2.3 FOREST FIRE EMISSIONS UNDER CLIMATE CHANGE: IMPACTS ON AIR QUALITY

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1 INTRODUCTION

Each summer, wildland fires burn a considerable area of the south European landscape. Most of the fires take place in the Mediterranean region, which suffers over 95% of the forest fire damage. Portugal is one of the European countries most affected by forest fires, mainly during the summer season, which is characterized by a hot and dry weather (EC, 2005).

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 significant amounts of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x), ammonia (NH_3), particulate matter (PM), non-methane volatile organic compounds (VOCs), sulphur dioxide (SO_2) and other chemical species (Miranda *et al.*, 2005a). The effects of these emissions are felt at different levels: from the contribution to the greenhouse effect to the occurrence of local atmospheric pollution episodes (Miranda *et al.*, 1994; Borrego *et al.*, 1999; Simmonds *et al.*, 2005). The air pollution episodes related to forest fire activity have been addressed by several studies worldwide (*e.g.* Hodzic *et al.*, 2007). In a changing climatic scenario forest fires may become an even larger source of air pollutants to the atmosphere (Amiro *et al.*, 2001; Carvalho *et al.*, 2007a).

The impact of climate change due to anthropogenic emissions on air quality is one of the main threats to the sustainable development particularly in what concerns human health and environmental resources. Several studies have been addressing this issue worldwide. Hauglustaine *et al.* (2005) suggest that ozone (O_3) could increase during the 21st century as a direct consequence of enhanced anthropogenic emissions of O_3 precursors like NO_x, CO and VOCs. An evaluation of the high-emissions IPCC SRES A2 (Nakicenovic *et al.*, 2000) emissions scenario showed global mean surface O_3 increases of about 5 ppb by 2030 and 20 ppb by 2100 (Prather *et al.*, 2003). Under the SRES-A2 scenario, Szopa *et al.* (2006) estimated that by 2030, O_3 July levels may increase up to 5 ppb over Europe. Based on the ensemble mean of 26 global atmospheric chemistry-transport models (CTMs), Dentener *et al.* (2006) predict that by 2030, global surface ozone may increase globally by 4.3±2.2 ppb for the IPCC SRES A2 scenario. The same study points out that the more polluting SRES A2 scenario would compromise attainment of any existing air quality standard in most industrialized parts of the world by 2030.

In a changing climatic scenario forest fire activity is predicted to increase in the Mediterranean region (Moreno *et al.*, 2005; Carvalho *et al.*, 2007b) leading to an increase of pollutants release to the atmosphere (Carvalho *et al.*, 2007a). The interaction between climate change, forest fires, area burned, air pollutants emissions and the associated influence on air quality is still poorly studied. In this sense, this work intends to evaluate the effect of a changing climate and future forest fire emissions on the air quality over Portugal.

2 DATA and METHODS

2.1 *Statistical analysis*

O_3 and particles with mean diameter lesser than 10 µm (PM_{10}) concentration values were measured at the air quality network stations between 1995 and 2005, and the area burned and number of fires, by district, were determined for the same period. We focused on three different periods: annual, June to September, and August. The daily area burned and the daily number of fires were correlated with the daily maximum O_3 concentration and daily average PM_{10}, registered in each air quality station, by district. Figure 1 presents the air quality stations used in this analysis.

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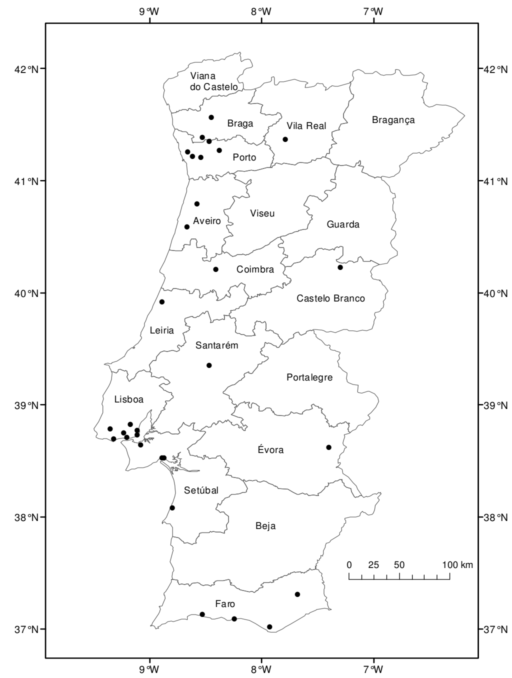
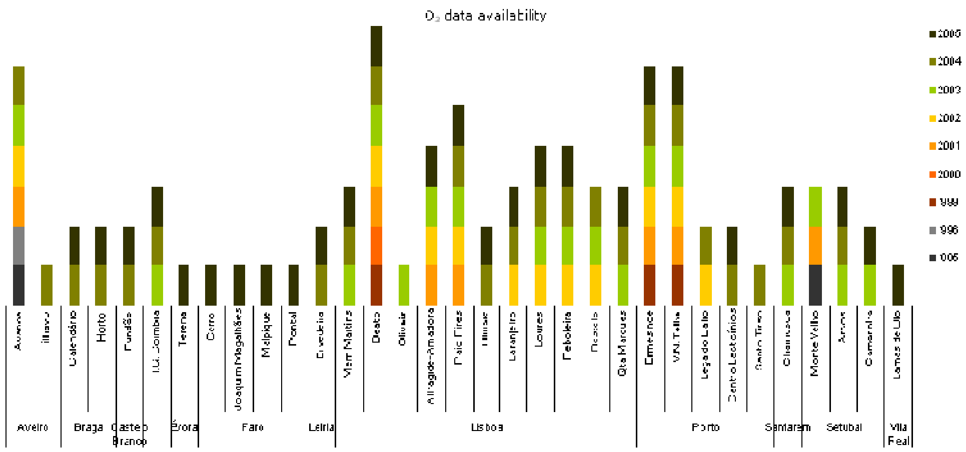


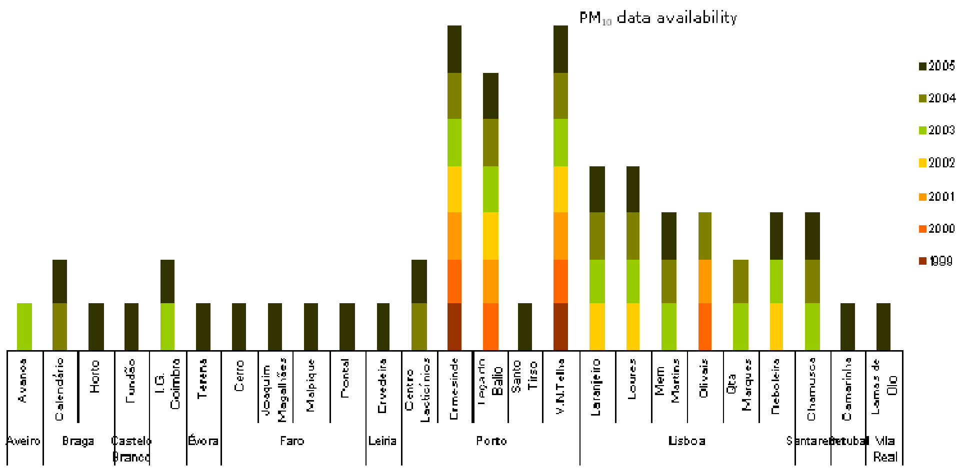
Figure 1. Air quality stations location (dot points) and Portuguese districts identification.

Air quality data were available at 12 districts in Portugal (Aveiro, Braga, Coimbra, Castelo Branco, Évora, Faro, Leiria, Lisboa, Porto, Santarém, Setúbal, Vila Real). For each district several air quality stations were considered except in Vila Real, Coimbra, Leiria, Castelo Branco, Santarém and Évora (Figure 1). Only the background stations were included in the analysis.

Figure 2 presents the data availability between 1995 and 2005 for O_3 and PM_{10} by station. Considering the monitoring station acquisition efficiency is 75% for O_3 (DL 320/2003) and 85% for PM_{10} (EC, 2002), the data availability is quite different among all the analysed background stations. Some of the stations, namely in Faro district, only have one year of data.



a)



b)

Figure 2. Data availability for O_3 a) and PM_{10} b), by station, for the 1995-2005 period.

In order to assess the pollutants' concentrations measured during the analysed period a brief analysis was conducted. The median of the O_3 maximum concentrations ranged between 75 and 100 µg.m^{-3} in all districts, except in Vila Real (Lamas de Olo station) where reaches 120 µg.m^{-3} (Figure 3). The maximum value is also attained at this measuring station 361 µg.m^{-3}, in 2005. Concerning PM_{10}, during this period the maximum value was attained at Leiria district (Ervedeira station), 360 µg.m^{-3} (Figure 3) and the percentile 75 was always below 50 µg.m^{-3}, except in Aveiro district.

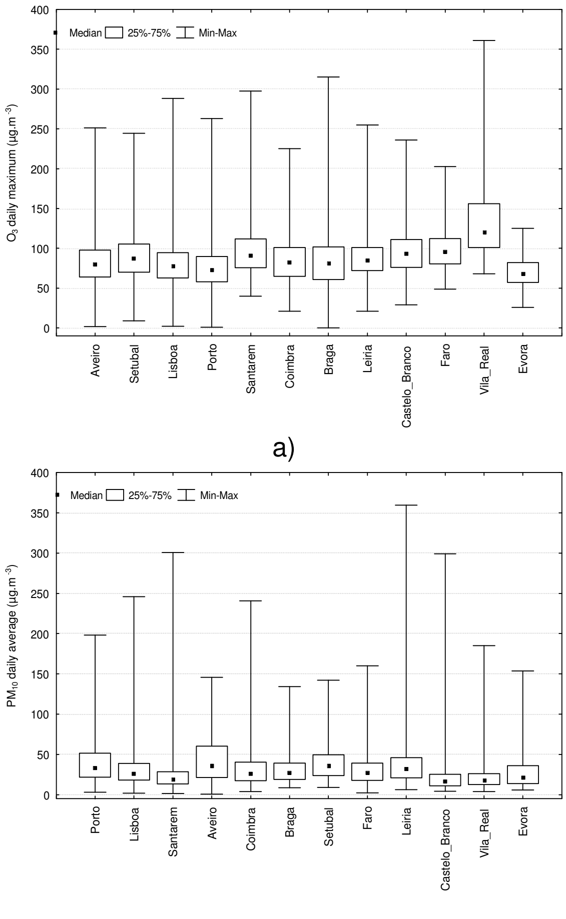


Figure 3. O_3 daily maximum concentration (µg.m^{-3}) a) and PM_{10} average concentration (µg.m^{-3}) b), by district, between 1995 and 2005

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 number of fires. All results are statistically significant at a 0.05 significance level.

2.2 *Area burned in a 2xCO_2 scenario*

Carvalho *et al.* (2007b) present the area burned projections for Portugal for the IPCC SRES A2 scenario. Here we describe a brief summary of the main results relevant for this work.

Daily climatic data were collected from the regional climate model HIRHAM (Christensen *et al.*, 1996) at two spatial resolutions, 12 km and 25 km, from the Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects – PRUDENCE – project (PRUDENCE, 2005), considering the SRES A2 scenario. The HIRHAM 12 km and 25 km climate scenarios were used to assess the fire weather under a 2 x CO_2 climate and to estimate future area burned in Portugal. Historical relationships between the area burned, the number of fires, the Canadian Fire Weather Index (FWI) System components (Van Wagner, 1987) and the weather were established for the 1980-2004 period. These relationships were applied under a climate change scenario in order to estimate future area burned, by district, in Portugal. At a 0.05 significance level there is no statistical significant difference between the area burned projections at 12 km and 25 km resolution. Table 1 presents the observed annual area burned for the 1980-1990 period along with the predicted area burned for each district and for all analyzed districts for the 2 x CO_2 scenario. The 1980-1990 period was used as the reference climate validation and was also considered in the area burned analysis. As there was not any statistically significant difference between HIRHAM 2 x CO_2/1 x CO_2 ratios at 12 km and 25 km, the area burned projection was based on the average ratios obtained from both simulations.

Table 1 presents a strong increase of area burned, particularly in Bragança and Porto districts showing increases of 643% and 606%, respectively. All districts exhibit increases in area burned above 250% except Lisboa (238%) district. In the 1980s Coimbra district already represented the higher percentage of contribution (20.9%) to the overall area burned in the 11 districts. In a 2 x CO_2 scenario Coimbra also presents the highest contribution to the total area burned and, in addition, this contribution also increases (23.2%). Almost all districts face an increase in the area burned percentage contributions to the total area burned except the districts of Lisboa and Santarém and the Southern region formed by Portalegre, Évora and Beja. Vila Real district shows a decrease in its contribution percentage. The results seem to point to a North/South dichotomy with higher increases in the North and Central part and lesser in the South.

Table 1. Annual area burned (ha) by district, observed in 1980-1990 period and predicted for the 2 x CO_2 climate, considering the average 2 x CO_2 /1 x CO_2 ratio between HIRHAM 12 km and HIRHAM 25 km simulations. Percent of total annual area burned by district for observed and 2 x CO_2 scenario and percent of increase in area burned in future scenario.

District	Annual area burned in 1980-1990		$2xCO_2$ area burned		$2xCO_2$/ observed (%)
	(ha)	(%)	(ha)	(%)	
Bragança	2804.5	5.3	20837.4	6.8	643
Vila Real	5717.1	10.8	29185.8	9.5	411
Porto	2970.5	5.6	20956.9	6.8	606
Viseu	9064.7	17.1	55022.7	18.0	507
Coimbra	11089.4	20.9	70861.3	23.2	539
Castelo Branco	6897.5	13.0	47523.8	15.5	589
Santarém	4160.6	7.9	22716.9	7.4	446
Lisboa	5717.1	10.8	19295.2	6.3	238
Portalegre, Évora and Beja	2017.6	3.8	8141.0	2.7	304
Faro	2500.9	4.7	11479.2	3.8	359
All districts	52939.9	100.0	306020.1	100.0	478

2.3 *Forest fire emissions estimation*

Forest fire emissions depend on multiple and interdependent factors such as forest fuel characteristics, burning efficiency, burning phase, fire type, weather and geographical location. Fuel type and load are one of the most important factors affecting fire emissions. Variations in fuel characteristics and consumption may contribute to 30 percent 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 are frequently estimated using a simplified methodology, which includes emission factors, burning efficiency, fuel loads and area burned. Generically, emissions can be estimated through:

$$E_i = A \times B \times \beta \times EF_i$$

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-methane 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 European Commission SPREAD Project - Forest Fire Spread Prevention and Mitigation (Miranda *et al.*, 2005b).

Forest fire emissions estimation, for reference and future scenario, was based on annual area burned presented in Table 1 and on data exhibited in Table 2. The ratio of shrub and forested lands burned during the 1980-1990 period, by district, was analysed and used to estimate reference and future fire emissions. The forest type distribution, by district, was also considered. Figure 4 presents forest fire emissions for reference and future scenarios.

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

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
Shrub	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

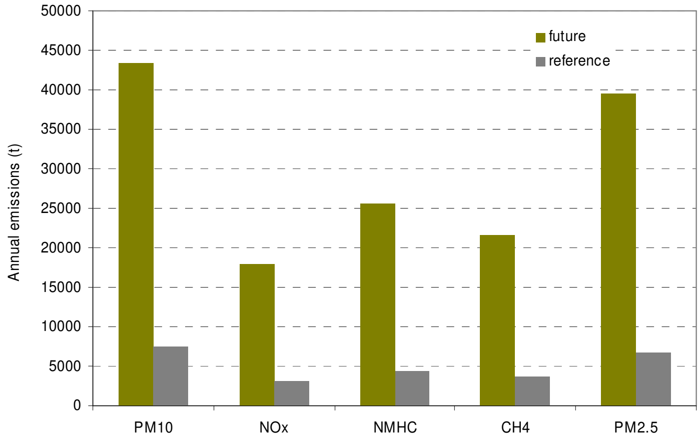


Figure 4. Annual emissions (t) for IPCC SRES A2 scenario and for the reference scenario (1980-1990).

2.4 *Air quality modelling*

The air quality modelling application was performed using the chemistry-transport model CHIMERE (Schmidt *et al.*, 2001; Bessagnet *et al.*, 2004), forced by the mesoscale model MM5 (Grell *et al.*, 1994). It was applied first at a continental scale with 50 x 50 km^2 resolution and then to mainland Portugal domain, using the same physics and a one-way nesting technique, with 10 x 10 km^2 horizontal resolution.

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 nitrous acid (HONO) and nitrate. The aerosol model accounts for both inorganic and organic species, of primary or secondary origin, as secondary organic aerosol (SOA). The CHIMERE model has been widely used in several air quality studies namely over Portugal (Monteiro *et al.*, 2007 Monteiro *et al.*, 2005) and also in climate change assessment studies (Szopa *et al.*, 2006).

The vertical domain in the CHIMERE model was divided into 8 layers with an extension of 3000 meters. For the European simulation emission data from the inventory of the EMEP Program (Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe) for 2001, were used. Over Portugal it was used the most recent annual emission inventory (2003 year) developed by the Portuguese Agency for the Environment. Methodology as in Simpson *et al.* (1999) was adopted to calculate biogenic emissions. Time disaggregation was obtained by application of monthly, weekly and hourly profiles from the University of Stuttgart.

The Fifth-Generation Penn State University/National Center for Atmospheric Research (PNU/NCAR) Mesoscale Model, known as the MM5, is a nonhydrostatic, vertical sigma-coordinate model designed to simulate mesoscale atmospheric circulations. MM5 has multiple nesting capabilities, availability of four-dimensional data assimilation (FDDA), and a large variety of physics options. The MM5 model has been used in several regional climate studies (Boo *et al*., 2004; Leung *et al*., 2004; Leung and Ghan, 1999)

Reference (1990) and SRES A2 climate scenario (2100) for Portugal were simulated by dynamical downscaling using the daily outputs of the global atmospheric climate model HadAM3P (Buonomo *et al*. 2006), as initial and boundary conditions to the MM5 model that then drives the CHIMERE air quality model. The Hadley Centre's HadAM3P is based on HadAM3H, an improved version of the atmospheric component of the latest Hadley Centre coupled AOGCM, HadCM3 (Gordon *et al*., 2000).

In order to better evaluate the influence of the future fire activity on air quality, the anthropogenic emissions were kept constant in both simulations over Portugal for the 2100 simulation. They were not scaled in accordance to the IPCC SRES A2 scenario. For Portugal the forest fire annual emissions were estimated for 1990 and for 2100 climates and then included in the CHIMERE model application. The annual forest fire emissions were uniformly distributed within each Portuguese district. Monthly and daily profiles of forest fire activity were considered in the emissions temporal disaggregation. For the reference simulation, the monthly profiles were estimated based on the monthly area burned registered between 1980 and 1990 in Portugal. The monthly area burned estimates between 2071 and 2100 were used to calculate the monthly profiles under the SRES A2 scenario. The hourly smoke emissions were constructed by applying the WRAP daily profiles (WRAP, 2005) since some studies suggest that biomass burning exhibits a pronounced diurnal cycle with peak emissions during early afternoon (12 -14 LST) and very low emissions during the night (Eck *et al*., 2003; WRAP, 2005).

3 RESULTS and DISCUSSION

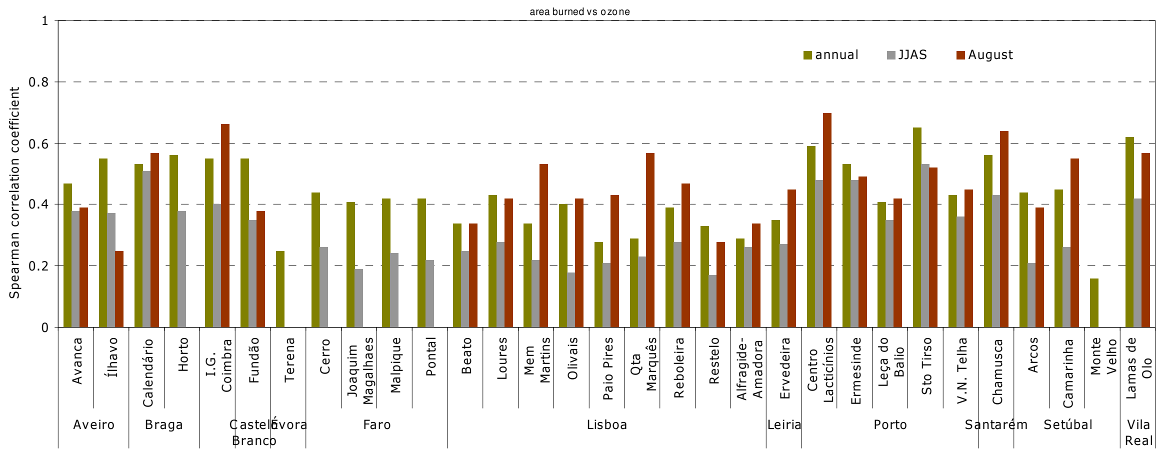
3.1 *Relationship between forest fires and atmospheric pollutants*

Figure 5 presents the Spearman coefficients for each station for the analysed time periods. The stations that do not present any value for a specific time period indicates that the obtained results were not statistically significant.

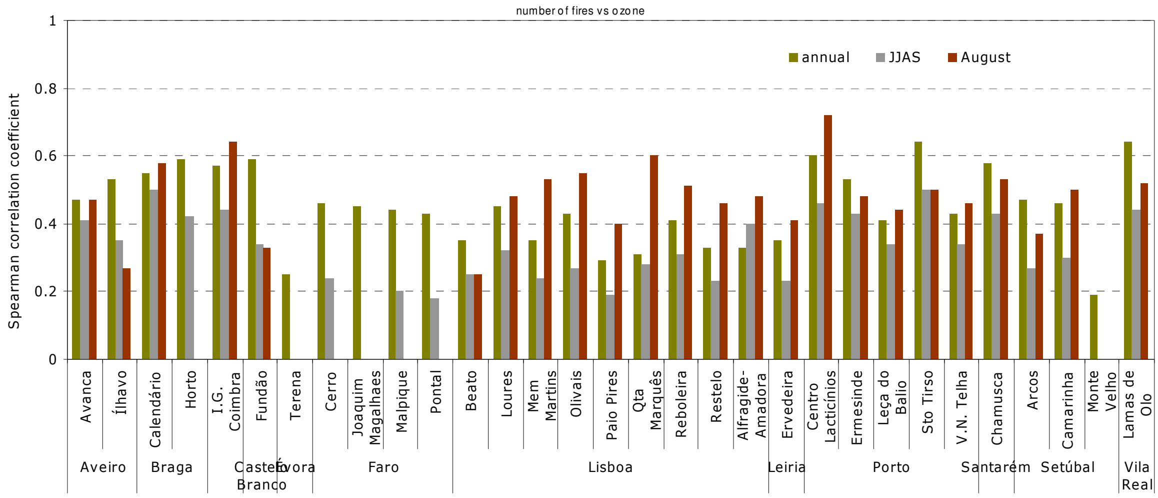
The relationship between O_3 maximum concentrations and fire activity presents higher Spearman coefficients with the number of fires than it does with the area burned (Figure 4). There is not a clear tendency about the time period for which the obtained correlations are the highest. Depending on the district, the Spearman coefficients are either higher on an annual basis or just in August. In Porto district, Centro de Lacticínios station presents the highest correlation with area burned and number of fires reaching 0.70 and 0.72, respectively.

Concerning the PM_{10} daily average the highest correlations are obtained for the number of fires and for August (not shown). All stations, except Lamas de Olo, in Vila Real district, exhibit an increase in the Spearman coefficients from the annual basis to the monthly analysis. The districts of Porto, Braga and Aveiro present the highest correlation coefficients between the PM_{10} daily average and the number of fires.

For the 1995 to 2005 period Porto district registered the highest number of forest fire occurrences accounting for 22% of the total, followed by Braga with 14% and Aveiro with 7%. The highest Spearman coefficients are obtained in August at Centro de Lacticínios (0.88), Calendário (0.71), Santo Tirso (0.70) and Chamusca (0.68) stations. It should be noted that the data availability at these stations (Figure 2) is reduced from one to three years maximum. The relationship between PM_{10} daily average and area burned is not as high. The highest correlations are also obtained for the month of August and the maximum value is also attained at Centro de Lacticínios (0.85) station in Porto district.



a)



b)

Figure 5. Spearman coefficient between the daily maximum O_3 concentration and the a) area burned and b) the number of fires, by station, between 1995 and 2005.

The results point to statistically significant correlations between fire activity in Portugal and PM_{10} and O_3 levels in the atmosphere. The same analysis was repeated just for the year of 2003. This year was the most severe in terms of fire activity in Portugal, consuming almost 430,000 ha of forested lands and shrublands (DGRF, 2006). The Spearman coefficients were higher, reaching the highest correlations in August for PM_{10} at Chamusca station (Santarém district) with 0.95 and 0.99 for area burned and number of fires, respectively. For O_3 daily maximum the correlation coefficient is also higher reaching 0.80 and 0.56 for area burned and number of fires, respectively.

3.2 *Forest fire impacts on air quality in a 2xCO$_2$ scenario*

Figure 6 presents the model system results regarding the monthly mean of surface O_3 changes in August between the 2100 climate and 1990 climate numerical simulations. Since the anthropogenic emissions have not been scaled in accordance to the SRES A2 scenario, the obtained changes in O_3 surface levels are only due to climate change. Climate-driven increases in temperature and water vapor tend to decrease surface O_3 in the cleanest regions but tend to increase O_3 in more polluted areas (Dentener *et al.*, 2006). The obtained modelling results show that the highest changes are observed over Central Europe registering O_3 increases of almost 30 $\mu g.m^{-3}$ (~15 ppb). Over the ocean, where the destruction due to water vapor prevails, O_3 decreases by up to 14 $\mu g.m^{-3}$. These results are in the same range of magnitude of those found by Hauglustine *et al.* (2005).

Figure 7 presents the hourly mean of surface ozone over Portugal in August for different simulation conditions, for 1990 climate, 2100 climate with 1990 fire emissions and 2100 climate and fire emissions, respectively.

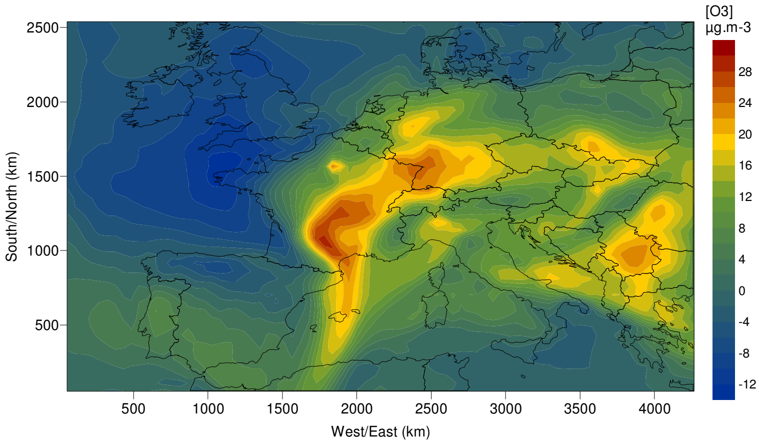


Figure 6. Monthly mean surface O_3 changes in August simulated over Europe with CHIMERE between 2100 climate and 1990 climate.

Between 15UTC and 19UTC the principal difference relies on the ozone concentrations that are attained. At 19UTC higher O_3 levels are estimated and this may be related to its photochemical origin and its formation/accumulation processes in the atmosphere. At both analyzed time periods it is possible to detect the increase of the ozone concentrations due to climate change and to climate change combined with future forest fire emissions. At 15UTC and 19UTC we can clearly detect the influence of the forest fire activity and climate change on the O_3 levels. At 15UTC, O_3 concentrations register an increase of almost 36 $\mu g.m^{-3}$ in the North and Centre part of the country only due to climate change (Figure 7b). This difference rises to 38 $\mu g.m^{-3}$ (Figure 7c) when future fire activity is considered. In addition, the plume with the highest ozone levels is more pronounced and extended influencing a larger region in the Centre of Portugal.

At 19UTC the reference simulation (Figure 7d) clearly shows the ozone consumption in Porto and Lisbon regions. The climate change simulation (Figure 7e) presents an enhancement in the O_3 levels of almost 140 $\mu g.m^{-3}$ (~70 ppb)in the central part of Portugal. This increase reaches 170 $\mu g.m^{-3}$ (~85 ppb) when climate change and future fire emissions are considered (Figure 7f). The Central part of Portugal registers the highest O_3 levels due mainly to higher area burned projections in this region. Coimbra district is one of the most affected districts due to forest fires in future climate presenting also significant air quality degradation.

Figure 8 presents the monthly average of surface PM_{10} in August over Portugal. When climate change and forest fire emissions are considered (Figure 8c) the highest differences are attained in Porto and Coimbra regions. The PM_{10} levels increase almost 19 $\mu g.m^{-3}$ in Porto and Coimbra areas. Climate change alone has an impact on PM_{10} atmospheric concentrations of 17 $\mu g.m^{-3}$ (Figure 8b). The pollution plume also attained higher values in larger regions comparatively to the reference simulation (Figure 8a).

There are some limitations in this study. Other climatic scenarios should be analysed and longer time periods should be simulated (*e.g.*, 5 years for each climate). The role of forest dynamics under climate change is another variable that should be studied and included in this analysis.

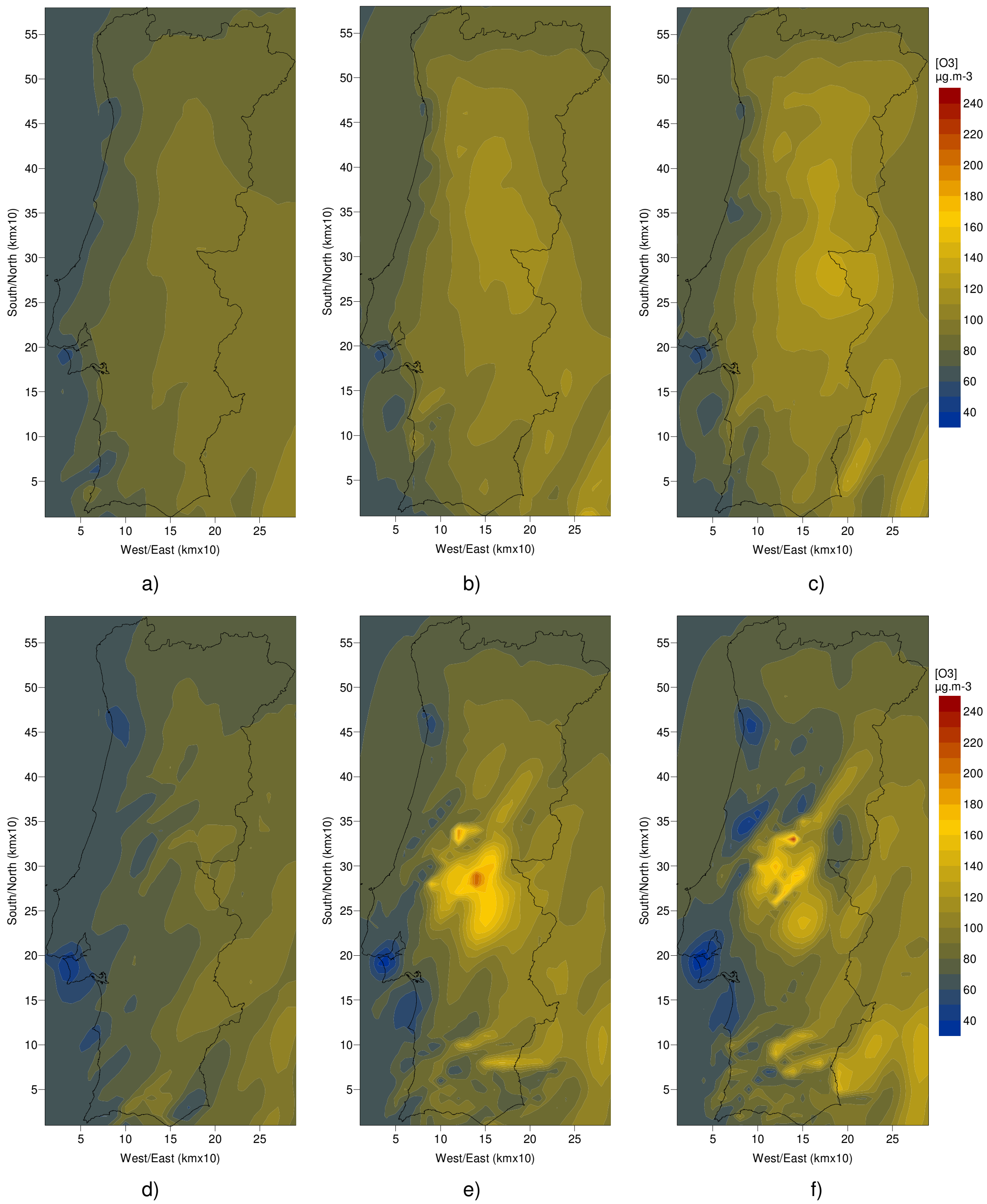


Figure 7. Hourly surface O_3 concentrations for August at 15 UTC (simulations a, b, and c) and at 19 UTC (simulations d, e, and f) for (a,d) 1990 climate, (b,e) 2100 climate and 1990 fire emissions, and (c,f) 2100 climate and fire emissions.

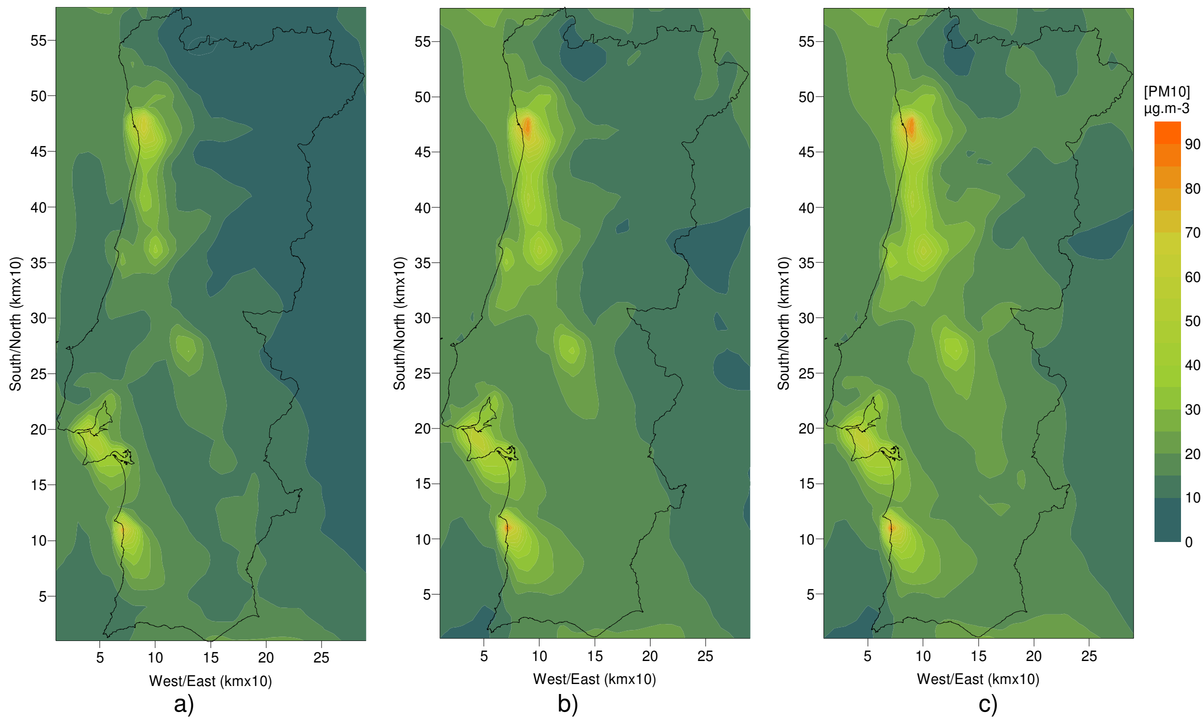


Figure 8. Monthly surface PM_{10} concentrations for August for (a) 1990 climate, (b) 2100 climate and 1990 fire emissions, and (c) 2100 climate and fire emissions.

4 FINAL REMARKS

This work investigated the impact of climate change and forest fire emissions on air quality over Portugal for the SRES A2 scenario. In addition, a statistical analysis was performed in order to assess the relationship between forest fire activity and air pollutants in the atmosphere.

Concerning the statistical analysis, the 1995-2005 period was analysed, at district level, and significant correlation coefficients were obtained. The O_3 maximum concentrations are highly correlated to the area burned and number of fires reaching 0.70 and 0.72, respectively, at Porto district. PM_{10} daily average also presents significant correlation coefficients especially in August in Porto district. It is clear, from this analysis, that there is a significant correlation between forest fire activity in Portugal and the concentration of air pollutants in the atmosphere.

The role of forest fire emissions in future climate scenario was another point of study. Projections of future area burned over Portugal point to increases of 238% to 643%, depending on the district. These projected increases will deeply impact future forest fire emissions. All districts suffer a substantial increase in PM_{10} emissions due to the projected increases on area burned. All analysed pollutants present increases in its emissions leading to greenhouse gases (GHGs) enhancement in the atmosphere.

For 2100, under the SRES A2 scenario, the O_3 monthly mean levels in the atmosphere may increase almost 15 ppb over Europe in August. This estimate only considers the impact of climate change because the anthropogenic emissions were kept constant. Over Portugal this increase may reach 70 ppb at 19UTC in August. If we also consider the influence of future forest fire activity the O_3 concentrations may rise to 85 ppb by 2100. Future forest fire emissions and climate change may intensely impact the O_3 air quality.

Concerning PM_{10}, climate change alone may increase the monthly mean values by almost 17 $\mu g.m^{-3}$ in August. This value rises to 19 $\mu g.m^{-3}$ when future forest fire emissions are also considered.

Numerical simulations performed with the MM5-CHIMERE air quality system pointed out that there may be a significant increase of O_3 and PM_{10} values under climate change conditions. This air quality degradation is even more pronounced when the effect of forest fire emissions is considered.

The understanding of climate change impacts and future fire activity may help the Portuguese authorities and policy-makers to develop and adapt mitigation plans namely in what concerns forest fire emissions and air quality management and its implications in international commitments, namely the Kyoto

Protocol, and subsequent impacts on human health and environmental resources.

Acknowledgements

The authors thank the Portuguese Foundation for Science and Technology for the Ph.D. grants of A. Carvalho (SFRH/BD/10882/2002) and A. Monteiro (SFRH/BD/10922/2002) and for the Project INTERFACE (POCI/AMB/60660/2004). ACCENT Network of Excellence (GOCE/CT/2004/505337) is also acknowledged. David Hein at the Met Office Hadley Centre, U.K., for the HadAM3P climate simulations. SAS Portugal is also acknowledged for the free software availability. Special thanks to Lynn Gowman for all valuable comments.

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