Forest fire impact on air quality: the Lançon-De-Provence 2005 case

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FOREST FIRE IMPACT ON AIR QUALITY: THE LANCON-DE-PROVENCE 2005 CASE

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Abstract. Forest fires release significant amounts of gases and aerosols into the atmosphere. Depending on meteorological conditions, fire emissions can efficiently spoil air quality and visibility far away from the source. The aim of this study is to evaluate the fire impact on air quality downwind of the burning region in the Mediterranean zone.

Wildfire behaviour is simulated using a semi-physical model, ForeFire, based on an analytical resolution of the rate of spread. ForeFire provides the burnt area at high temporal and spatial resolutions; in the mesoscale non-hydrostatic meteorological model Meso-NH fire forcings, as heating and water vapor fluxes, are computed scaling them to the burnt area data given by ForeFire. A chemical scheme is coupled to Meso-NH to account for air quality evolution. Chemical emissions are scaled to the heating fluxes and based on emission factors for the Mediterranean vegetation. The model is used both in a 3D regional and 2D LES configurations.

In 2005, an arson forest fire burned nearly 700 ha near Lançon-de-Provence, southeast France. ForeFire was successfully tested on this case study. Here, results from the coupled model, MesoNH-ForeFire, show the sensitivity of atmospheric dynamics and air quality situation to the coupling fire-atmosphere. Simulations put also on evidence how initial conditions and heat fluxes control fire emissions injection height. Finally, tracer distribution is simulated and its pattern shows that although the impact of the fire is visible several kilometres downwind of the burnt area, it remains confined within the planetary boundary layer. This behaviour is confirmed by comparing simulated aerosol particles concentrations with the air quality survey network available in southeastern France.

Keywords: air quality, coupled fire-atmosphere model, Mediterranean fire, chemistry, dynamics.

1. Introduction

In Mediterranean region climate change is making weather conditions more extremes, allowing huge forested areas to become ignited with increasing frequence, as noted by Pausas (2004).

Forest fires are a risk to the environment and to public health as wildfires represent a significant source of gases and aerosols. Depending on meteorological conditions, these emissions can efficiently perturb air quality and visibility far away from the sources (Miranda et al., 2008; Takegawa et al., 2003; Bytnerowicz et al., 2010).

The aim of this work is to simulate the interactions of a Mediterranean fire with its environment both in terms of dynamics and air quality.

2. Fire-Atmosphere Coupled System

The fire spread model ForeFire has been coupled with the French mesoscale atmospheric model Meso-NH to better characterize the impact of fire dynamics and chemistry on the air quality downwind of the burnt area.

The case study is Lançon-de-Provence 2005 forest fire, a typical Mediterranean wildfire burst in the southeast of France.

The Lançon-de-Provence case has already been successfully simulated by several fire propagation models, including ForeFire, thus constitutes a good benchmark for testing the coupling and its forecasting performances.

The Atmospheric Model: Meso-NH

Meso-NH is an anelastic, non-hydrostatic mesoscale meteorological model, designed to simulate atmospheric circulation from large synoptic to large eddy scales (Lafore et al., 1998). The model was jointly developped by Météo-France and Laboratoire d'Aérologie (CNRS).

Meso-NH incorporates many options for the physical parametrisations. All prognostic variables are advected in an Eulerian way by the Piecewise Parabolic Method (Colella and Woodward, 1984). The microphysics included three water phases with five species of precipitating and nonprecipitating liquid and solid water (Pinty and Jabouille, 1999). Radiative processes are represented are represented using the radiation scheme developed by the European Centre for Medium-Range Weather Forecast (ECMWF) (the Rapide Radiative Transfer Model, RRTM, Mlawer et al., 1997).

The model simulates the concentration of 40 chemical species utilising 73 chemical reactions (Crassier et al., 2000). Chemical species are initialized using ESCOMPTE campaign results (Cros et al., 2004; MediasFrance, 2001) thanks to similarities in the geographical area and in the period of the year between the two studied cases. For the ESCOMPTE campaign MOCAGE, a multi-scale chemistry and transport model, has simulated concentrations of different chemical species. Results from MOCAGE simulations at 00:00 UTC 21 June, 2001, are taken as initial vertical profiles for some selected background species. Profiles from the nearest location to Lançon-de-Provence were used for the entire domain (*i.e.* initial concentrations are homogeneous over the entire domain).

At the resolution commonly used for mesoscale simulation, forest fires are sub-grid scale processes (Freitas et al., 2007). In order to constrain the effect of the fire in the 3D simulation we performed a 2D simulation of the perturbed atmosphere at high resolution.

- **3D model configuration**

  The 3D Meso-NH is run with three two-way grid-nested domains, whose horizontal mesh size is, respectively, 25, 5 and 1 km. The three domains are shown in the Figure 1. The vertical grid has 72 points up to an elevation of 23 km with a level spacing ranged from 40 m near the surface to 600 m higher in the atmosphere.

  The simulation covers 19 h, starting on 00:00 UTC 1 July 2005, with different time steps for each domain. Dynamical variables are initialized and constrained at the boundaries using 00:00 and 12:00 UTC operational reanalysis from ECMWF (25 km horizontal resolution).

  The turbulence parametrisation is based on a 1.5-order closure (Cuxart et al., 2000). The surface energy exchanges are parametrised according to four different physical model depending on the surface type (nature surface, urban area, ocean and lake). In particular, natural land surfaces are handled by the Interactions Soil-Biosphere-Atmosphere scheme (ISBA, Noilhan and Planton, 1989). Land use informations and soil occupation at 1 km resolution are provided by the global database Ecoclimap (Masson et al., 2003).

- **2D model configuration**

  In 2D, Meso-NH is run with horizontal resolutions set to 65 m along the y-axis and 250 m along the x-axis, over a flat terrain. The x-axis direction is defined along the plume trajectory simulated by the 3D model. The vertical grid has 120 levels, getting a maximal altitude of 23 km; the level spacing stretches from 2 m up to 500 m at the top of the model. At this resolution, convective fluxes are explicitly resolved by the model. A complete three dimensional scheme was used for resolving turbulent fluxes (Cuxart et al., 2000).

  Simulation starts on 1 July, 2005, at 11:00 UTC and it is integrated for 3 h, corresponding to the period of maximum of fire intensity. Initial and boundary meteorological conditions are defined from a radiosonde taken on 1 July, 2005, at 12:00 UTC in Nimes (located 63 km northwest away from Lançon-de-Provence).

The fire propagation model: ForeFire

Predicting wildfire behaviour asks for a Rate of Spread (RoS) equation: a ratio between the heat flux received by the potential fuel ahead of the fire and the heat required to ignite this fuel (Pyne et al., 1949).

In the field of wildland fire behaviour modelling, a large used and well-known method is the Rothermel's one. This is an empirical fire spread model whose fomulation was drawn from fitting the solution of the energy balance equation to experimental data.

In this study, the semi-physical model ForeFire, developed at the University of Corte (Filippi et al., 2009), is used to simulate the propagation of fire. ForeFire has an

Figure 1: Meso-NH nested domains used in the Lançon-de-Provence case study from the coarse 25-km grid down to the fine 1-km grid.

analytical formulation for the RoS where wind, slope effects and fuel parameters are explicitly taken into account, so, unlike Rothermel's model, no *a priori* knowledge is required (Balbi et al., 2009).

In ForeFire the advance of the fire is controlled by a front tracking algorith. At each time step, the algorithm reconstructs the shape of the front fire by displacing each front agent according to the RoS information, along propagation vectors directed normal to the fireline.

The coupling method: Meso-NH-Fire model

At the grid resolutions considered in 3D simulation, forest fires are subgrid scale processes. For this reason, an off-line coupling is initiated between the fire and the atmospheric model, i.e with no feedback from the atmosphere to the fire.

ForeFire provides the burnt area, A (in m^2), and the location of the burning cells to the meteorological model. The surface scheme ISBA accomplishes the fire-atmosphere coupling by computing wildfire contribution to latent and sensible heat fluxes at each time step of the meteorological model.
The sensible heat flux ϕ_S is set to 100 kW m^{-2} according to observations during a prescribed fire in Corsica (Silvani and Morandini, 2009). Latent heat flux contribution, ϕ_L is fixed to 100 kg m^{-2} following Filippi et al. (2009).

At low resolution ($\Delta x = 1$ km), the burnt area is much smaller than the Meso-NH grid cell which results in a dilution of the fire signatures.
Coupling of subgrid scale fire properties and the thermal plume model in Meso-NH (Pergaud et al., 2009) is currently being explored. On the contrary, at high resolution ($\Delta x = 250$ m), the turbulent motions, forced by fire heat fluxes, are explicitly resolved.

In 2D simulation, only the front of the fire is considered: its surface measures about 3 ha and it is stationary. At each 2D model time step, sensible and latent heat fluxes are computed imposing same nominal values for ϕ_S and ϕ_L.

Ref.	Vegetation type	Fuel Load (kg m^{-2})	Combustion Efficiency %
Miranda et al. (2008)	Shrubs	1.00	0.80

Ref.	Gases	EF (g kg^{-1})
Miranda et al. (2008)	CO	82.0
	NO	7.0
	NO_2	7.0
Trentmann et al. (2003)	HCHO	2.0
	Ethane C_2H_6	0.7
	Alkanes (HC_3, HC_5, HC_8, CH_3OH)	1.0
	Alkene: C_2H_4	1.2
	Alkene: C_3H_6	0.5
	Ch_3COOH	2.0
Andreae and Merlet (2001)	CH_3CHO	0.5
	Aromatics (Toluene, Xylenes, Phenol)	0.2

Table 1: Values for southern European forest fire emissions.

Burnt area information is required also to calculate chemical emissions due to forest fires. Emissions are obtained in a two-step process. First, an estimate of carbon monoxide (CO) emission (in gr) for a specific compound i is calculated by the well-known equation of Seiler and Crutzen (1980):

$$\mathrm{E}_i = A \times FL \times \beta \times EF_i \tag{1}$$

where A is the burnt area (in m^2); FL is the fuel loading (fuel material per unit area, in kg m^{-2}); β is the burning efficiency of the aboveground biomass; EF_i (in gr/kg) is the emission factor for the considered i specie. Second, an estimate of the emissions for the other gases is deduced using emission ratios with respect to carbon. The first part of the Table 1 gives values found in the litterature for fuel loading and burning efficiency for Mediterranean scrublands (Miranda et al., 2008); the second part resumes emission factors for some selected chemical species (Miranda, 2004; Miranda et al., 2008; Trentmann et al., 2003; Andreae and Merlet, 2001).

3. The Lançon-de-Provence 2005 Case Study

Meteorological situation and fire behaviour

On 1 July, 2005, a forest fire broke out southeast of Lançon-de-Provence (southeastern France), threating downwind inhabitated areas and cultivated lands. The fire started at about 07:40 UTC (09:40 AM local time). Thanks to low humidity and strong winds it lasted nearly 8 h. Lançon-de-Provence fire spread over 626 ha (roughly

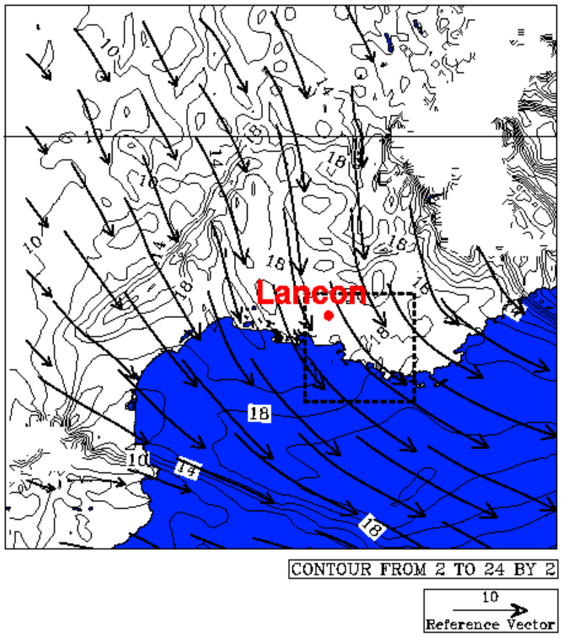

Figure 2: Wind pattern over southeast France at 1500 m above the mean sea level for 07:00 UTC 1 July, 2005, on 5 km grid-mesh domain. The dash line indicates boundaries of the 1 km grid-mesh domains. Wind arrows fly with the wind, contour levels indicate wind speed in m/s.

6 square kilometers), on a surface mainly covered by *garrigues*, a type of low, soft-leaved scrubland found around the Mediterranean Basin, generally near the seacoast.

On 30 June, 2005, the 3D Meso-NH simulated synoptic situation over western Europe is characterized by a strong pressure gradient with high pressure over the Atlantic Ocean and a cyclonic situation over the Gulf of Genova. This gradient together with the tunnel between the Alps and the Massif Central favours a strong northwesterly wind, the so-called *Mistral* (Fig. 2).

On 1 July, 2005, at 07:00 UTC, simulated atmospheric conditions shows a boundary layer (BL) height (not shown) of $\sim$ 1 km near Lançon-de-Provence, BL height goes decreasing towards the sea to $\sim$ 0.8 km. At this time in the morning, the convective mixing layer is beginning to grow in depth; it acts as a stable cap for the atmosphere. Moreover, looking at the virtual potential temperature (not shown), a temperature inversion is located between 2 and 3 km: this inversion can control the injection height of the fire plume, preventing it from reaching higher altitudes (Trentmann et al., 2003).

4. Model results

In the following, fire impacts on atmospheric dynamics and air quality are discussed comparing 2D and 3D simulations results.

Results from 2D configuration are given after 2 h of simulation time. For 3D Meso-NH-Fire model results correspond to the simulation of 1 July, 2005, at 12:00 UTC, on

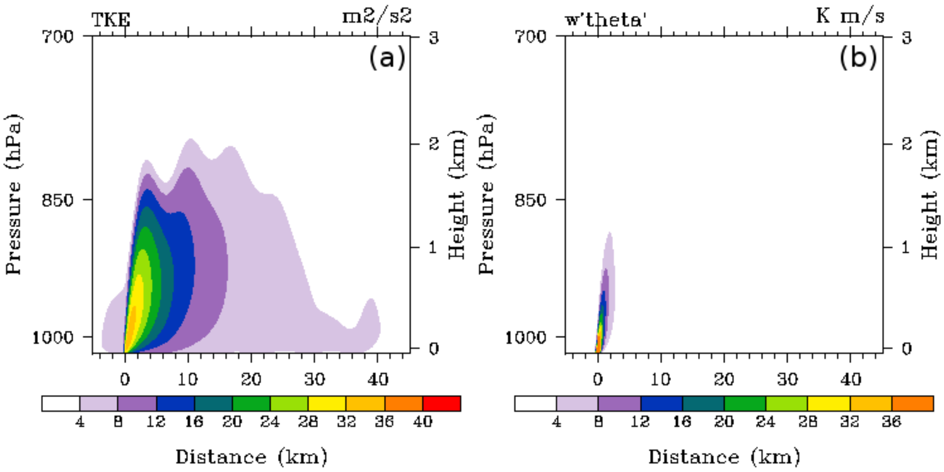

Figure 3: Cross sections of TKE ($m^2/\ s^{-2}$, Fig. **(a)**) and turbulent vertical kinematic heat flux ($w'\theta'$, in K m/s, Fig. **(b)**) for simulation with 2D Meso-NH configuration, after 2 h of simulation time.

the finest nested grid (1 km increment). For 3D simulations, all cross sections have been obtained along the red tilted axis shown in Figure 5(a), along the plume trajectory.

Fire impacts on atmospheric dynamics

Biomass burning is a strong source of sensible and latent heat fluxes that are emitted in the atmosphere in the form of hot gases and water vapour (Luderer et al., 2006). The interaction between the hot fire plume and the cooler surrounding air triggers turbulent eddies; turbulence associated to fire can efficiently mix colder air into the smoke plume, diluting the hot plume and reducing convection (Freitas et al., 2007). For this reason, it is interesting to examine how atmospheric turbulence and turbulent vertical fluxes can be affected by the ignition and the spread of a forest fire. In the following, turbulent kinetic energy (TKE, in $m^2/\ s^2$) and the turbulent vertical kinematic heat flux ($w'\theta'$, in K m/s) are shown for 2D and 3D simulations.

Figure 3 shows that the structure of the boundary layer is strongly perturbed over the point of ignition in the 2D model. Elevated TKE ($> 20 m^2/\ s^{-2}$) extend over more than 10 km downwind of the fire, toward the sea. Fire-induced effects remain confined in the boundary layer, below 2 km altitude.

Figure 4 puts on evidence that fire impacts on atmospheric stability are too much diluted at mesoscale resolutions, in the 3D configuration of Meso-NH-Fire model. It is hard to distinguish fire-induced turbulence from orographic turbulence.

Air quality downwind of the fire

In spite of being a good benchmark for fire spread models, unfortunately Lançon-de-Provence forest fire is not a well documented wildfire. The lack of data makes difficult to validate the way the fire has been parametrised in the coupled model. Anyway, a MODIS image and measurements of pollutants provided by the air quality survey network ATMOPACA have been used to evaluate modelling results.

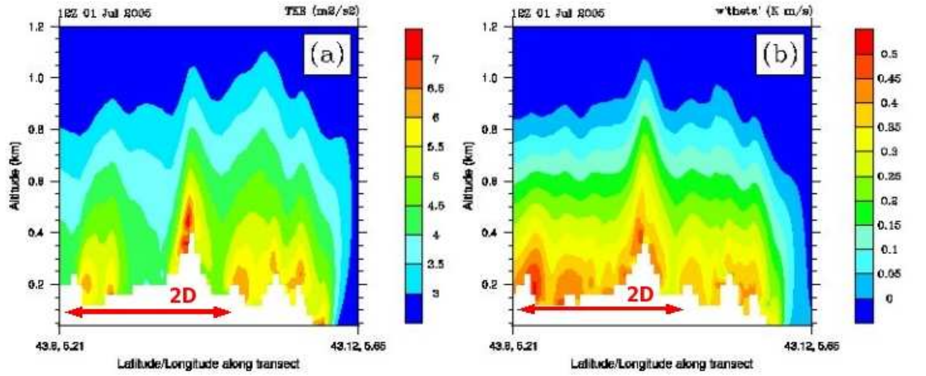

Figure 4: Cross sections of TKE (m^2/ s^{-2}, Fig. **(a)**) and turbulent vertical kinematic heat flux ($w'\theta'$, in K m/s, Fig. **(b)**) for simulation with 3D Meso-NH configuration on 1 July, 2005, at 12:00 UTC. The red line highlights the area covered by 2D LES simulation.

MODIS-AQUA captured Lançon fire plume on 1 July, 2005, at 13:00 UTC. MODIS image, Fig. 5a, is compared to the horizontal pattern of CO simulated with the 3D Meso-NH-Fire model at altitude of 400 m, just 1 h before MODIS crossing time, Fig. 5b. CO is an insoluble species and has a lifetime of about one month in the troposphere, so it can be considered a good fire tracer. In term of trajectory the comparison is encouranging: Meso-NH-Fire model can reproduce fairly well the overall direction of the fire plume. The simulated plume is lightly rotated towards East compared to the real fire plume: this is due to a shift in Meso-NH wind patterns.
Figure 5b shows very high mixing ratios in carbon monoxide ($\sim$ 1000 ppbv) above the ignition point. CO mixing ratios go decreasing downwind the burning area. Inside the plume, CO levels are of $\sim 100 - 200$ ppbv, a typical background concentration at these latitudes (Fisher et al., 2006), only 60 km away of the fire.

Figure 6 shows the cross section of carbon monoxide concentration, in ppbv, simulated by the 2D and the 3D Meso-NH-Fire model. 2D LES simulation shows very high CO concentrations near the ignition point: $\sim$ 20000 ppbv (Fig. 6a). Such high mixing ratios were observed during prescribed (Miranda et al., 2005) and natural (Jost et al., 2003) fires. Then CO mixing ratios decrease downwind the fire, but still remain above background conditions.
Figure 6b shows the vertical cross section of carbon monoxide concentration in the 3D version of the model, in units ppbv. This picture shows how CO, low reacting species, is primarly transported high in the atmosphere at a maximum altitude of 1 km. Near the fire location a strong gradient is observed with CO concentration halves over a distance of $\sim$ 20 km. Finally, the vertical structure of the CO plume confirms that Lançon fire plume remains confined in the BL. It is worth noting that the simulation at low resolution (Fig. 6b) understimates the CO mixing ratios and the injection height by 1 km compared to the LES simulation.

Figure 7 shows difference in nitrogen oxides (NOx, Fig 7a) and ozone (O_3, Fig 7b) mixing ratios between a *fire-induced* and a *no-fire* simulation at an altitude of 400 m after one hour of simulation. Directly over the burning area, the strong production

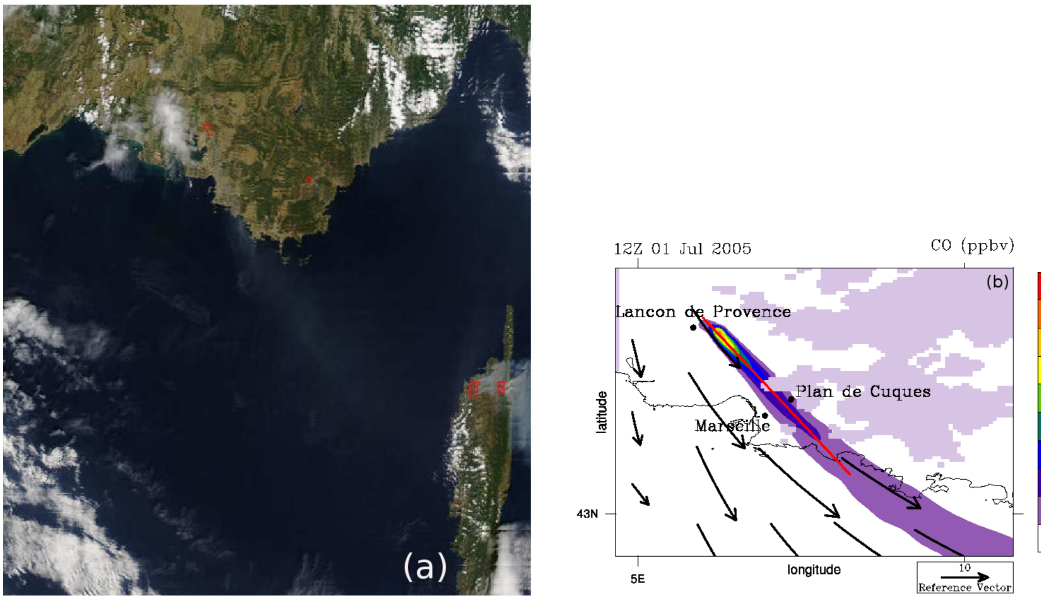

Figure 5: Qualitative comparison between Lançon fire plume seen by MODIS-AQUA and simulated with the 3D Meso-NH-Fire model. **(a)** MODIS-AQUA image captured on 1 July, 2005, at 13:00 UTC. Lançon-de-Provence fire is the first red spot on the left of the picture. **(b)** Carbon monoxide plume (ppbv) simulated on 1 July, 2005, at 12:00 UTC, on the finest grid (1 km increment) at altitude of 400 m. The tilted axis indicates direction along with cross sections are traced for 3D simulation.

of NOx immediately induces a titration of ozone which levels fall below ambient concentration. Ozone levels recover their background concentrations several kilometers downwind of the fire.

Figure 8 presents the observed PM10 hourly concentrations registered on 30 June, 1 July and 2 July, 2005, by three air quality stations located near the burning area. MODIS AQUA image shows that the city of Marseille was affected by the smoke plume on 1 July, 2005. This critical situation in term of air quality is confirmed by PM10 levels recorded at three different air quality stations in Marseille (only one is shown here). The day before and after the fire, PM10 concentrations remained well below $70\mu g/m^3$. The day of the fire, a pick of $151\mu g/m^3$ is registered at 12:00 UTC at the Marseille Timone station (Fig. 8a). Air quality stations located at the edge of the smoke plume, Avignon Mairie and Le Pontet, do not exhibit such increase. Meso-Nh simulates the increase of PM10 in the smoke plume, ~ 40 km, downwind the fire. The observed and simulated increases of PM10 concentrations near the surface confirm that the smoke plume has remained trapped in the boundary layer rather than being transported to the free troposphere. This behaviour follows the global trend of Mediterranean fires that mostly deposit their emission into the atmospheric boundary layer, below 5 km (Langmann et al., 2007; Labonne and Chevallier, 2007).

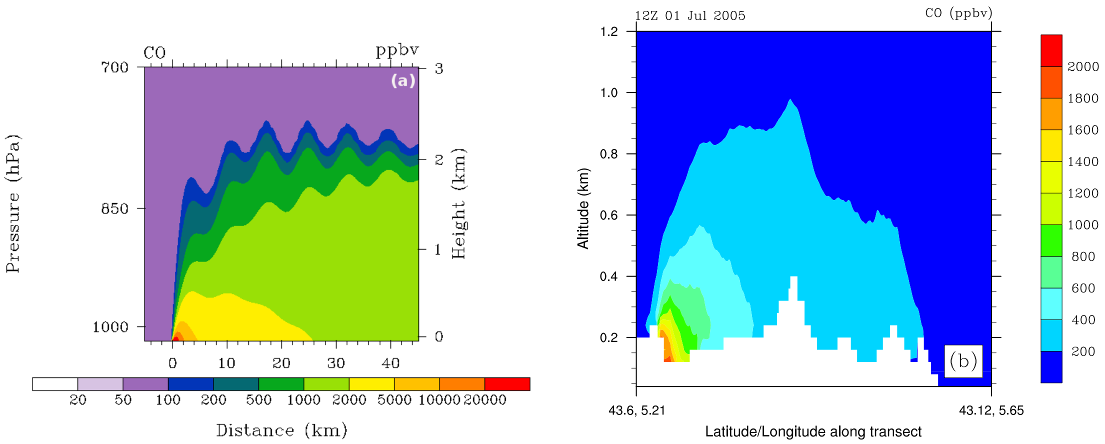

Figure 6: Cross sections of the carbon monoxide (CO) concentration (in ppbv). **(a)** Simulated with the 2D Meso-NH-Fire model after 2 h of simulation time. **(b)** Simulated with the 3D Meso-NH-Fire model on 1 July, 2005, at 12:00 UTC.

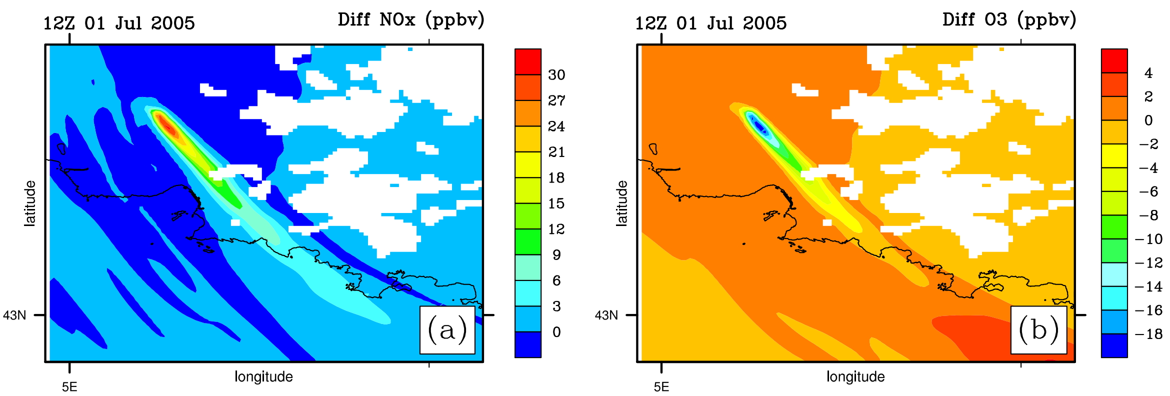

Figure 7: Concentration contour maps of nitrogen oxides (NOx, Fig. **(a)**) and ozone (O_3, Fig. **(b)**) (ppbv) at 400 m above sea mean level on 1 July, 2005, at 12:00 UTC. The two plots show the concentration difference between the simulations with and without fire forcings.

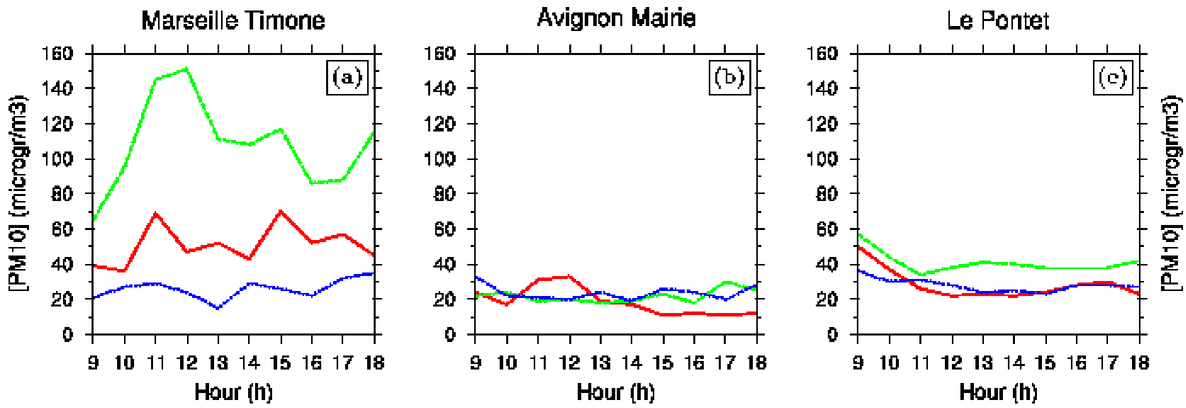

Figure 8: Daily pattern for PM10 concentration (in $\mu g/m^3$) measured on 30 June (red line), 1 July (green) and 2 July (blue), 2005, by the air quality survey network available in south-eastern France: ATMOPACA. Air quality stations: **(a)** Marseille Timone affected by the fire plume; **(b)** Avignon Mairie and **(c)** Le Pontet located outside the plume trajectory.

5. Conclusions

The study illustrates the sensitivity of the atmospheric dynamics and air quality situation to the coupling between a fire and an atmospheric model.

Concerning atmospheric dynamics, in the 3D Meso-Nh-Fire model fire-induced flows are too much diluted and masked by orographic effects. On the contrary 2D LES simulation clearly shows an increase of turbulent motions due to fire forcings in term of heat fluxes. Both simulations show that the impact of fire on atmospheric tracers is visible several kilometers downwind of the burnt area, as confirmed by the MODIS-AQUA image. The fire impact on air quality spreads over more than 60 km. Both low resolution and LES models simulate a smoke plume trapped in the boundary layer, however at 1 km resolution the signatures of the fire are significantly diluted. The comparison between the air quality forecasting and the ground-based measurements of pollutants provided by the French air quality network confirms the advection of the smoke plume within the boundary layer.

In the future, some enhancements are planned for different aspects of the coupled model. In regards to atmospheric feedbacks induced by wildfires, an important aim is to improve the way fire processes are parametrised in lower resolution models and to implement new schemes for a better modelling of the plume rise. Concerning air quality study, sensitivity studies are planned on the ozone production efficiency in the fire plume as a function of the dynamics of the plume and the strenght of the emissions. Particular efforts are needed in the chemical reaction schemes to account for fire specific products (HCN, HCHO ...) and in refining emission factors database for Mediterranean region. Finally, for the numerical part, future enhancements are planned to test the on-line coupling between ForeFire and Meso-NH.

References

M. O. Andreae and P. Merlet. Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles*, 15:955–966, 2001.

J. H. Balbi, F. Morandini, X. Silvani, J. B. Filippi, and F. Rinieri. A physical model for wildland fires. *Combustion and Flame*, 156:2217–2230, 2009.

A. Bytnerowicz, D. Cayan, P. Riggan, S. Schilling, P. Dawson, M. Tyree, L. Wolden, R. Tissell, and H. Preisler. Analysis of the effects of combustion emissions and Santa Ana winds on ambient ozone during the October 2007 southern California wildfires. *Atm. Env.*, 44(5):678–687, 2010.

P. Colella and P. R. Woodward. The piecewise parabolic method (PPM) for gas-dynamical simulations. *Journal of Computational Physics.*, 54:174–201, 1984.

V. Crassier, K. Suhre, P. Tulet, and R. Rosset. Development of a reduced chemical scheme for use in mesoscale meteorological models. *Atmos. Env.*, 34:2633–2644, 2000.

B. Cros, P. Durand, E. Frejafon, Ch. Kottmeier, P. E. Perros, V-H. Peuch, J.L. Ponche, D. Robin, F. Said, G. Toupance, and H. Wortham. The ESCOMPTE program: an overview. *Atm. Res.*, 69:241–279, 2004.

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

J. B. Filippi, F. Bosseur, C. Mari, C. Lac, P. Lemoigne, B. Cuenot, D. Veynante, D. Cariolle, and J. H. Balbi. Coupled atmosphere-wildland fire modelling. *Journal of Advances in Modeling Earth Systems*, 1(11), 2009. URL `http://dx.doi.org/10.3894/JAMES.2009.1.11`.

H. Fisher, M. Lawrence, Ch. Gurk, P. Hoor, J. Lelieveld, M. I. Hegglin, D. Brunner, and C. Schiller. Model simulations and aircraft measurements of vertical, seasonal and latitudinal O_3 and CO distributions over europe. *Atm. Chem. Phys.*, 6:339–348, 2006.

S. R. Freitas, K. M. Longo, R. Chatfield, D. Latham, M. A. F. Silva Dias, M. O. Andreae, E. Prins, J. C. Santos, R. Gielow, and J. A. Carvalho Jr. Including the sub-grid scale plume rise of vegetation fires in low resolution atmospheric transport models. *Atm. Chem. Phys.*, 7:3385–3398, 2007.

C. Jost, J. Trentmann, D. Sprung, M. O. Andreae, J. B. McQuaid, and H. Barjat. Trace gas chemistry in a young biomass burning plume over Namibia: Observations and model simulations. *J. Geophys. Res.*, 108:3676–3682, 2003.

M. Labonne and F.-M. Bréonand F. Chevallier. Injection height of biomass burning aerosols as seen from a spaceborne. *Geophys. Res. Letters*, 34:11806–11811, 2007.

J. P. Lafore, J. Stein, N. Ascencio, P. Bougeault, V. Ducrocq, J. Duron, C. Fisher, P. Hereil, P. Mascart, J. P. Pinty, J. L. Redelsperger, E. Richard, and J. Vila-Guerau de Arellano. The Meso-NH atmospheric simulation system. Part I: adiabatic formulation and control simulations. *Annales Geophysicae*, 16:90–109, 1998.

B. Langmann, B. Duncan, C. Textor, J. Trentmann, and G. R. van der Werf. Vegetation fire emissions and their impact on air pollution and climate. *Atm. Env.*, 43:107–116, 2007.

G. Luderer, J. Trentmann, T. Winterrath, C. Textor, M. Herzog, H. F. Graf, and M. O. Andreae. Modeling of biomass smoke injection into the lower stratosphere by a large forest fire (Part II): sensitivity studies. *Atm. Chem. Phys.*, 6(12):5261–5277, 2006.

V. Masson, J. L. Champeaux, F. Chauvin, C. Meriguet, and R. Lacaze. A Global Database of Land Surface Parameters at 1-km Resolution in Meteorological and Climate Models. *Journal of Climate*, 16(9):1261–1282, 2003.

MediasFrance. ESCOMPTE EXERCISE Homepage. `http://escompte.mediasfrance.org/exercice/HTML/exe.html`, 2001.

A. I. Miranda. An integrated numerical system to estimate air quality effects of forest fires. *Int. J. of Wildland Fire*, 13:217–226, 2004.

A. I. Miranda, J. Ferreira, J. Valente, P. Santos, J. H. Amorim, and C. Borrego. Smoke measurements during Gestosa-2002 experimental field fires. *Int. J. of Wildland Fires*, 14:107–116, 2005.

A. I. Miranda, A. Monteiro, V. Martins, A. Carvalho, M. Schaap, P. Builtjes, and C. Borrego. Forest Fire Impact on Air Quality over Portugal. In C. Borrego and A. I. Miranda, editors, *Air Pollution Modeling and its Application XIX*, pages 190–198. Springer Science-Business Media B. V., 2008.

E. J. Mlawer, S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough. Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-K model for the longwave. *J. Geophys. Res.*, 102:16663–16682, 1997.

J. Noilhan and S. Planton. A simple parameterization of land surface processes for meteorological models. *Mon. Wea. Rev.*, 117:536–549, 1989.

J. G. Pausas. Changes in fire and climate in the eastern iberian peninsula (Mediterranean basin). *Climatic Change*, 63:337–350, 2004.

J. Pergaud, V. Masson, S. Malardel, and F. Couvreux. A Parameterization of Dry Thermals and Shallow Cumuli for Mesoscale Numerical Weather Prediction. *Boundary-Layer Met.*, 132:83–106, 2009.

J. P. Pinty and P. Jabouille. A mixed-phase cloud parameterization for use in mesoscale non-hydrostatic model: simulations of a squall line and of orographic precipitations. In *Proc. Conf. of Cloud Physics*, pages 217–220, Everett, WA, USA, 1999.

S. J. Pyne, P. L. Andrews, and R. D. Laven. *Introduction to wildland fire*. John Wiley & Sons, Inc., 1949.

W. Seiler and P. J. Crutzen. Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Clim. Change*, 2:207–247, 1980.

X. Silvani and F. Morandini. Fire spread experiments in the field: Temperature and heat fluxes measurements. *Fire Safety J.*, 44:279–285, 2009.

N. Takegawa, Y. Kondo, M. Ko, M. Koike, K. Kita, D. R. Blake, W. Hu, C. Scott, S. Kawakami, Y. Miyazaki, J. Russel-Smith, and T. Ogawa. Photochemical production of O_3 in biomass burning plumes in the boundary layer over northern Australia. *Geophys. Res. Letters*, 30(10), 2003.

J. Trentmann, M. O. Andreae, and H.-F. Graf. Chemical processes in a young biomass-burning plume. *J. Geophys. Res.*, 108, 2003.