J 3.6 A LOCAL-SCALE MODELLING SYSTEM TO SIMULATE SMOKE DISPERSION

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1 INTRODUCTION

A forest fire is a large-scale natural combustion process consuming various ages, sizes and types of botanical specimens, growing outdoors in a defined geographical area. Although wildland fires are an integral part of ecosystems management and are essential to maintain functional ecosystems (Sandberg *et al*., 2002), their proportions can give rise to disastrous results. Within the consequences of biomass burning is the emissions of various environmentally significant gases and solid particulate to the atmosphere that interfere with local, regional and global phenomena in the biosphere (Miranda and Borrego, 2002) and, consequently, essential when trying to relate emissions with air quality.

Smoke from forest fires includes important amounts of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NOx), ammonia (NH_3), particulate matter (PT), particles with mean diameter lesser than 2.5 μm ($PM_{2.5}$) and particles with mean diameter lesser than 10 μm (PM_{10}), non-methane hydrocarbons (NMHC), volatile organic compounds (VOC), sulphur dioxide (SO_2) and other chemical species. These air pollutants can cause serious consequences to regional and local air quality by reducing visibility, generating smog and threatening human health and ecosystems.

Currently there is a growing awareness about the effects that smoke from wildland fires can have in the environment. This concern is also associated to prescribed fires, namely in Australia and North America where this fire management technique is frequently used. Although the long term health effects from occupational smoke exposure remain unknown, the evidence to date suggests that brief, intense smoke exposures can easily exceed short-term exposure limits in peak exposure situations such as direct attack and holding fire lines downwind of an active wildfire or prescribed burn (Sandberg *et al*., 2002).

The main purpose of this paper is to present a fire behaviour system, developed to estimate fire progression, smoke dispersion and visibility impairment, in a local scale, and to evaluate its performance comparing results with measurements from experimental field fires.

The system is an improvement of two numerical tools already available, DISPERFIRE (Miranda *et al*., 1994) and FireStation (Lopes *et al*., 2002), which were integrated together.

2 METHODOLOGY

DISPERFIRE and FireStation models were combined aiming to obtain a more complete and powerful system of models. The whole system was developed under a graphical interface, previously developed for FireStation, allowing a friendly use and providing easily readable output to facilitate its application under operational conditions.

The improvement of DISPERFIRE consisted in the development and integration of a model for the estimation of visibility impairment, based on the relationship between the air pollutants concentration and visibility.

Air quality and visibility impairment, during the GESTOSA 2004 experimental fires where simulated with this new integrated tool. The emission, dispersion and effect on visibility of NOx, $PM_{2.5}$ and PM_{10} were calculated and results were compared with measured pollutant concentration values, as a complement of the air quality evaluation experimentally performed in GESTOSA 2004.

This comparison allowed to verify the performance of the developed system of models that can be used to assess the air quality and visibility impairment of the area affected by a small-scale wildfire.

2.1 *FireStation*

FireStation is a software system aimed at the simulation of fire spread over complex topography. It implements five distinct mathematical models for the simulation of the rate of spread, fire shape, fire growth, fire weather index and the wind field.

The fire behaviour model is based on the Rothermel's surface fire spread model

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(Rothermel, 1972), and has as input local terrain slope, parameters describing fuel properties, as well as the wind speed and direction. The fire shape is described with recourse to two ellipse type models: one proposed by Anderson (1983 *in* Lopes *et al.*, 2002) and the other by Alexander (1985 *in* Lopes *et al.*, 2002). Both these models take as input the wind speed at mid-flame height. In terms of implementation, the fire growth is carried out using a raster approximation. The topography is divided into cells, over which fuel properties are assumed constant. Fire growth simulation thus becomes a contagion process between burning and non-burning cells. This process, based on the Dijkstra's dynamic programming algorithm, leads to a time progression that may not be constant (Lopes *et al*., 2002).

Both models, DISPERFIRE and FireStation, have wind modules based on the diagnostic wind model NUATMOS (Ross *et al*., 1988).

2.2 *DISPERFIRE*

DISPERFIRE is a real time system developed to simulate the dispersion in the atmosphere of the pollutants emitted during a forest fire. It is based in the diagnostic wind model NUATMOS, and in a Lagrangean dispersion model. The dispersion module results from the development of a "quasi-three dimensional" Lagrangean model to a 3D model. The Lagrangean approach assumes that a large number of marker particles statistically reproduce the turbulent transport. The displacement of each particle can be described as the sum of three components: the deterministic contribution from the average wind field, known from the meteorological module; the random 3D displacement; and the component linked with gravity effects, taking into account the difference in density between the gaseous particle an its environment. The random 3D displacement, which is a function of local conditions, is by definition unrelated in each of the three axes. This component has a random displacement of mean zero and variance proportional to the effective components. Once the particle trajectories are determined, a given mass of pollutant is associated with each marker particle. Then, the mean concentration at a point is determined by counting the number of particles present in an appropriate control volume around that point.

Wind and dispersion models were adapted to work together and to simulate specific conditions of forest fire behavior (Miranda, 1998), namely the dispersion module is adapted for fire situations by the inclusion of the plume height estimation, using the Sestak and Riebau (1988) formula, and has been adapted to directly work with the results from the modified diagnostic meteorological module.

A model for the estimation of visibility impairment, based on the relationship between the air pollutants concentration and visibility, was developed and included in DISPERFIRE.

2.3 *Simulation of visibility conditions*

The DISPERFIRE system of models was improved with the development and integration of a visibility module based on the relationship between the air pollutants concentration and visibility. This model uses the air pollutants concentration fields given by the local smoke dispersion model.

Based on the analysis of typical atmospheric emissions from wildfires, in the relevance of each pollutant in visibility and in the temporal scale at which DISPERFIRE is applied, it was found that the visibility model should consider PM_{10}, $PM_{2.5}$ and NO_x as the relevant pollutants for the calculation of visibility. None of these pollutants is hygroscopic at this scale of modeling, clearing away the difficulties associated to the correct estimation of relative humidity (RH) and its influence on pollutants. Sulphates and nitrates are the pollutants in which the estimation of RH is essential. At the temporal scale of DISPERFIRE, sulphates and nitrates, both secondary pollutants, are not relevant.

The 3D concentration fields of $PM_{2.5}$, PM_{10} and NO_2, estimated by DISPERFIRE are used as input to the visibility module. With these concentrations, and according to eq. 1 (Gray and Kleinhesseling, 1996), the model calculates the visibility impairment caused by these pollutants for each cell of the chosen domain (2D).

$$bext = \sum_i (Ci \times ei) \qquad \text{Eq. 1}$$

where,

C_i - concentration of pollutant i [$\mu g.m^{-3}$];

e_i - extinction efficiency of pollutant i [$m^2.\mu g^{-1}$].

The outputs of the model are in deciview (dV) which is an easily understood visibility index (Pitchford and Malm, 1999), and has a linear response to perceived visual changes over its entire range: a one to two dV difference corresponds to a small visible perceptible change in scene appearance; a zero value represents extremely good visibility and an increase in dV corresponds to an increase in visibility impairment. This index in given by eq. 2:

$$dV = 10\, x \ln\left(\frac{b_{ext}}{0{,}01}\right) \qquad \text{Eq. 2}$$

where
dV – deciview index;
bext – extinction efficiency [Mm^{-1}].

The developed module is a simple tool, not prepared to give very accurate results, but to quantify the visibility impairment caused by the emission and dispersion of some relevant pollutants. Despite its limitations, results may allow that both aerial and terrestrial fireman teams work in safer conditions.

2.4 *NUATMOS*

Both models, DISPERFIRE and FireStation, have wind modules, based on the diagnostic wind model NUATMOS (Ross *et al.*, 1988), which produces a 3D mass consistent wind field through the interpolation of observations arbitrarily located throughout the domain of interest. Minimal adjustments are made in order to eliminate divergence. The atmospheric stability is taken into account through an input parameter ALPHA, which is related to the Froude number and determines the amount of adjustment made in the vertical component relative to the horizontal adjustment during the divergence-free solution phase. The numerical equations are solved in terrain-following co-ordinates and variable vertical grid spacing.

2.5 *The integration of the models*

DISPERFIRE and FireStation were integrated resulting in a new and more powerful tool (Figure 1).

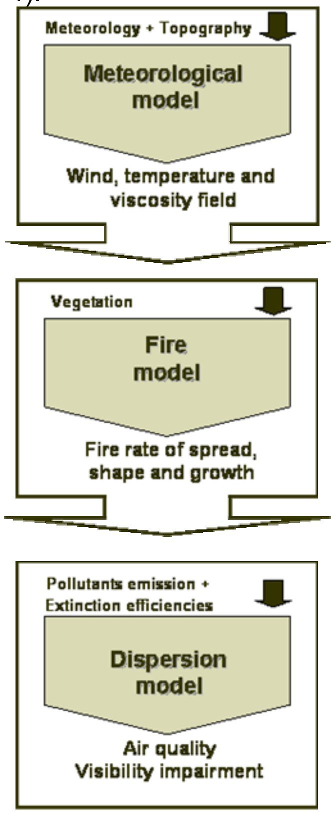

Figure 1. Scheme of the developed fire behavior system.

FireStation was modified in order to produce input data for DISPERFIRE: topography, wind speed and direction, ignition time, fire rate of spread and heat released for each cell of the domain. DISPERFIRE was prepared to read these specific input formats and to produce output results readable by the visualization module created in FireStation.

The FireStation interface was also changed allowing the user the management of the smoke dispersion simulation. In the menu *Applications*, *FireStation*, the field *Dispersion* (Figure 2) is now available. It accesses the *Smoke Dispersion* dialog-box ().

Figure 2. Menu *Dispersion* created in FireStation that allows the access to the *Smoke Dispersion* dialog-box.

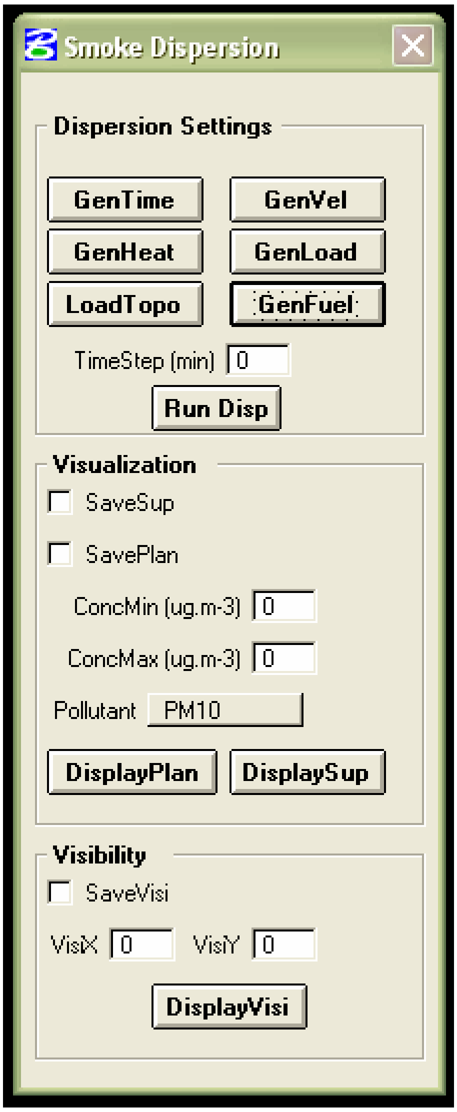

Figure 3. *Smoke Dispersion* dialog-box.

With this dialog-box is possible to define the smoke dispersion and visibility calculation. It is divided in three main areas:

Dispersion Settings – management of the smoke dispersion inputs and simulation command;

Visualization – area with the necessary information to the visualization of the dispersion simulation;

Visibility – allows the management of the simulation and visualization of visibility impairment.

2.6 *Case-study*

The burning experiments performed since 1998 at Central Portugal, Gestosa, aim to collect a large range of different but complementary experimental data, which can be used to support the development of new concepts and models and to validate existing methods or models in various fields of fire management (Viegas *et al.*, 2002), constituting a particularly important opportunity to measure and analyze air pollutants concentrations during experimental field fires. Experiments undertaken in 2004 are the basis for the system evaluation. The system was applied to an experimental field fire and main results were compared with measured values. Two mobile laboratories were parked near the experimental burning plots (15 plots with 0.1 ha each) measuring in continuum concentrations of $PM_{2.5}$ and PM_{10}, NO_2, nitrogen monoxide (NO), and CO. Figure 4 presents the location of Gestosa, the burning plots and the mobile laboratories.

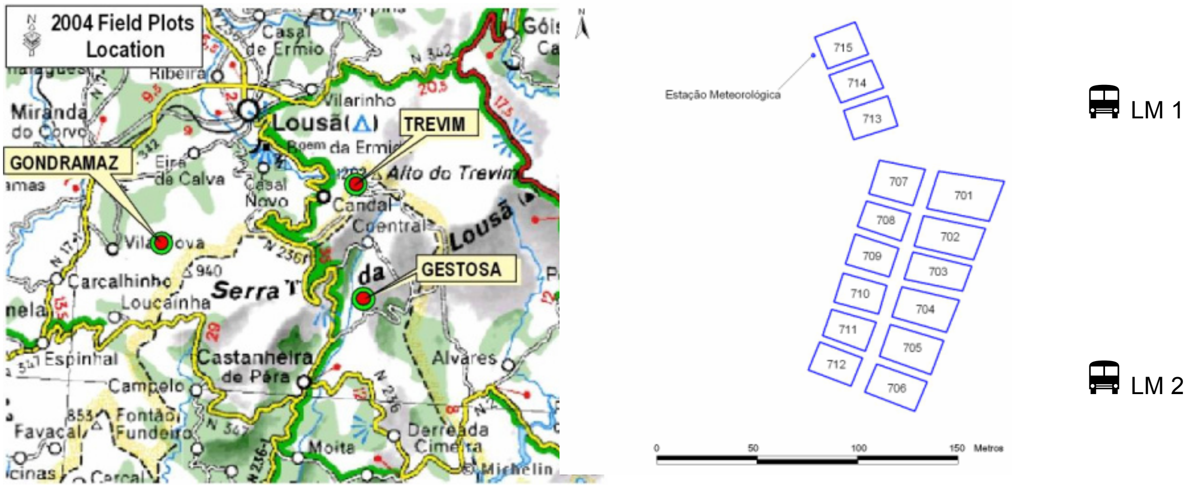

Figure 4. Map and schematic view of Gestosa 2004 plots and location of mobile laboratories, in Trevim area (adapted from Viegas, 2004).

During the experimental fires, which occurred in warm and dry May days, temperature, humidity, and wind speed and direction were measured at several locations, namely near the fire plots. Distinct techniques and equipment were used to obtain the concentrations of different pollutants. Table 1 summarizes the applied measuring techniques.

The continuous acquisition of NO and NO_2 concentrations in air was performed using the automatic equipment Environnement AC31MTM (Dual Chamber Chemiluminescent Nitrogen Oxides). CO was measured in continuum with the Environnement CO11M analyser, whose functioning principle is based on the selective absorption of infrared radiation by the CO molecules. To monitor PM_{10} and $PM_{2.5}$ concentrations, two Environnement MP101M analyzers were used with adequate sampling inlets for each diameter. A beta gauge mass monitor determines the particle's mass.

Table 1. Summary of air pollutant measurement techniques during Gestosa-2004 experiments.

Pollutant	Technique	Type of data	Equipment	Characteristics
NO_x (NO, NO_2)	Automatic equipment LM 2	Continuous measurement: 1 min average	Environnement AC31M^{TM}	Range: 0-10 ppm (programmable) Noise: 0.17 ppb Lower detectable limit: 0.35 ppb Response time: automatic and programmable (minimum 20 s)
CO	Automatic equipment LM 2	Continuous measurement: 1 min average	Environnement CO11M^{TM}	Range: 0-200 ppm (prog.) Noise: 0.025 ppm Lower detectable limit: 0.05 ppm Response time: automatic and programmable (minimum 30 s)
Particulate matter: $PM_{2.5}$ PM_{10}	Automatic equipment LM 2 LM 1	Continuous measurement: 15 min average	Environnement MP101M^{TM}	Range: 0-10000 μg m^{-3} (prog.)

2.7 *Measured values*

Aiming to better understand the experimental field fires effects on the air quality, the measured results were compared to European air quality legislation values, which also are the Portuguese standards. Table 2 presents the limit values for the pollutants monitored with the air quality equipment.

Table 2. Limit air quality values for the protection of human health established by European legislation.

Pollutant	Limit value	Averaging period	Directive of the Council
PM_{10}	50 $\mu g.m^{-3}$	24 hours	1999/30/EC
NO_2	200 $\mu g.m^{-3}$	1 hour	1999/30/EC
SO_2	350 $\mu g.m^{-3}$	1 hour	1999/30/EC
CO	10 $mg.m^{-3}$	Maximum daily 8-hour mean	2000/69/EC

In Figure 5 are presented the measured concentrations of PM_{10} (15 minutes average), the calculated 24 hours average, and the limit value (24 hours average).

The measured concentrations of PM_{10} (15 minutes average) surpass the limit value of 50 $\mu g.m^{-3}$ (24 hours average) during three hours. Nevertheless, the daily calculated average, 33 $\mu g.m^{-3}$, never reaches this value.

Figure 6 presents the measured values of CO (1 minute average), the calculated 8 hours average, and the limit value, 10 $mg.m^{-3}$, (8 hours average).

The measured concentrations of CO are also clearly influenced by the emissions of the burning plots. The maximum measured concentration is 35 $mg.m^{-3}$. However, when the 8 hours average is calculated the limit value established in legislation is never surpassed.

In Figure 7, a graph presents the measured concentration values of NO and NO_2 (1 minute average), the calculated hourly average of NO_2 and the NO_2 limit value (1 hour average).

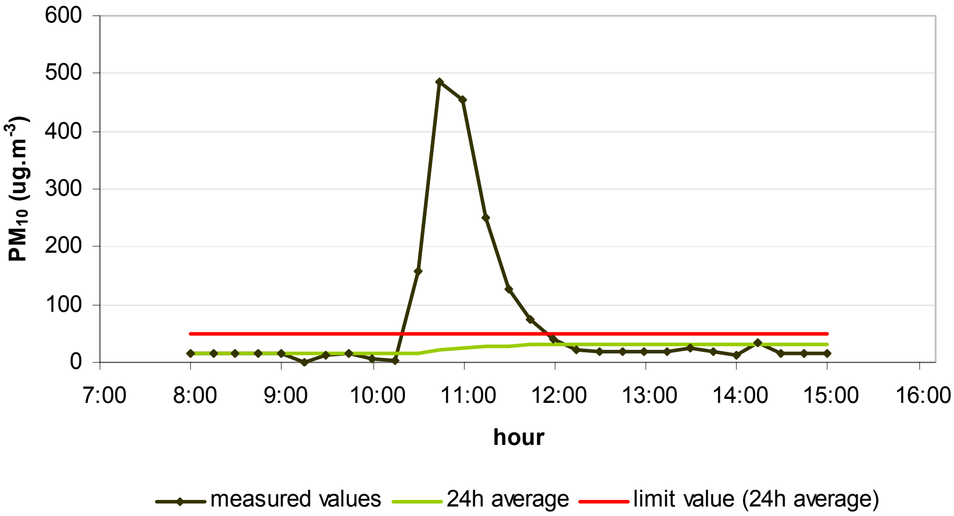

Figure 5. PM_{10} concentration values measured in LM 1 at 12th of May 2004.

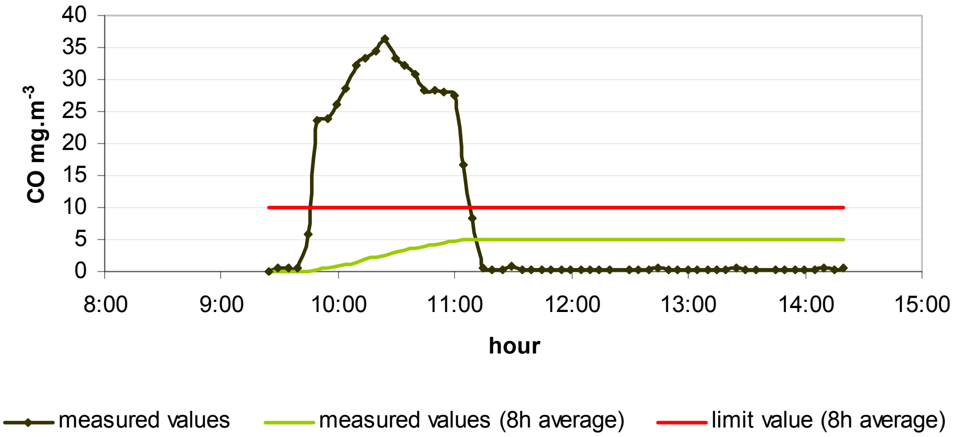

Figure 6. CO concentration values measured in LM 1 at 12th of May 2004.

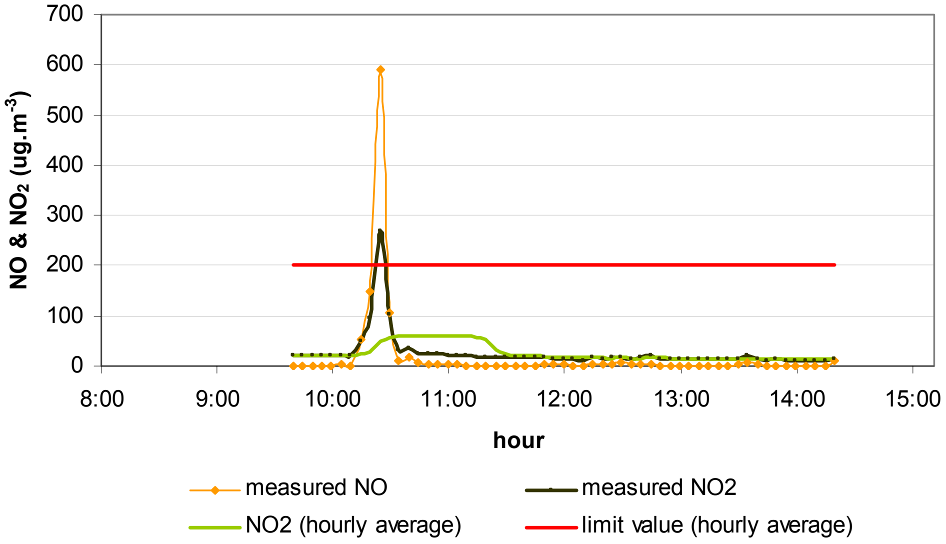

Figure 7. NO e NO_2 concentration values measured in LM 1 at 12th of May 2004.

The emissions from the burning plots influenced the measured concentrations of NO and NO_2. Concerning the NO_2, although the measured values surpassed 200 µg.m^{-3}, when the hourly average is calculated the limit value is never attained.

3 APPLICATION OF THE DEVELOPED TOOL

Air quality and visibility impairment, during the GESTOSA 2004 experimental fires were simulated with the new integrated tool. The fire spread, emission and dispersion of pollutants, and their effect on visibility were calculated.

A modeling domain of 1830 x 1130 m horizontally with a constant grid spacing of 10 m was considered. In the vertical direction, 3070 m were considered and divided into 23 non-equidistant levels, with a maximum resolution close to the ground. Meteorological conditions were updated with values from various meteorological stations. Fire intensity was estimated using the available fuel in each plot and the total time of the plot burning.

Emissions from the experimental burns were calculated using an average fuel loading for each plot and appropriate emission factors for the specific conditions of Gestosa, presented in Table 3. Taking into account the vegetation cover of the study area, a heat content of 22.8 kJ.kg^{-1} of dry biomass was also considered (Viegas, 2004).

Table 3. Pollutants and emission factors considered for the simulation of Gestosa 2004 burns (Valente, 2005).

pollutant	emission factor (g.kg^{-1})
NO_2	2
PM_{10}	11
$PM_{2.5}$	8
CO	100

Table 4. Pollutants and extinction coefficients considered for the simulation of Gestosa 2004 plots - Trevim (Heisler, 2002).

pollutant	extinction coeficient (m^2.µg^{-1})
NO_2	0.21
PM_{10}	1
$PM_{2.5}$	1.2

After the analysis of the measured concentrations and the burn schedule it was decided to simulate the burn of the plots 702, 701 and 707. The burn of these plots was responsible for the peak concentrations registered in LM1 analyzers between 10.00 h and 10:30 h.

In Figure 8 are presented, the NO_2, $PM_{2.5}$, PM_{10} and CO concentration fields, as a result of the simulation of the burn of plots 702, 701 and 707.

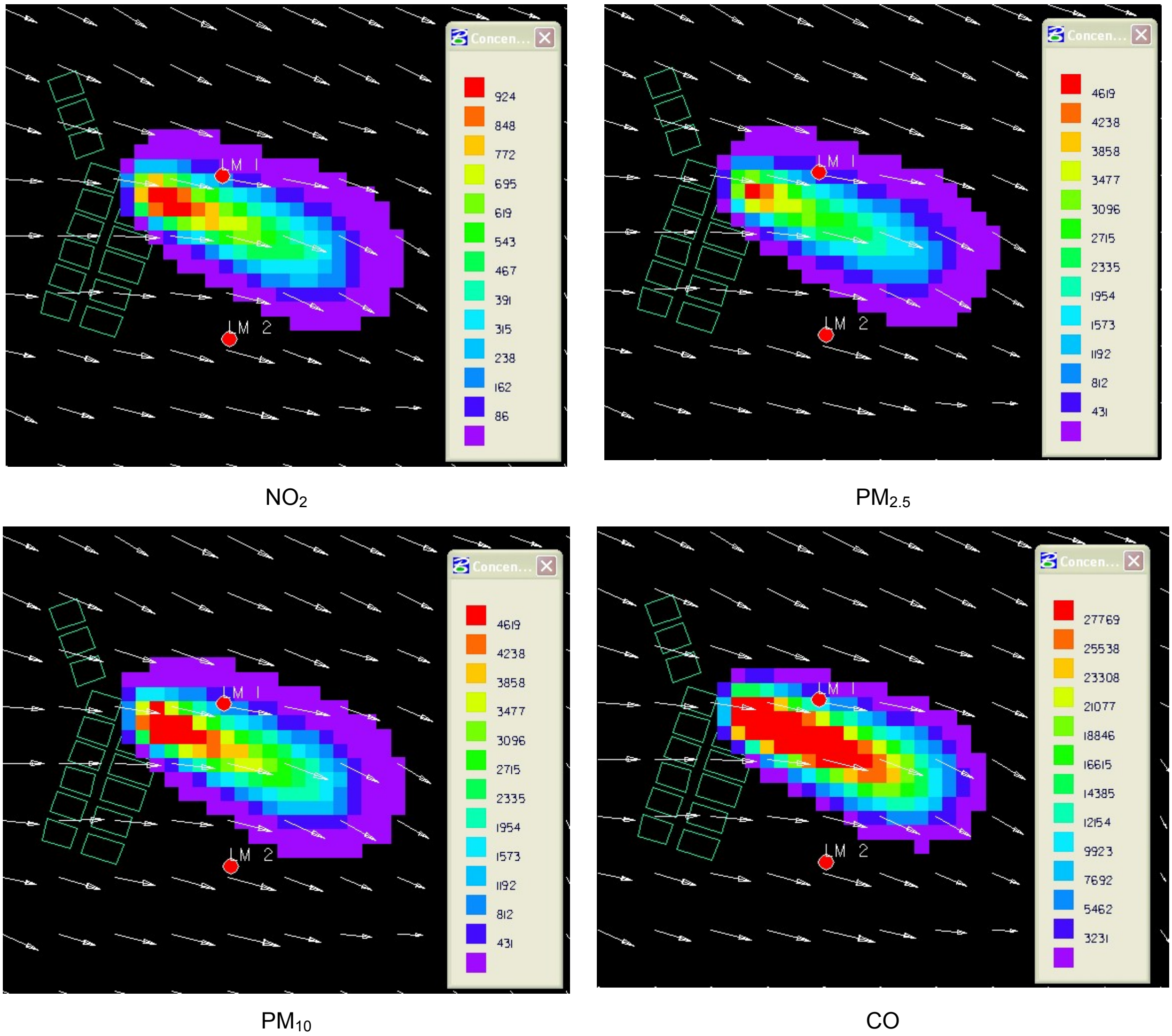

Figure 8. Pollutant concentration fields ($\mu g.m^{-3}$), at ground level, after the burn of plots 702, 701 and 707 (400m x 330 m).

Concerning NO_2, the concentration obtained in the simulation, between 162 $\mu g.m^{-3}$ and 238 $\mu g.m^{-3}$, is close to the measured value 250 $\mu g.m^{-3}$. When comparing the simulation results for PM_{10}, in the 435-812 $\mu g.m^{-3}$ range, with the measured values, one can conclude that it is close to the registered values in LM1, at 10:45h, 486 $\mu g.m^{-3}$.(15 minutes average). The simulated concentration of CO is the one that is more distant to the measured value. At 10:33h, the measured value was 32000 $\mu g.m^{-3}$, while the simulated value is between 12000 $\mu g.m^{-3}$ and 14000$\mu g.m^{-3}$. Nevertheless, the concentration values obtained in the adjacent cells are close to 30000 $\mu g.m^{-3}$. This result can be considered reasonable, having in mind the proximity of the adjacent cells (10 m) and the associated error of the positioning device (10 m) itself.

It is difficult to compare the $PM_{2.5}$ estimated and measured values because the plume didn't reach LM2, where the $PM_{2.5}$ analyzer was installed.

Table 5 summarizes this comparison between measured and simulated concentration values. In general, the model has a good performance, being the calculated values close to the measured ones.

Table 5. Comparison between measured and simulated concentration values.

pollutant	simulated concentration ($\mu g.m^{-3}$)	measured concentration ($\mu g.m^{-3}$)
NO_2	162 - 238	250
PM_{10}	431 - 812	486
CO	12000 - 14000	32000

Figure 9 presents the visibility impairment vertical field (in dV), caused by the emissions and dispersion of NO_2, PM_{10} and $PM_{2.5}$, during the burn of plots 702, 701 and 707.

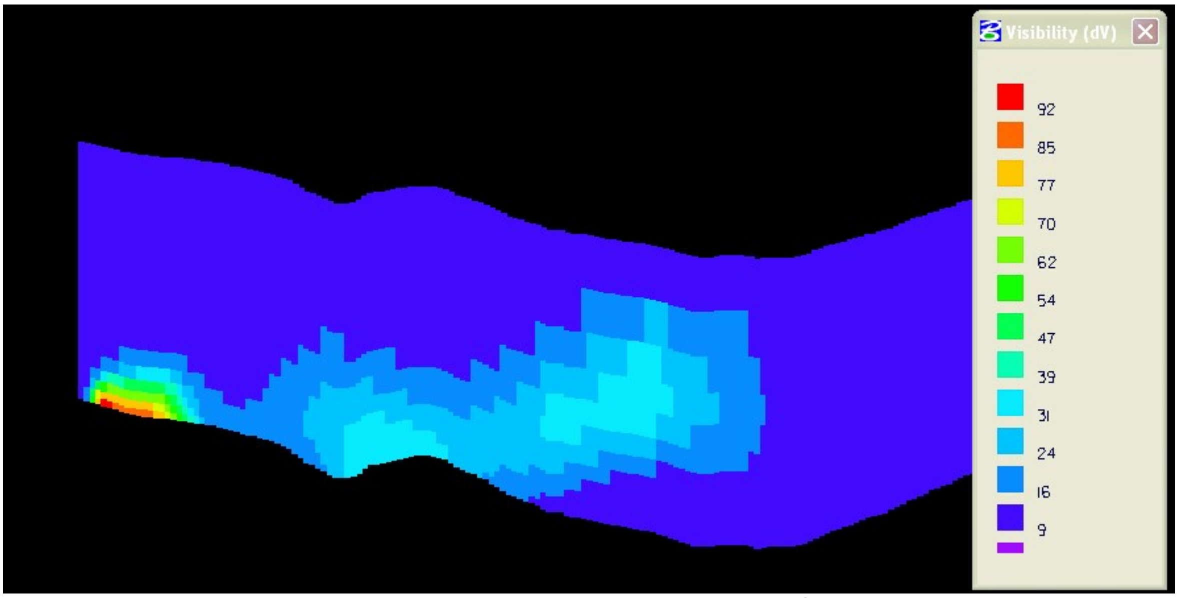

Figure 9. Vertical visibility plot, in dV, associated to the burning of plots 702, 701 and 707.

As can be seen in Figure 9, and despite the small size of the experiments, the burn of an experimental plot can produce a significant impairment of visibility, which is felt over an area much larger than the dimensions of the fire itself. The area reached by the smoke plume presents values between 24 dV and 70 dV that correspond to a visual range of 35 km and 400 m, respectively. These values of visual range are considerably low, when compared with the clean atmosphere visual range, 200 km.

4 FINAL REMARKS

Visibility reduction and air quality degradation are a common consequence of biomass burning and a recurring problem in almost every parts of the world. It may lead to a pronounced diminishing of safety conditions during fire fighting operations and terrestrial and aerial traffic.

Notwithstanding the small size of the burning plots when compared to real wildfires, the measured levels of pollutants were considerable. Simulation results confirmed that smoke from vegetation burning influences air quality, namely regarding concentration values of particulate matter, NOx and CO, which concentrations attained levels of some concern. Also, visibility impairment can be expected during experimental field fires, like the Gestosa ones.

Comparison between estimated and measured values indicates a good performance of the modeling system.

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