6.7 THE 2003 FIRE SEASON IN PORTUGAL: IMPACTS ON AIR QUALITY

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Abstract. The statistical analysis applied for 2003 show that O_3 maximum concentrations are highly correlated to the area burned and number of fires for August ranging from 0.49 to 0.80 and 0.51 to 0.74, respectively, depending on the district. PM_{10} daily average also presents significant correlation coefficients especially in August. It is clear, from this analysis, that there is a significant correlation between forest fire activity, in Portugal, and air pollutants concentrations in the atmosphere. The application of the air quality modelling system MM5-CHIMERE over continental Portugal domain, with 10x10 km^2 horizontal grid resolution allowed to evaluate the relationship between forest fire activity and air pollutants concentrations in the atmosphere. Forest fire emissions were estimated based on specific southern European emissions factors, on type of vegetation and area burned, and incorporated in the emission input data of the numerical modelling system. Results were compared with the baseline scenario estimates (without forest fire emissions) and evaluated against monitoring data. Model results showed a significant performance improvement when forest fires are taken into account.

1 INTRODUCTION

In 2003 Portugal experienced by far the worst forest fire season of the last 27 years, with a total area burned of almost 5 times the average.

A number of about 4,600 fires burned 8.6% of the Portuguese forest area (EC, 2004). The highest values of area burned were registered in the central eastern districts with a total of 126,589 hectares of forest consumed. A large number of fires occurred in August, with 86% of total area burned (EC, 2004).

Smoke is considered as one of the several disturbing effects of forest fires. Its impacts on air quality and human health can be significant, because large amounts of pollutants are emitted into the atmosphere.

Smoke from forest fires includes important amounts of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x), ammonia (NH_3), particulate matter (PM), 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, what interfere in several atmospheric processes.

The effects of these emissions are felt at different levels: from the contribution to the greenhouse effect (Miranda *et al*., 1994) to the occurrence of local atmospheric pollution episodes (Miranda, 2004), including ozone levels at medium distances (inter-regional scale or mesoscale) of emissions sources (Monteiro *et al*., 2005).

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The identification and quantification of emissions of these pollutants during forest fires, and the associated levels of pollutants in the air ambient are important for understanding the effects of forest fires on air quality.

Biomass burning is a complex process, because depend on multiple and interdependent factors like forest fuels types, burning efficiency, burning phase, fire type, meteorology and geographical location. These factors change at each instant and consequently the amount, rate and type of pollutants vary widely. Fuel type and load are one of the most important factors affecting fire emissions.

The main purpose of this paper is to evaluate the impacts of forest fire emissions on air quality applying two approaches: (i) a statistical analysis was performed to investigate a potential relationship between forest fire activity and air pollutants concentrations in the atmosphere, and (ii) the MM5-CHIMERE numerical modelling system was applied, over summer 2003, in order to evaluate the impact of the forest fire emissions on the air quality over Portugal.

2 STATISTICAL ANALYSIS

The statistical analysis was based on the concentration values of atmospheric pollutants measured at the Portuguese air quality monitoring network in 2003, and on the area burned and the number of fires by district, for the same period.

This analysis was focused in three different periods: annual, June to September (JJAS) and

August. The daily area burned and the number of fires was correlated with the daily maximum ozone (O_3) concentration and the daily averaged PM_{10}, registered in each air quality station, by district.

Air quality data were available at six districts in Portugal (Aveiro, Coimbra, Lisboa, Porto, Santarém and Setúbal). For each district several air quality stations were considered except in Santarém, Chamusca station (Figure 1).

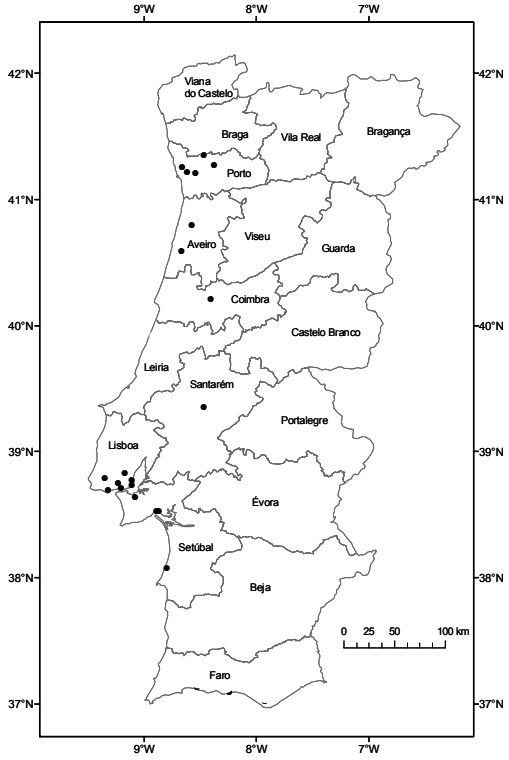


Figure 1. Air quality stations location (dot points) and Portuguese districts identification.

Only background stations with the required acquisition efficiency were considered in the analysis. Considering the measuring station acquisition efficiency of 85% for PM_{10} (EC, 2002a) and 75% for O_3 (EC, 2002b), the data availability is quite different among all the analyzed background stations.

SAS program version 9.1.3 (SAS, 2004) was used to estimate the Spearman correlation coefficients between the pollutants concentrations and the area burned and the number of fires.

Table 1 present the average Spearman correlation coefficient, by district and for each period between PM_{10} daily average and O_3 daily maximum and the area burned and the number of fires. All results are statistically significant at a 0.05 significance level.

Concerning PM_{10} daily average, the best correlations are obtained for the number of fires and for August. The northern coastal districts present the highest correlation coefficients between the PM_{10} daily average and the number of fires, reaching 0.75 for Porto. For the period under analysis (2003) these districts registered the highest number of forest fire occurrences accounting for 43%, of the total number. The relationship between PM_{10} daily average and area burned is not so high. The best correlations were obtained for August and Porto district shows a 0.63 correlation also in August.

The relationship between O_3 daily maximum concentrations and fire activity presents higher correlation coefficients with the number of fires comparatively to the area burned. Coimbra and Porto districts present the highest correlations with the number of fires reaching 0.73 and 0.74, respectively, in August.

Table 1. Correlation between concentration values PM_{10} daily average and O_3 daily maximum and area burned and number of fires, in average, by district.

District	PM_{10}						O_3					
	Spearman correlation coefficients											
	area burned			number of fires			area burned			number of fires		
	Annual	JJAS	August	Annual	JJAS	August	Annual	JJAS	August	Annual	JJAS	August
Aveiro	0.32	0.46	0.57	0.34	0.58	0.63	0.48	0.36	0.49	0.49	0.40	0.51
Coimbra	0.38	0.41	0.66	0.39	0.53	0.78	0.60	0.42	0.59	0.62	0.50	0.73
Lisboa	0.16	0.20	*	0.16	0.29	0.43	0.39	0.22	*	0.41	0.36	0.49
Porto	0.26	0.51	0.63	0.25	0.52	0.75	0.57	0.49	0.53	0.55	0.48	0.74
Santarém	0.37	0.33	0.95[+]	0.37	0.36	0.99[+]	0.68	0.54	0.80	0.68	0.54	0.56
Setúbal	0.26	*	0.45	0.27	0.21	0.48	0.36	0.28	0.52	0.39	0.38	0.63
Average	0.29	0.38	0.58	0.30	0.42	0.61	0.51	0.39	0.59	0.52	0.44	0.61

* Correlations not significantly

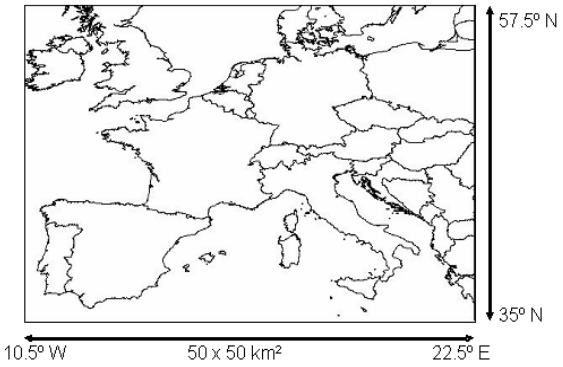
[+] Only seven days available for analysis

3 AIR QUALITY MODELLING

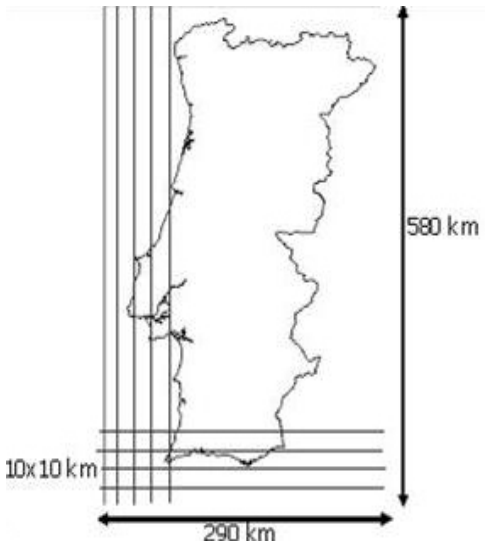
3.1 *Description and application of the modelling system*

The air quality modelling applications were performed with the CHIMERE chemistry-transport model (Schmidt *et al.*, 2001), forced by the MM5 meteorological fields (Dudhia, 1993), over Portugal with a horizontal dimension of 290 x 580 km^2 (Monteiro *et al.*, 2007).

This is an operational 3D chemistry transport model aimed to simulate air pollution in the lower troposphere. It was applied first at a continental scale, with 50 x 50 km^2 resolution (Figura 2a) and then over Portugal, using the same physics and a one-way nesting technique, with 10 x 10 km^2 horizontal resolution (Figura 2b).



a)



b)

Figure 2. European a) and Portuguese b) domain used by the air quality modelling system MM5-CHIMERE.

Input data necessary for CHIMERE model includes meteorological information (ex. wind velocity and direction, temperature and specific humidity and superficial pressure), emissions data, boundary conditions and also geomorphologic characterization (topography and land use).

CHIMERE was specifically developed for simulating gas-phase chemistry, aerosol formation, transport and deposition at European and urban scales. The model simulates the concentration of 44 gaseous species and 6 aerosol chemical compounds. The gas-phase chemistry scheme, derived from the original complete mechanism MELCHIOR, has been extended to include sulfur aqueous chemistry, secondary organic chemistry and heterogeneous chemistry of HONO and nitrate. The aerosol model accounts for both inorganic and organic species, of primary or secondary origin, as SOA (Monteiro *et al.*, 2007).

The vertical domain in the CHIMERE model was divided into 8 layers with an extension of 3,000 meters. It was used the most updated annual emission inventory (2003 year) developed by the Portuguese Agency for the Environment. Simpson *et al.* (1999) methodology was adopted to calculate biogenic emissions with the CHIMERE model. Time disaggregation was obtained by application of monthly, weekly and hourly profiles from the University of Stuttgart. For the European simulation emission data from the inventory of EMEP Program (Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe) for 2001, were used.

In this study we have coupled the fire emission data to model through the previously developed algorithm. Simulations were performed for August 2003, regarding gaseous and particulate pollutants. A baseline simulation (BS) was performed, including reference emissions, and a forest fire simulation (FS), which also considered emissions from forest fires larger than 1,000 hectares.

Hence, forest fire emissions values were added to the anthropogenic and biogenic grid emissions, according to the fire location and assuming a uniform fire spread and a constant injection altitude above 50 m in the MM5-CHIMERE system.

3.2 *Forest fire emissions estimation*

Forest fire emissions depend on multiple and interdependent factors. Variations in fuel characteristics and consumption may contribute to 30% uncertainties in estimates of wildfires emissions (Peterson, 1987; Peterson and Sandberg, 1988). This is a critical factor when describing forest fuels in the south-European forests, because available fuel mass depends on the location, fuel type and time of the year.

Burning efficiency is also a significant fire emissions factor, which is usually defined as the ratio of carbon released as CO_2 to total carbon present in the fuel. In laboratorial and field experiments, the burning efficiency can be expressed as the fraction burned related to the total biomass available.

Emissions from forest fires can be estimated using models. They are frequently estimated using a simplified methodology, which include emission factors, burning efficiency, fuel loads and area burned. Generically, emissions can be estimated through:

$$E_i = A \times B \times \beta \times EF_i \quad (1)$$

where, E_i – compound i emissions (g); A – area burned (m^2); B – fuel load ($kg.m^{-2}$); β – global burning efficiency; EF_i – compound i emission factor ($g.kg^{-1}$).The selected fuel load, emission factors and combustion efficiency for CO, CH_4, PM_{10}, non-metane hydrocarbons (NMHC) and NO_x are the most suitable for Mediterranean ecosystems namely for the Portuguese land use types (Table 2). This data was gathered under the scope of the SPREAD European Project (Miranda *et al.*, 2005).

The described approach allowed developing an algorithm to calculate forest fire emissions. They were estimated for the year 2003, for each large fire, and compared to anthropogenic emissions (Table 3) aiming to understand their potential contribution to the total values.

Forest fires can represent a significant percentage of the total annual emissions, reaching 40% for CO and CH_4 and 30% for CO_2 and PM_{10}.

Table 2. Fuel load, emission factors and combustion efficiency for Portuguese conditions (Miranda *et al*., 2005).

Fuel	Fuel load ($kg.m^{-2}$)	Combustion efficiency	Emission factor ($g.kg^{-1}$)						
			CO_2	CO	CH_4	NMHC	$PM_{2.5}$	PM_{10}	NO_x
Shrubs	1.00	0.80	1477	82	4	9	9	10	7
Resinous	8.60	0.25	1627	75	6	5	10	10	4
Deciduous	1.75	0.25	1393	128	6	6	11	13	3
Eucalyptus	3.90	0.25	1414	117	6	7	11	13	4

Table 3. Comparison between anthropogenic and forest fires emissions in Portugal, for 2003 year.

Activity source	Estimated emissions 2003 (t)						
	CO_2	CO	CH_4	NMHC	$PM_{2.5}$	PM_{10}	NO_x
Forest fires	22 167 772	456 858	25 773	31 616	25 773	53 440	21 194
Transports	19 472 820	315 265	35 660	62 847	9 849	9 877	130 109
Industry and Services	30 919 120	357 701	2 760	120 887	80 372	106 365	140 371
Forest fires/ total emissions (%)	30.6	40.4	40.2	14.7	22.2	31.5	7.2

3.3 *Modelling results*

Estimated emissions were included in the air quality model system using a numerical module developed for this purpose, which add the forest fire emissions to the anthropogenic and biogenic emissions, in each correspondent cell of the simulation grid. Fire spread simulation was considered uniform in all directions of each ignition point.

Modelling results were compared to background monitoring data of the national air quality network. Statistical parameters were used to evaluate the simulations results: root mean square error (RMSE), systematic error (BIAS) and correlation coefficient (r). Table 4 presents the model scores for both simulations (with and without forest fire emissions) for PM_{10} and O_3. Similarly to the statistical analysis, model results were analysed considering the averages for each district.

Table 4. Statistical analysis of models performance for BS and FS, for PM_{10} and O_3.

District	PM_{10}						O_3					
	RMSE ($\mu g.m^{-3}$)		BIAS ($\mu g.m^{-3}$)		r		RMSE ($\mu g.m^{-3}$)		BIAS ($\mu g.m^{-3}$)		r	
	BS	FS	BS	FS	BS	FS	BS	FS	BS	FS	BS	FS
Aveiro	35,8	33,6	28,1	26,7	0,67	0,73	40,5	40,3	-23,3	-26,1	0,75	0,75
Coimbra	52,1	48,7	43,0	39,4	0,75	0,77	28,4	25,2	13,8	9,5	0,85	0,88
Lisboa	30,2	27,2	27,3	24.2	0,83	0,86	14,7	14,9	5,8	5,5	0,94	0,92
Porto	17,4	15,8	5,6	5,2	0,77	0,82	40,9	29,4	28,4	-0,4	0,77	0,77
Santarém	43,8	34,2	-11,2	-6,4	0,73	0,75	37,8	34,0	-5,5	3,7	0,65	0,64
Setúbal	41,3	40,0	28,6	26,6	0,74	0,87	68,3	61,8	56,6	49,6	0,86	0,83
Average	22,7	21,0	-3,1	-2,4	0,67	0,71	24,1	27,9	-2,1	4,6	0,77	0,73

$RMSE = \sqrt{\sum_{i=1}^{N}(O_i - M_i)^2}$ $BIAS = \frac{1}{N}\sum_{i}^{N}(O_i - M_i)$ N is the number of samples, O_i are observations and M_i are model predictions

Model performance increase substantially when forest fire emissions are included, mainly regarding PM_{10}. In average correlation coefficients increase in average from 0.67 to 0.71 for PM_{10} and RMSE decreases 7 and 16% for PM_{10} and O_3, respectively.

The model system presents a tendency to underestimate O_3 and PM_{10} values. Nevertheless, both pollutants concentrations are overestimated in Porto and Setúbal districts (BIAS >0).

In what concerns O_3, there is a substantial number of districts where the impact of forest fires is overestimated, and the inclusion of its emissions did not improve the model performance. This could be explained by the presence of high concentration of aerosols, released by the forest fires, that significantly alter atmospheric radiative properties and decrease photolysis rates (Hodzic *et al.*, 2007), which was not taken into account in the present simulations.

The highest difference between both simulations was verified in Coimbra and Santarém districts, for PM_{10}, and in Setúbal, Porto and Santarém for O_3. These were the most affect districts in Portugal.

In order to contribute to the analysis of the spatial impact of forest fire emissions on the air quality Figure 3 shows the spatial differences between both simulations (FS-BS), concerning daily values for PM_{10} and O_3, for one of the most critical days (August, 3). The model results indicate a severe degradation of PM_{10} and O_3 levels due to forest fires, which can achieve PM_{10} daily averages higher than 200 $\mu g.m^{-3}$. For this specific day, the impact of forest fires is higher at the central inland part of Portugal, where air quality monitoring stations are not available.

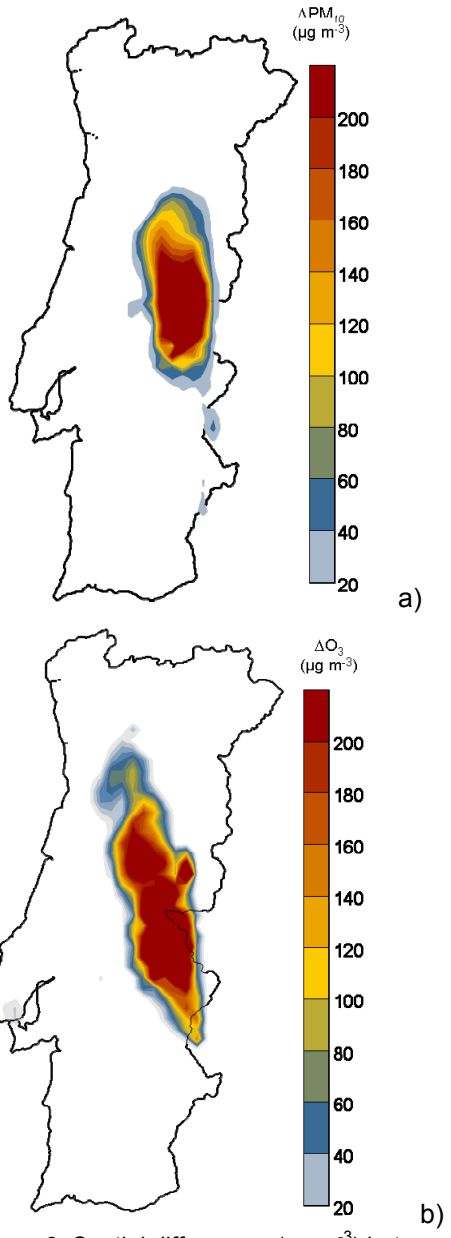


Figure 3. Spatial differences ($\mu g.m^{-3}$) between simulation with (FS) and without (BS) forest fire emissions, for PM_{10} daily averages (a) and O_3 daily maximum (b) on August 3rd, 2003.

4 FINAL REMARKS

This work investigated the relationship between forest fire activity and air quality in Portugal. Both statistical and numerical approaches applied in this work confirm the impact of forest fire emissions on atmospheric pollutants concentrations.

The 2003 year was analysed, at district level, and significant correlation coefficients were obtained. The O_3 daily maximum concentrations are highly correlated to the area burned and the number of fires, reaching 0.59 and 0.61, respectively. PM_{10} daily average also presents significant correlation coefficients especially in August.

The inclusion of forest fire emissions in the MM5-CHIMERE numerical system substantially improved model performance, with better statistical indicators.

The Chamusca station (Santarém district), that usually presents low pollution levels, is an example of this influence. It exhibits statically significant correlation factors between area burned and PM_{10} and O_3 concentration values of 0.95 and 0.80, respectively. Moreover, in this station a significant improvement of the model performance (in order of 10-15%) is verified when forest fire emissions are included.

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