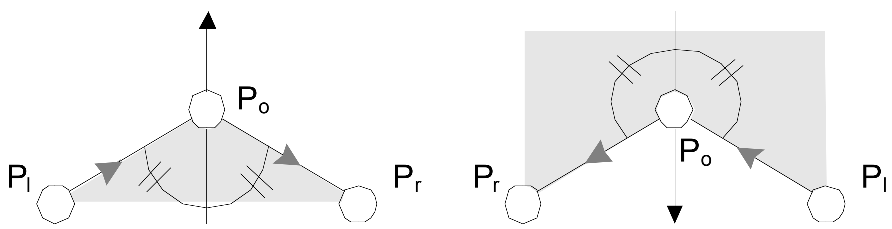

Fig. 1. Front tracking and markers. Circles represent markers along the firefront line. Arrows show the propagation vector (bisector of the local angle at the marker P_0 between the point at left, P_l and point at right, P_r). Grey area represents the burned fuel.

The fire front thickness is constructed by projecting the location of the marker along the propagation vector after the burning duration of the fire, noted R_T for "Residence time" (see fig. 3).

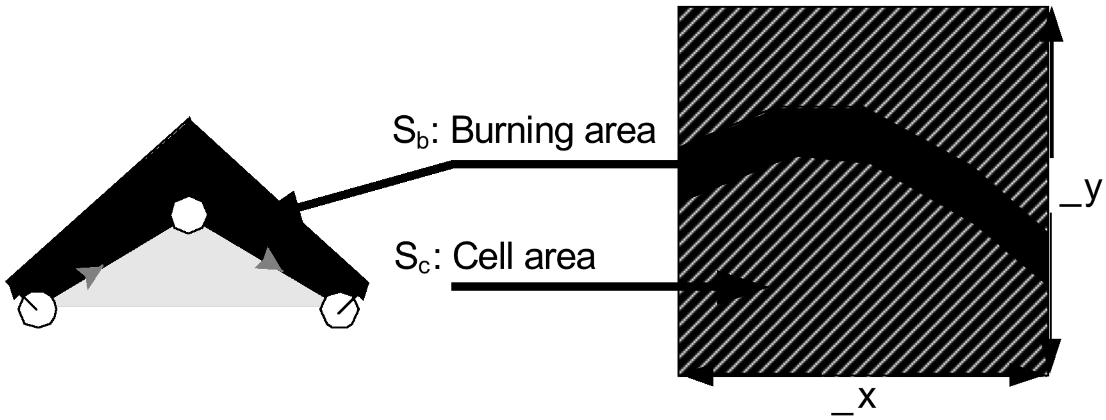

Fig. 2. Integration of burning area. Red shape represents the fire front. Integration is performed on each atmospheric cell to compute the ratio of the burning area over the cell area.

Wind and elevation fields are interpolated at the location of the marker using a bi-cubic method at the very location of the markers. The wind is estimated from the value interpolated at the marker location, while the slope angle in the fire propagation direction is estimated from the elevation difference between the elevation at the fire marker and the elevation at the location projected after R_T.

Meso-NH atmospheric model

Meso-NH is an anelastic non hydrostatic mesoscale model (Lafore *et al.*, 1998), intended to be applicable to all scales ranging from large (synoptic) scales to small (large eddy) scales and can be coupled with an on-line atmospheric chemistry module. For the fire coupling application Meso-NH is run in Large Eddy Simulation configuration ($\Delta x \le 50$m) mode without chemistry. Turbulence parameterization is based on a 1.5-order closure (Cuxart *et al.*, 2000), with a prognostic equation for turbulent kinetic energy in 3D. We selected open boundary condition for all tests. Momentum variables are advected with a centered 4^{th} order scheme, while scalar and other meteorological variables are advected with a so-called monotonic Piecewise Parabolic Method (Woodward and Colella, 1984). An externalised surface module is used for the fire feedback in the simulation.

Coupling atmospheric and wildfire model

The wildfire model forces the atmospheric model at the first (ground) level injecting heat fluxes in $W.m^{-2}$, flux of water vapour in $kg.m^{-2}$ and radiant temperature in K. Polygon clipping is used to derive the burning surface of an atmospheric cell (noted S_b) over the total cell area noted S_c ($\Delta x \Delta y$) (Figure 2). The burning ratio for each atmospheric grid cell is noted R_b, $= S_b / S_c$.

As only a portion of the cell is burning, an equivalent radiant temperature (T_e) for the whole cell is averaged from a nominal flame temperature (T_n) and the soil temperature from the atmospheric model (T_s). T_e is given by:

$$T_e = \sqrt[4]{(1 - R_b)T_s^4 + R_b T_n^4} ,$$

Equivalent heat fluxes (Q_e) in W.m^{-2}, corresponding to the energy of the hot gaseous column over an atmospheric cell, is approximated from a nominal convective heat flux (Q_n) with $Q_e = R_b Q_n$.
Finally, equivalent water vapour fluxes (Wv_e) in kg.m^{-2}, representing the amount of water vapour evaporated from the vegetation is interpolated over an atmospheric cell from nominal water vapour content (Wv_n) with $Wv_e = R_b Wv_n$.

The operation is performed for all atmospheric grid point at ground level, allowing to construct three matrices that are passed to the atmospheric model just before updating the wind matrix used by the fire simulation. Wind matrices forcing the fire model are updated at each atmospheric time step and wind is assumed to be constant during the entire duration of the time step.

3. Idealised experimental set-up

In order to evaluate the ability of the coupled code to estimate the coupled influences of topography and wind on fire spread, five tests were run corresponding to a partial set of the set-ups proposed by Linn *et al.* (2007). Base functions used to create the different topographies are taken from Linn *et al.* (2007), those functions are used to create an idealized flat, canyon, hill ridge and up can terrains.
For all cases the domain size has been set to 640*320*500m with horizontal spacing of 16m and an average vertical spacing of 20m. Unlike the test cases in Linn *et al.* (2007), vegetation is assumed homogeneous in the domain with parameters given in Table 1 for all simulations. These values are based on mean values deduced from experimental studies (Santoni *et al.*, 2006). In this experiment, vegetation was shrubs with an average dry fuel load of 7kg.m^{-2}.

A	R0	r0	u0	R_T.	Q_n.	Wv_n	T_n
1.5	0.1m.s^{-1}	0.01m.s^{-1}	5m.s^{-1}	30s	250kW.m^{-2}	0.1kg.m^{-2}	1000K

Table 1. Experimental parameters, with A: Radiant factor, R_0: rate of spread without wind and slope, r_0 flame thickness speed factor, u_0: flame gas velocity, R_T: fire residence time, Q_n: nominal heat flux, Wv_n: nominal water vapour flux and T_n: nominal radiant temperature.

Atmospheric model background wind field was of 6m.s^{-1} constant in height (with a maximum simulation height of 500m). A passive scalar tracer with a distribution set to the burning ratio of each grid point and for each atmospheric time step is used as a marker for smoke injection.

Figures 3, 4, 5, 6, and 7 present the simulation results for the flat, canyon, hill, ridge and upcan cases 120s after ignition.

In the flat Case (Fig 3a), the flow remains largely unaffected behind the fire. The simulation reveals an area of confluence ahead of the front with some recirculation that is located at the base of the fire plume (Fig 3b). The plume is relatively weak, affecting the flow to an altitude of 60m over ground. Overall flow speed does not greatly differ from the original flow speed of 6m.s^{-1}. However, local enhancement of the surface velocity due to the coupling between the fire and the atmosphere leads to a greater ROS at the head of the fire compared to the non-coupling case. This effect can be attributed to the induced wind being taken into account in the coupled simulation.

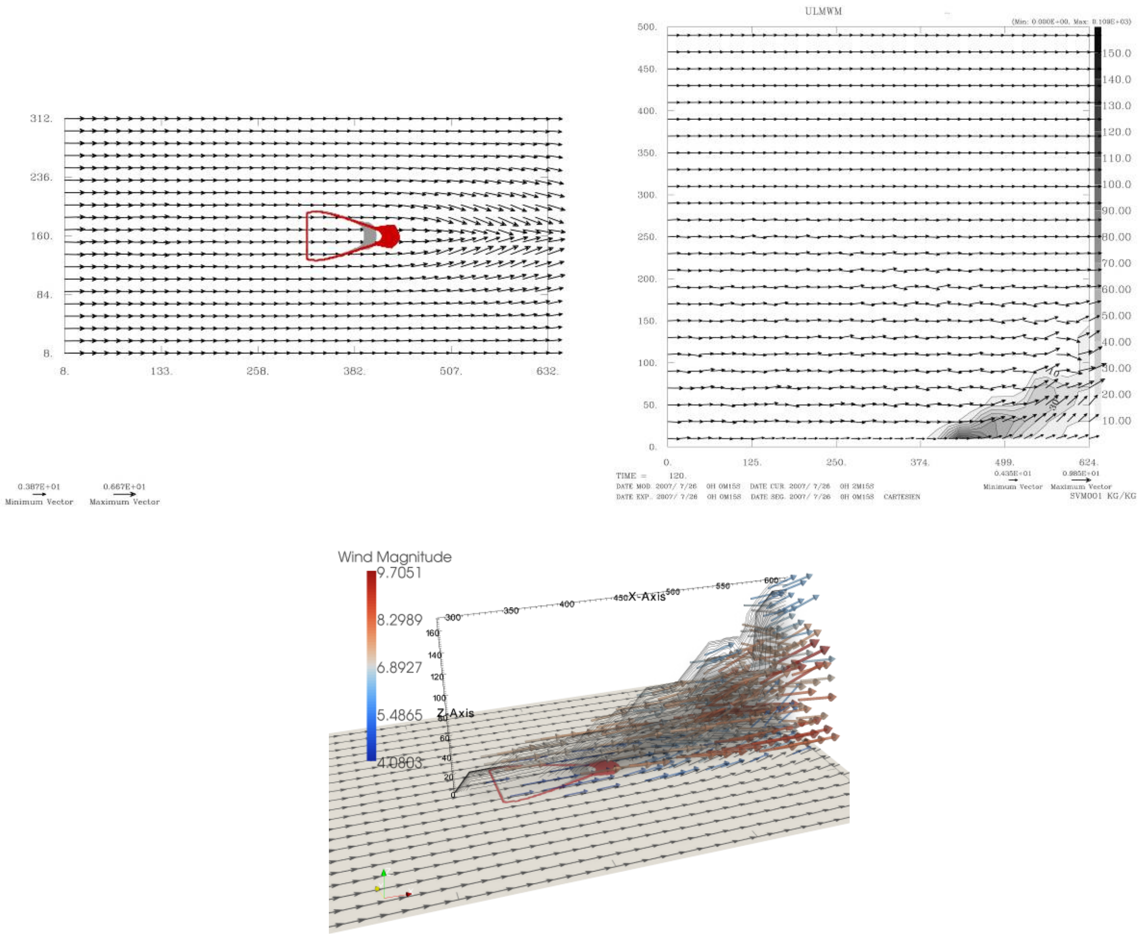

Fig. 3. FLAT (a) Horizontal section (x/y) at Z=10m, fire lines after 120 seconds for the coupled (red) and non-coupled (grey) simulations. Arrows denote the wind vectors at ground level for the coupled-case. (b) Cross section (x/z) of the coupled case at Y=160m, shading represents concentration of the injected passive tracer. (c) 3d wind field and passive tracer concentration isocontours.

The canyon case (figure 4) clearly enlightens the strong influence of taking into account the coupling between fire and atmosphere in the simulation of the fire dynamics. In that case the surface wind is strongly decreased in the canyon by topographic effects. These effects are not fully compensated by the increased slope and we observe weaker ROS than in the flat case. In such scenario the induced wind plays a major role in the dynamics of the fire spread and the use of a coupled model results in increased ROS and better accounting of the physics.

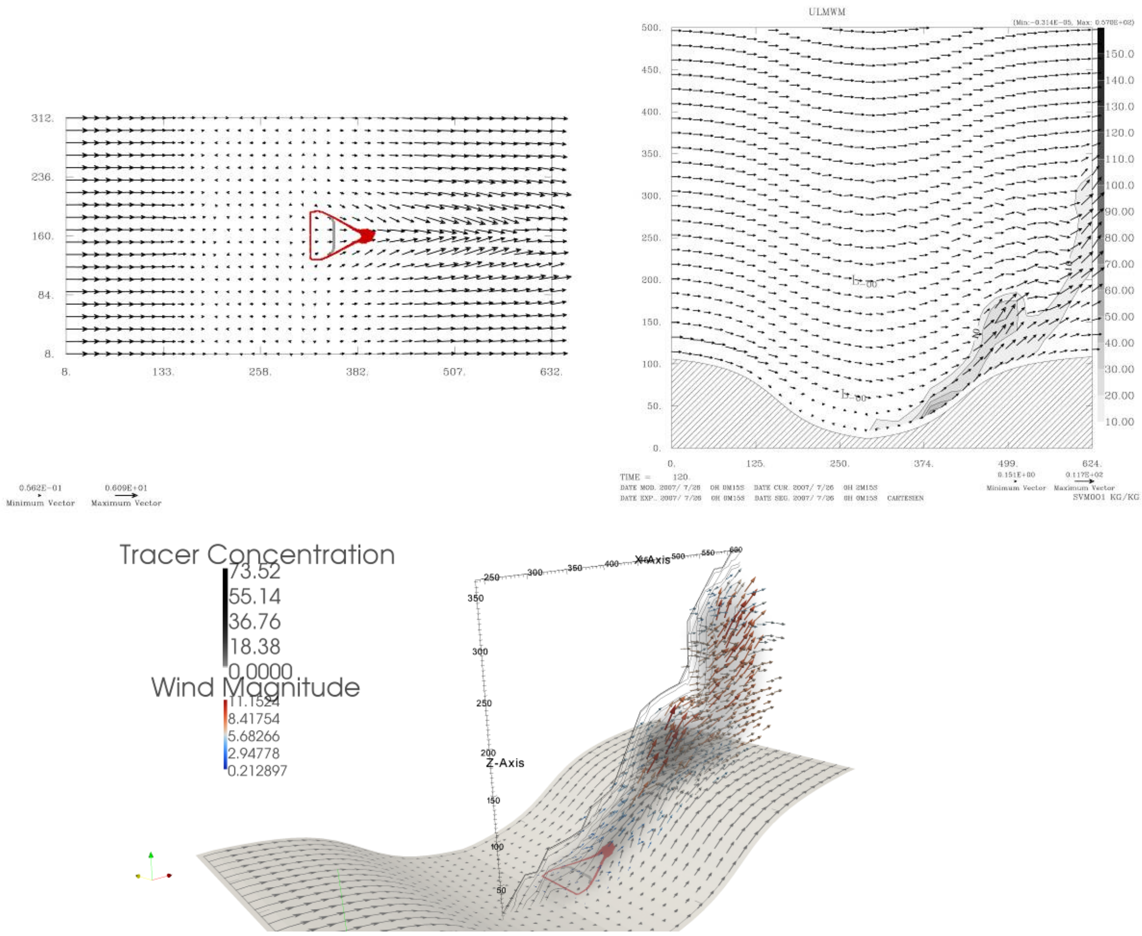

Fig. 4. CANYON (a) Horizontal section (x/y) at Z=10m, fire lines after 120 seconds for the coupled (red) and non-coupled (grey) simulations. Arrows denote the wind vectors at ground level for the coupled-case. (b) Cross section (x/z) of the coupled case at Y=160m, shading represents concentration of the injected passive tracer. (c) 3d wind field and passive tracer concentration isocontours.

With the same slope and same wind speed, the Hill case (Figure 5) presents a slightly different behaviour. The area of confluence is located here ahead of the fire front, so the maximum wind speed are just over the fire head. The resulting tilt angle results in a stronger ROS, and a larger burning injection area.

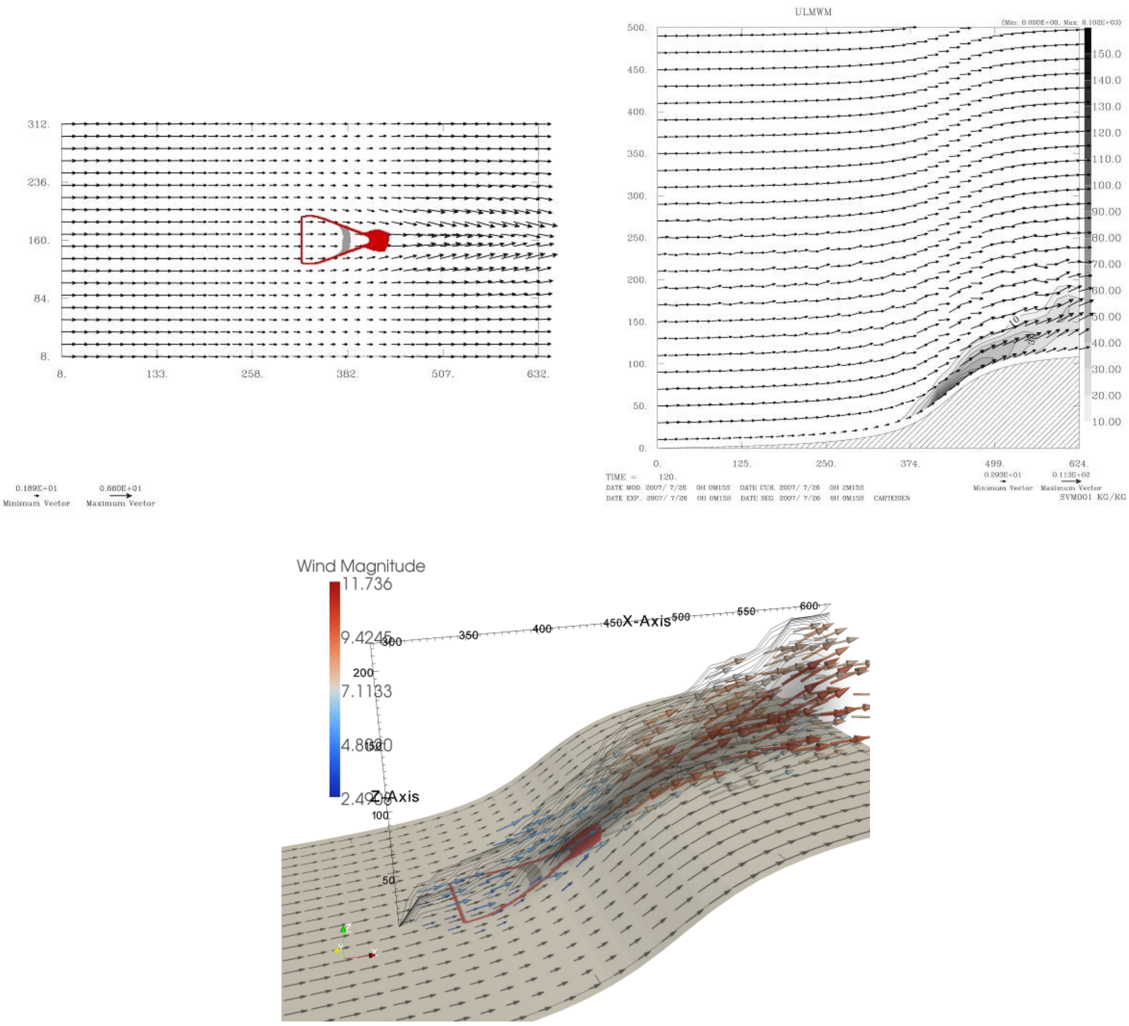

Fig. 5. HILL (a) Horizontal section (x/y) at Z=10m, fire lines after 120 seconds for the coupled (red) and non-coupled (grey) simulations. Arrows denote the wind vectors at ground level for the coupled-case. (b) Cross section (x/z) of the coupled case at Y=160m, shading represents concentration of the injected passive tracer. (c) 3d wind field and passive tracer concentration isocontours.

Figure 6 presents the results for the ridge test case. The topographic effects results in a widening of the burning area in the transverse direction of the wind due to slope gradient in that direction. This topographic/fire effect seems to be quantitatively superior as observed in Linn *et al*. (2007).

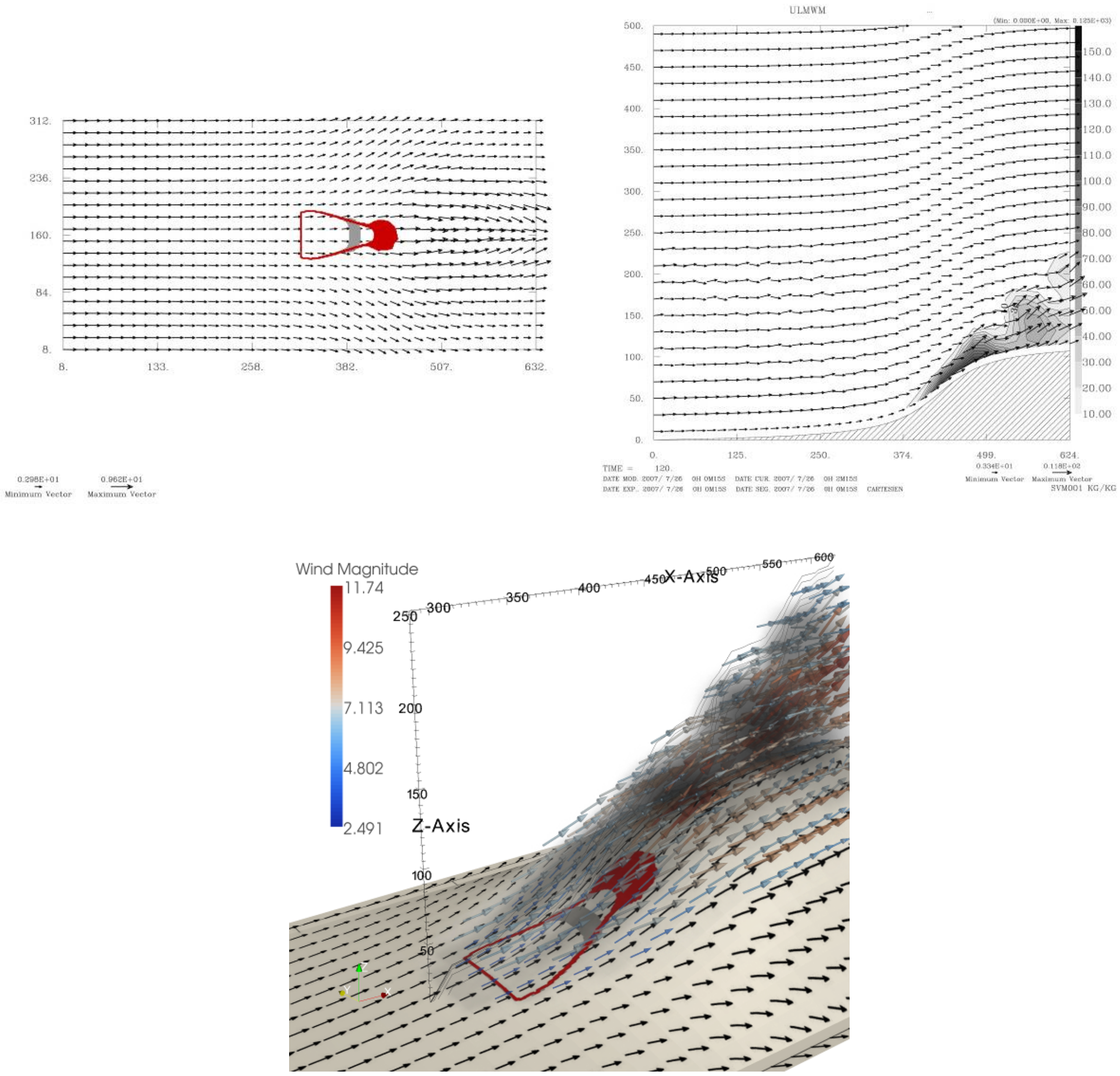

Fig. 6. RIDGE (a) Horizontal section (x/y) at Z=10m, fire lines after 120 seconds for the coupled (red) and non-coupled (grey) simulations. Arrows denote the wind vectors at ground level for the coupled-case. (b) Cross section (x/z) of the coupled case at Y=160m, shading represents concentration of the injected passive tracer. (c) 3d wind field and passive tracer concentration isocontours.

Results for the upcan test are shown in figure 7. Once again the topography has more influence in our simulations than in that of Linn *et al*. (2007). The narrowing of the fire head compared to the ridge case is of factor 3 in our case whereas Linn *et al*. (2007) results show a factor around 2.

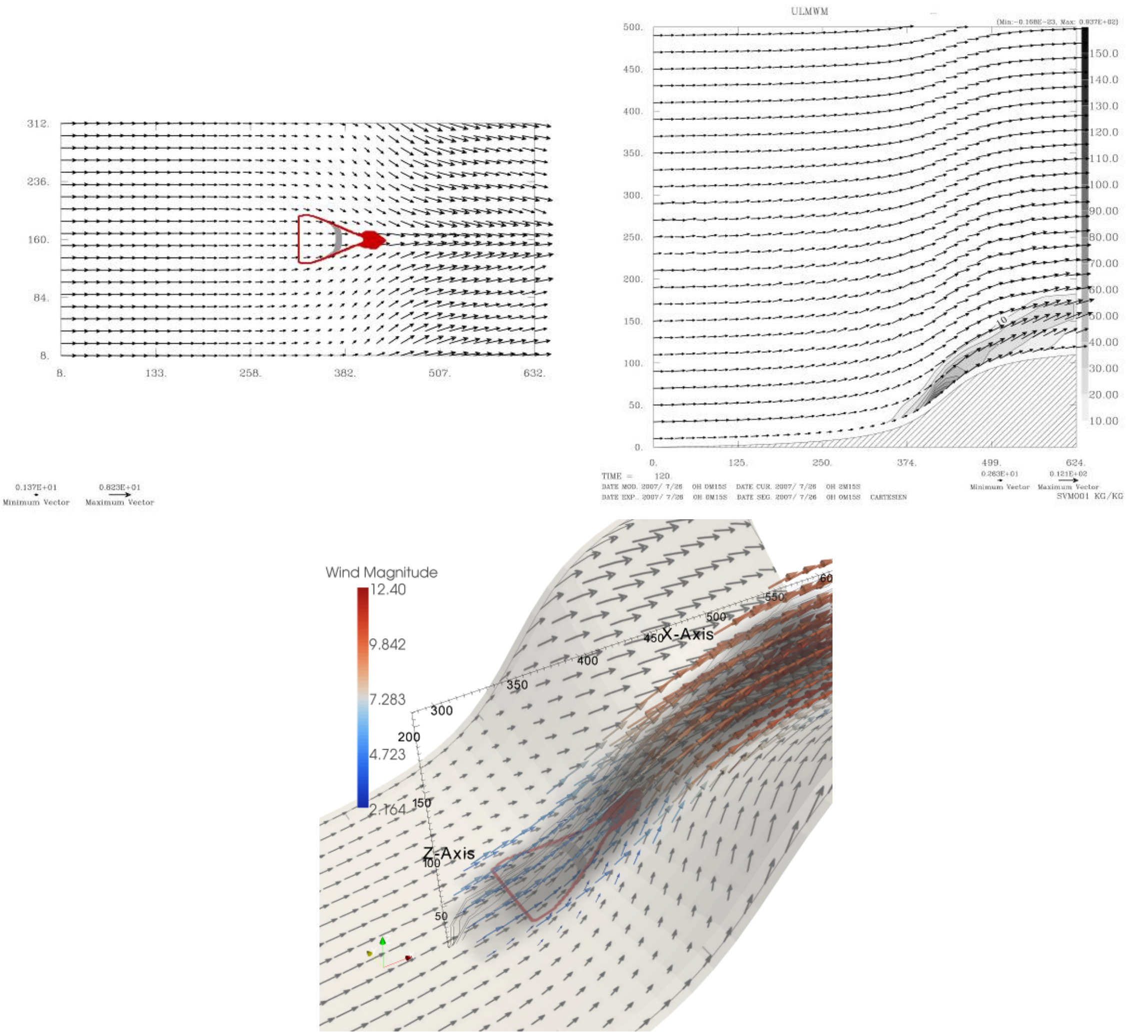

Fig. 7. UPCAN (a) Horizontal section (x/y) at Z=10m, fire lines after 120 seconds for the coupled (red) and non-coupled (grey) simulations. Arrows denote the wind vectors at ground level for the coupled-case. (b) Cross section (x/z) of the coupled case at Y=160m, shading represents concentration of the injected passive tracer.

Finally figure 8 presents the propagation distance of the fire front in the wind direction for all five cases. Though quantitatively different from the results of Linn *et al*. (2007) due to different fuel properties, our coupled model exhibits the same behaviour in simulating fire/atmosphere interaction. Our models also retrieves the grouping of behaviour between, on one hand, the flat and canyon cases, and on the other end the hill, ridge and upcan cases.

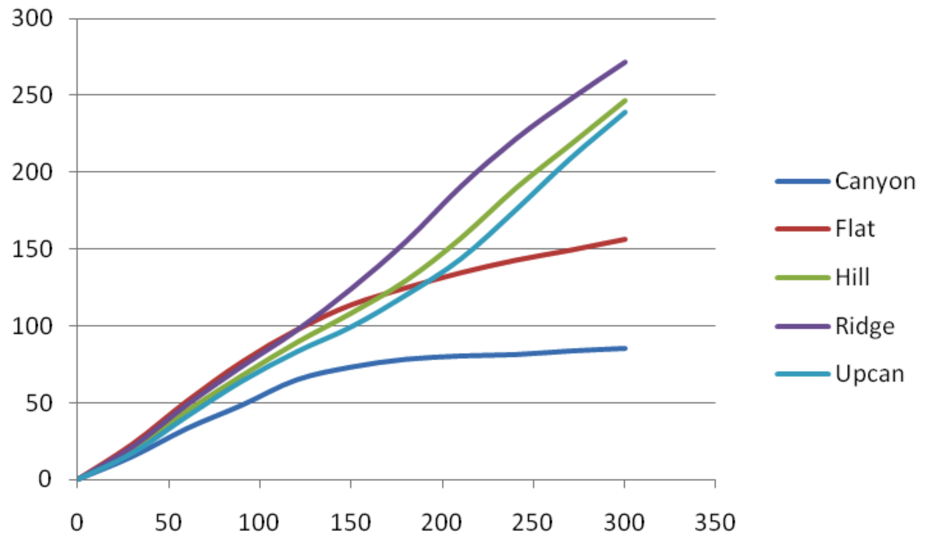

Fig. 8. Propagation distance of the fire front in function of time in the five cases.

4. Real-case simulation

Case description

Our coupled model has also been applied to a past real case fire that occurred on the 16th of October 2007 near Ajaccio at location called Vazzio. The fire ignited around 14:30 and experienced almost free propagation till 15:40 under a sustained and whirling wind of about 4 to $5m.s^{-1}$ and gusts of about the same magnitude. Finally the fire was stopped around 18:30 and burned up to $0.60km^2$ of land with the burned area contour reported in figure 10.

Simulation setup

The coupled simulation was run on a 2.5km×2.5km×1.5km domain discretized on a 50×50×30 mesh for the atmospheric model simulation ($\Delta x = \Delta y = \Delta z = 50m$). The wind is given by a radiosounding made at 12:00 at the Ajaccio airport which is located three kilometers away. Topography is given by the BDTOPO (IGN database) with a precision of 50m. Vegetation is extracted from the IFN database and classified between a homogeneous Mediterranean maquis where fuel is present and non-burnable areas representing roads and buildings.

The simulation was run on a Xeon 3.0 Ghz processor (4 cores) and took approximately 23 hours to perform 6h of real-time fire propagation.

Results and discussion

The aim of this preliminary study is to apply the presented couple model to a real fire and compare qualitatively the results with observations concerning the coupling between the fire and the atmosphere.

The authors are well aware of the incertitude on all the relevant parameters like wind magnitude and direction, vegetation properties and humidity. This simulation is thus not intended for quantitative comparison with observations but as a preliminary test to assess the proposed coupled model in simulating fire/atmosphere interaction.

Figure 9 presents some simulated contours of the fire compared to the observed final contour. The global shape of the simulated final contour is, overall, in good agreement with the observed contour, especially as a change of wind direction from west to north-west during the afternoon was not taken into account in the simulation.

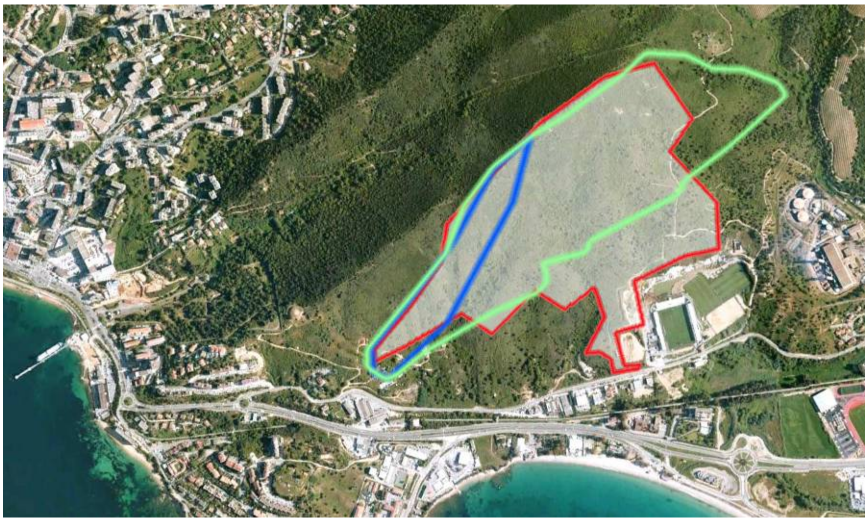

Fig. 9. Simulations results and observations for the Vazzio fire. Blue: simulated fire contour at 15:30 (after 1h), Green: simulated contour at 18:30, Red: final observed contour of the fire.

One major feature of the proposed model is the ability to simulate topographic effects such as fire confinement by crests. The simulated contours reported in figure 9 are indeed in very good agreement with the observations concerning the north side of the fire front where changing slope effects have maintained the fire on one side of the hill.

Concerning the fire/atmosphere coupling figure 10 presents a comparison between the simulated plume after one hour of fire and a photography of the fire which was supposedly taken around 15:30. The direction of observation in the simulation case was taken as close as possible from the one in the photography.

Once again qualitative agreement between simulation and observation is observed. The structures of the simulated plume are not as refined as in the real one but this is mainly due to the relatively low refinement of the grid for the atmospheric simulation (50m). Simulated direction and height of the plume are similar to the observed ones. Nevertheless dispersion seems to be underestimated in our simulation as the plume expansion is slightly lower in the simulation. This drawback supposedly mainly stems from the coupling fluxes injected by the fire simulation. As explained earlier in this article the forcing fluxes from the fire are the heat flux, the flux of water vapour and the radiant temperature. Thus no turbulent kinetic energy is injected in the atmospheric simulation whereas fine structures of characteristic length less than 50m are observed in the fire and are assumed to contribute to the agitation of the atmosphere.

Fig. 10. Simulated and observed plume. Simulated plume is given 1h after the fire ignition (the blue contour represents the fire front at that time); the observation was taken between 30 minutes and 1h30 after the ignition.

5. Conclusions

MesoNH/ForeFire coupled model of wildland fire spread is used to investigate the effect of topography on fire induced winds. With a straightforward coupling method, the atmospheric model is able to simulate the atmosphere dynamic induced by the fire and the subsequent effects on the RoS with meaningful results.

The five idealized scenarios allowed simulating induced flow patterns similar to those observed from the simulation by Linn *et al.* (2007) with HIGRAD/FIRETEC. Transverse topological effects seem to be of more importance in our model as the widening/narrowing of the head fire is significantly greater in our simulations. The main feature of these simulations still remains that the fire head spread rate in the wind direction exhibits similar behaviours to those found by Linn *et al*. (2007). This behaviour is of particular interest as performing HIGRAD/FIRETEC simulations of the flow and fire patterns over a complex vegetation distribution with high resolution are nowadays computationally unreachable for large scale wildland fires.

The proposed coupled model was then applied to a real-case scenario and compared with observations. The model's behaviour is qualitatively similar to the real fire in simulating the fire propagation as well as the fire/atmosphere interaction though some issues still remains such as the physics of the coupling or the collecting of the data necessary for such simulations.

The objective was here to move from fire area model with forced wind fields to coupled wind field that could represent the local perturbations that may greatly affect the fire behaviour. Further enhancements are planned to perform simulation of large past fire and simulation with the online chemistry module of Meso-NH to investigate fire smoke and particle transport.

Acknowledgements

This research is developed within the IDEA project ANR-09-COSI-006-01

References

Balbi JH, Rossi JL, Marcelli T, Santoni PA, (2007) A 3D physical real-time model of surface fires across fuel beds, Combustion Science and Technology, 179, 2511-2537. doi:10.1080/00102200701484449

Clark, T. L., Jenkins, M. A., Coen, J., Packham, D., 1996: A Coupled Atmospheric-Fire Model: Convective Froude number and Dynamic Fingering. International Journal of Wildland Fire, 6, 177-190. doi:10.1071/WF9960177

Clark, T.L., Coen, J., Latham, D.:(2004), Description of a coupled atmosphere-fire model, International J. of Wildland Fire, 13, 49–63. doi:10.1071/WF03043

J. L. Coen, T. L. Clark, and D. Latham. Coupled atmosphere-fire model simulations in various fuel types in complex terrain. In 4th. Symp. Fire and Forest Meteor. Amer. Meteor. Soc., Reno, Nov. 13-15, pages 39--42, 2001.

Cuxart, J., Bougeault, Ph. and Redelsperger, J.L., 2000: A turbulence scheme allowing for mesoscale and large-eddy simulations. Q. J. R. Meteorol. Soc., 126, 1-30.

Heilman WE, Fast JD (1992) Simulations of Horizontal Roll Vortex Development Above Lines of Extreme Surface Heating. International Journal of Wildland Fire 2, 55–68. doi:10.1071/WF9920055

Lafore, J. P., J. Stein, N. Asencio, P. Bougeault, V. Ducrocq, J. Duron,C. Fischer, P. Hereil, P. Mascart, J. P. Pinty, J. L. Redelsperger, E. Richard, and J. Vila-Guerau de Arellano, 1998: The Meso-NH Atmospheric Simulation System. Part I: Adiabatic formulation and control simulations. Annales Geophysicae, 16, 90-109. doi:10.1007/s00585-997-0090-6

Linn, R.R., Reisner, J., Colman, J., Winterkamp, J. (2002), Studying Wildfire Using FIRETEC, International Journal of Wildland Fires, 11, 1-14. doi:10.1071/WF02007

Linn RR, Winterkamp J, Edminster C, Colman JJ, Smith WS (2007) Coupled influences of topography and wind on wildland fire behaviour. International Journal of Wildland Fire 16, 183–195. doi:10.1071/WF06078

Masson V. 2000, A physically based scheme for the urban energy budget in atmospheric models, Bound. Layer Meteor., 94, 357-397. doi:10.1023/A:1002463829265

Mell, W., Jenkins, M.A., Gould, J., Cheney, P.: (2007), 'A physically based approach to modelling grassland fires', International J. of Wildland Fire, 16, 1--22. doi:10.1071/WF06002

Noilhan, J. and S. Planton, 1989: A simple parameterization of land surface processes for meteorological models. Mon. Weather Rev., 117, 536-549. doi:10.1175/1520-0493(1989)117<0536:ASPOLS>2.0.CO;2

Santoni PA, Simeoni A, Rossi JL, Bosseur F, Morandini F, Silvani X, Balbi JH, Cancellieri D, Rossi L (2006) Instrumentation of wildland fire: characterisation of a fire spreading through a Mediterranean shrub, Fire Safety Journal, 41(3) 171-184. doi:10.1016/j.firesaf.2005.11.010

Skamarock, W. C., J. B. Klemp, (2007), A Time-Split Nonhydrostatic Atmospheric Model for Research and NWP Applications. J. Comp. Phys. special issue on environmental modeling. Volume 227, Issue 7.

Rothermel R (1972). A mathematical model for predicting fire spread in wildland fuels. Research Paper INT-115, USDA Forest Service.

Woodward, P.R. and P.Colella, 1984 : The piecewise Parabolic Method (PPM) for gas dynamical simulations, J. Comput. Phys., 54, 174-201. doi:10.1016/0021-9991(84)90143-8