Forest fire emissions under climate change: an air quality perspective

Carvalho, A., Martins, V., Miranda, A.I. and Borrego, C.[1]

Abstract

The effects of forest fires emissions are felt at different levels: from the contribution to the greenhouse effect to the occurrence of local atmospheric pollution episodes. In a changing climatic scenario forest fires can become an even larger source of air pollutants to the atmosphere. A statistical analysis was made in order to establish the relationship between forest fires occurrences in Portugal, area burned and air pollutants concentrations in the atmosphere. Historical datasets of area burned, number of fires and ozone maximum concentrations and particulate matter daily average concentrations were evaluated from 1995 to 2005. Significant Spearman correlation coefficients were obtained between ozone maximum concentrations and particulate matter daily average concentrations and area burned and number of fires, at district level, over Portugal. The ozone maximum concentrations are highly correlated to the area burned and number of fires reaching 0.70 and 0.72, respectively, at Porto district. Area burned projections for the SRES-A2 climate scenario suggest substantial increases in several Portuguese districts leading to considerable amounts of pollutants released to the atmosphere. Forest fire emissions register substantial increases mainly in the North and Centre districts due to increases on area burned. CO_2 equivalent emissions point to a considerable contribution of these emissions to greenhouse effect.

Introduction

Each summer season wildland forest fires burn a considerable area of south European landscape, due to persistent extreme fire conditions, particularly critical in Portugal, where the area burned and number of fires in the last 26 years (1980-2005) was 461 685 ha and 2 714 574, respectively (EC, 2006). Smoke has to be considered as one of the several disturbing effects of forest fires. Its impacts on air quality and human health can be significant since large amounts of pollutants, like particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOC) and nitrogen oxides (NO_x), are emitted to the atmosphere (Ward and others, 1993; Reinhardt and others, 2001; Miranda and others, 2005a). The acute air pollution episodes caused by fires in Amazonia, Indonesia and Philippines in 1997, drawn worldwide attention to the problem. The effects of these emissions are felt at different levels: from the contribution to global climate change to the occurrence of local atmospheric pollution episodes (Miranda and others, 1994; Borrego and others, 1999; Simmonds and others, 2005). Currently, there is a growing awareness that smoke from wildland fires can expose individuals and populations to hazardous air pollutants. One of the concerns about forest fires impacts in the environment is related to the emission of greenhouse gases (GHGs), such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), and their contribution to the global climate

[1] CESAM & Department of Environment and Planning, University of Aveiro, 3810-193 Aveiro, Portugal

warming. A positive feedback between emissions and the occurrence of forest fires is possible to establish, because the release of GHGs from fires increases global warming, which, in turn, may cause more droughts that consequently may increase the severity and frequency of forest fires (Santos and others, 2002; Miranda and others, 2005b; Carvalho and others, 2007). The estimate of GHGs emissions released from forest fires is a significant environmental concern, but also is a political issue in the context of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. These estimates can have great importance at the regional level, namely for South-European countries, in which fires present high frequencies. The main purpose of this study is to establish the potential relationship between forest fires occurrences, area burned and air pollutants concentrations in the atmosphere, and to estimate forest fire emissions under future climate scenario in order to foresee its role on air quality under a changing climate.

Statistical analysis

The statistical analysis was based on the concentration values of ozone (O_3) and particulate matter measured at the air quality network between 1995 and 2005 and the area burned and 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 number of fires were correlated with the daily maximum ozone concentration and daily average PM with aerodynamic diameter below 10 µm (PM_{10}), registered in each air quality station, by district. 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 (*fig. 1*). Only the background stations were included in the analysis.

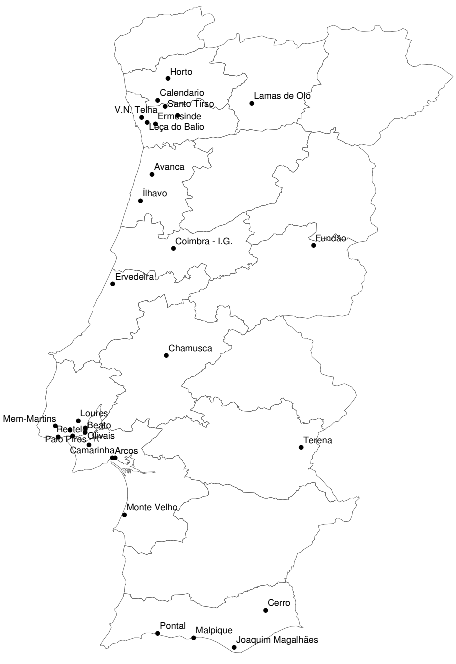
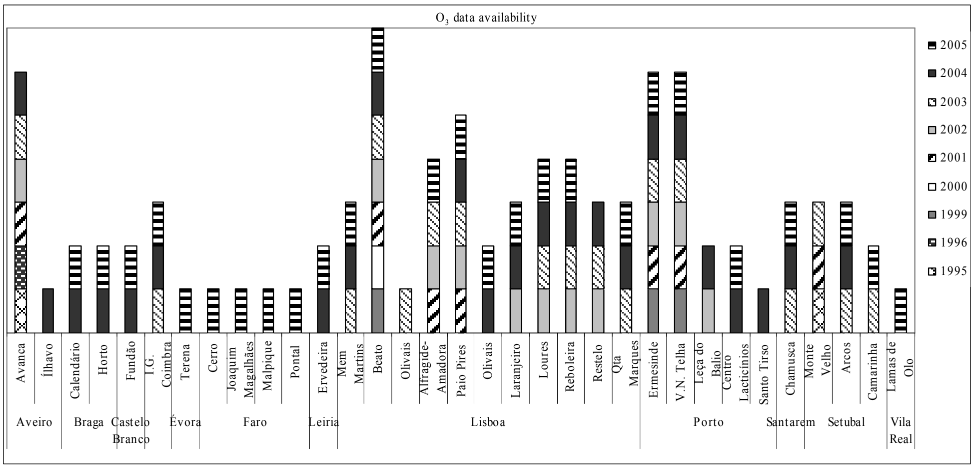
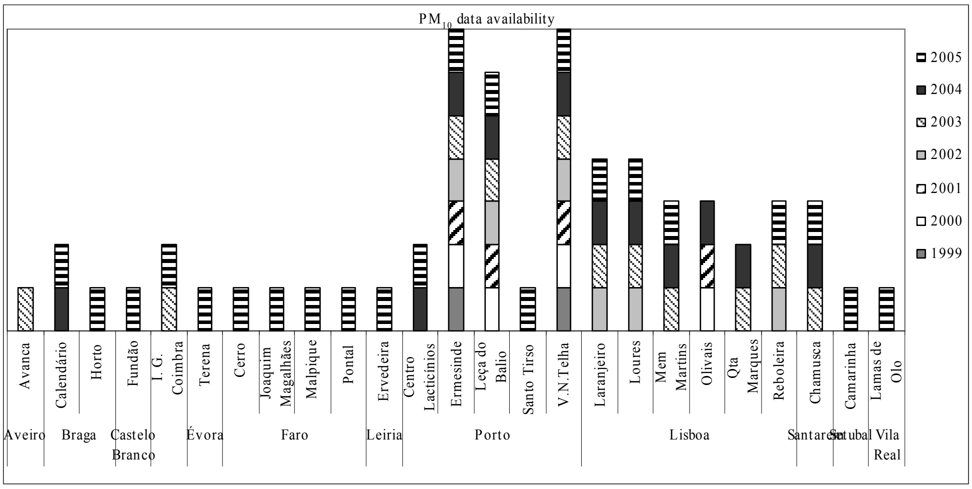


Figure 1—Air quality stations location.

Figure 2 presents the data availability between 1995 and 2005 for O_3 and PM_{10} by station. As can be noted and considering the measuring station acquisition efficiency of 75 percent for O_3 (DL 320/2003) and 85 percent 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.



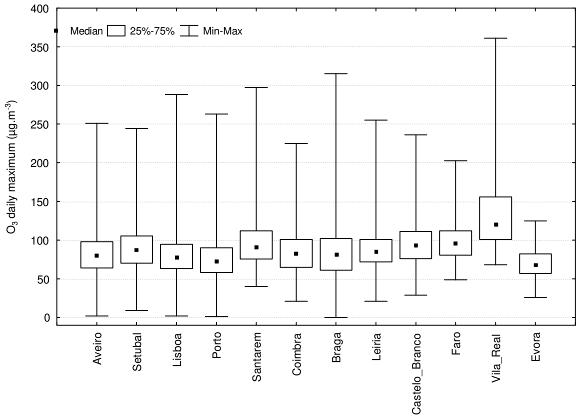
a)



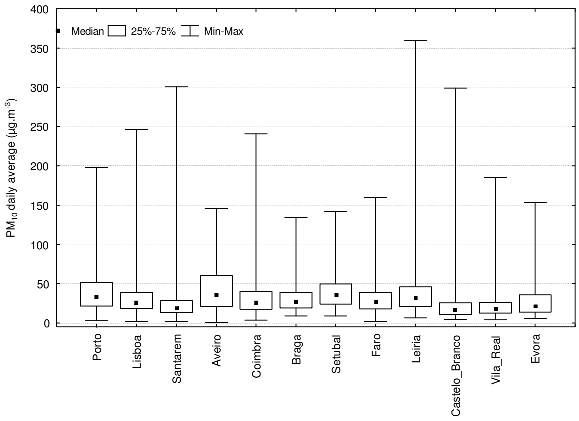
b)

Figure 2—Data availability for ozone a) and particulate matter 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 $\mu g.m^{-3}$ in all districts, except in Vila Real (Lamas de Olo station) where reaches 120 $\mu g.m^{-3}$ (*fig. 3*). The maximum value is also attained at this measuring station 361 $\mu g.m^{-3}$, in 2005. Concerning PM_{10}, during this period the maximum value was attained at Leiria district (Ervedeira station), 360 µg.m^{-3} (*fig. 3*) and the percentile 75 was always below 50 µg.m^{-3}, except in Aveiro district.



a)

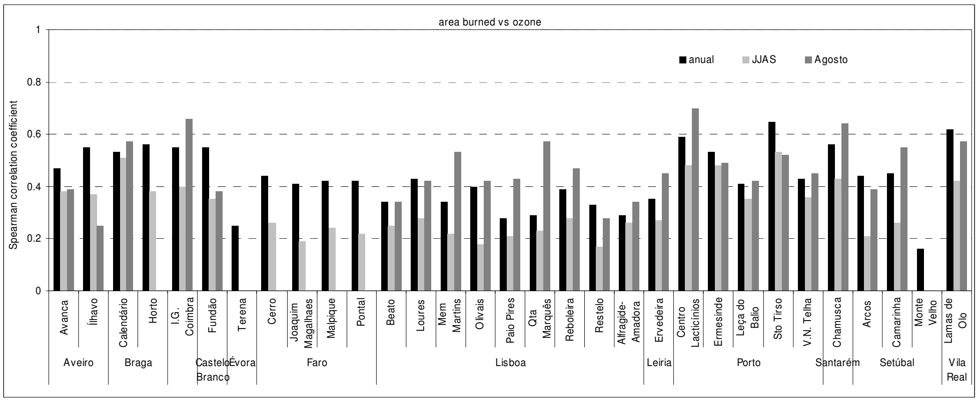


b)

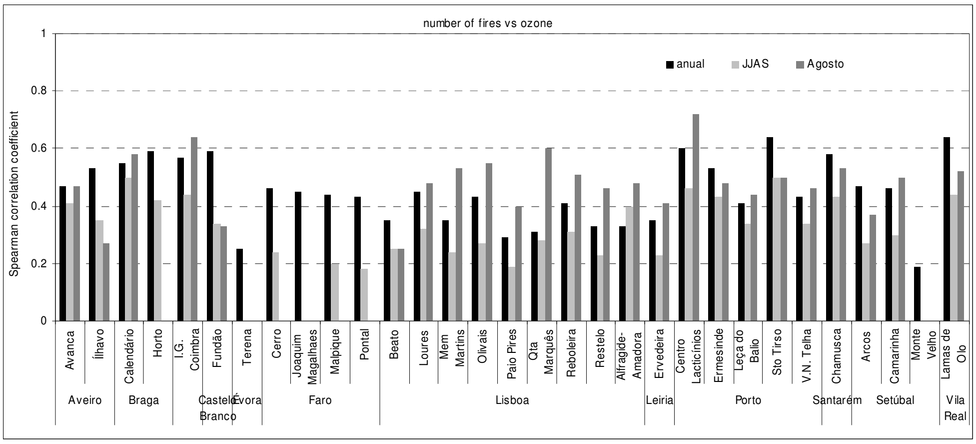
Figure 3—O_3 daily maximum concentration (µg.m^{-3}) a) and PM_{10} daily maximum concentration (µg.m^{-3}) b), by district, for the 1995-2005 period.

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. All results are statistically significant at a 0.05 significance level. Figures 4 and 5 present the obtained 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 comparatively to the area burned (*fig. 4*). There is not a clear tendency about the time period for which the obtained correlations are the best. Depending on the district, the Spearman coefficients are higher in annual basis or 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.



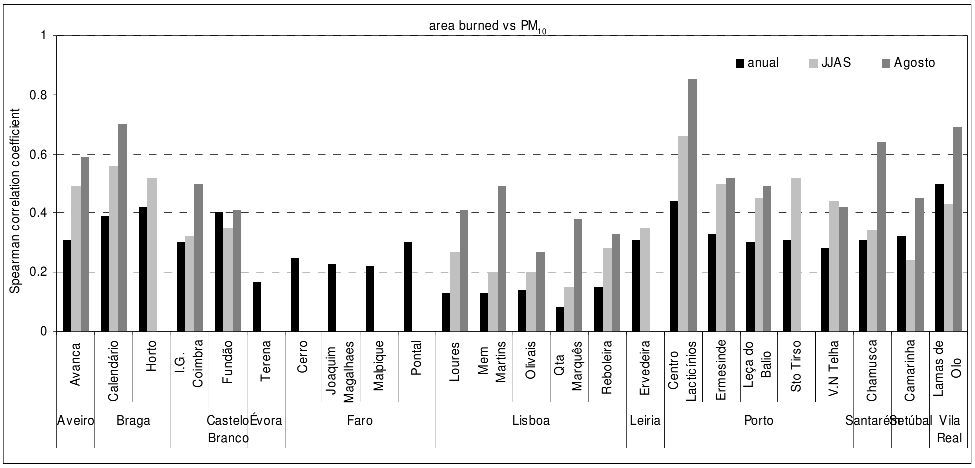
a)



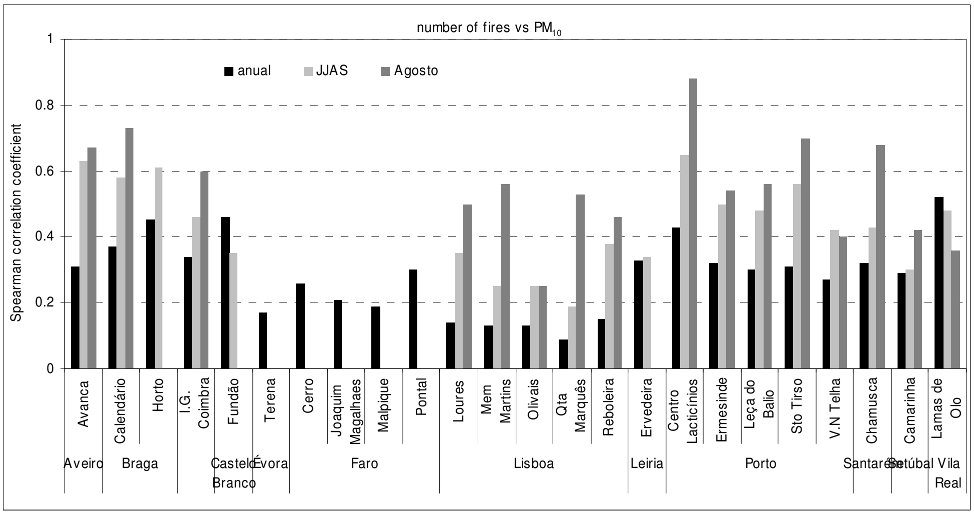
b)

Figure 4— Spearman coefficient between the maximum O_3 concentration and the area burned a) and the number of fires b), by station, for the analysed time periods.

Concerning the PM_{10} daily average the best correlations are obtained for the number of fires and for August (*fig. 5*). All stations, except Lamas de Olo, in Vila Real district, exhibit an increase in the Spearman coefficients from the annual basis to the month of August. 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 percent of the total, followed by Braga with 14 percent and Aveiro 7 percent. 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 (*fig. 2*) is reduced from one to three years maximum. The relationship between PM_{10} daily average and area burned is not as high. The best correlations are also obtained for the month of August and the maximum value is attained at Centro de Lacticínios (0.85) station in Porto district.



a)



b)

Figure 5—Spearman coefficient between the daily average PM_{10} concentration, and the area burned a) and the number of fires b), by station, for the analysed time periods.

The obtained 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. The obtained 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.

Area burned in a 2xCO_2 scenario

Carvalho and others (2007) present the area burned projections for Portugal for the A2-SRES 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 and others, 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 A2 SRES scenario (Nakicenovic and others, 2000). 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 and the number of fires and the Canadian Fire Weather Index (FWI) System (Van Wagner, 1987) components and the weather were establish for the 1980-2004 period. These relationships were applied under 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 all analyzed districts for the 2 x CO_2 scenario. The 1980-1990 period was used for the reference climate validation and was also considered in the area burned analysis. As there wasn't any statistical 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—*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)	(pct)	(ha)	(pct)	(pct)
Bragança	2804.5	5.6	20837.4	7.1	643
Vila Real	5717.1	11.3	29185.8	9.9	411
Porto	2970.5	5.9	20956.9	7.1	606
Viseu	9064.7	18.0	55022.7	18.7	507
Coimbra	11089.4	22.0	70861.3	24.1	539
Castelo Branco	6897.5	13.7	47523.8	16.1	589
Santarém	4160.6	8.2	22716.9	7.7	446
Lisboa	5717.1	11.3	19295.2	6.6	238
Portalegre, Évora and Beja (PEB)	2017.6	4.0	8141.0	2.8	304
All districts	50439.0	100.0	294541.0	100.0	484

Table 1 presents a strong increase of area burned particularly in Bragança and Porto districts showing increases of 643 percent and 606 percent, respectively. All districts exhibit increases in area burned above 250 percent except Lisboa (238 percent) district. In the 1980s Coimbra district already represented the higher percentage of contribution (22 percent) 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 (24.1 percent). 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.

Forest fire emissions estimation

Forest fire emissions depend on multiple and interdependent factors like forest fuels characteristics, burning efficiency, burning phase, fire type, meteorology 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. Emission factors are defined as mass of pollutant emitted per mass of burned fuel mass ($g.kg^{-1}$) or burned area (g or $kg.ha^{-1}$). Emissions from forest fires can be estimated using models. They are frequently based on a simplified methodology, which include emission factors, burning efficiency, fuel loads and area burned. The selected fuel load, emission factors and combustion efficiency for CO_2, CO, methane (CH_4), non-methane hydrocarbons (NMHC), PM with aerodynamic diameter below 2.5 µm ($PM_{2.5}$) PM_{10}, 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 and others, 2005b). 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 ($g.kg^{-1}$).

Table 2—*Fuel load, combustion efficiency and emission factors for Portuguese conditions (Miranda and others, 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

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. As an example, figure 6 presents PM_{10} emissions for both scenarios.

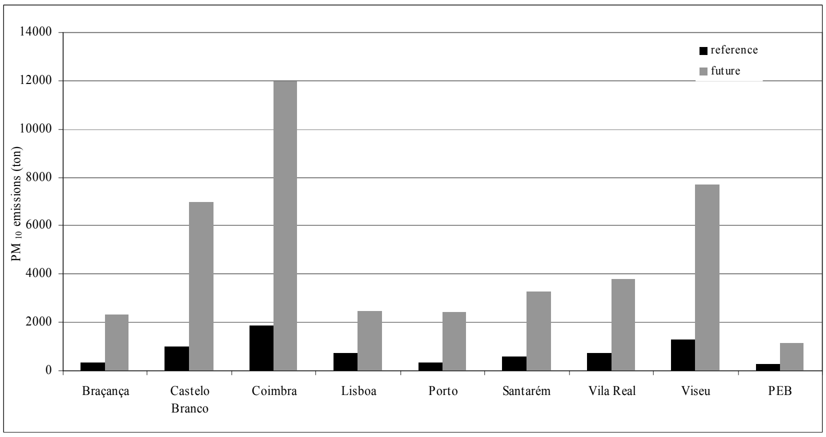


Figure 6—Annual PM_{10} emissions (ton) for a 2 x CO_2 scenario and for the reference scenario (1980-1990).

All districts suffer a substantial increase in PM_{10} emissions due to the projected increases on area burned (*fig.6*). All analysed pollutants present increases in its emissions leading to GHG enhancement in the atmosphere. CO, CO_2 and CH_4 emissions were converted in CO_2 equivalent emissions based on the global warming potential (GWP) for 100 years time horizon (IPCC, 1995) (*fig.7*).

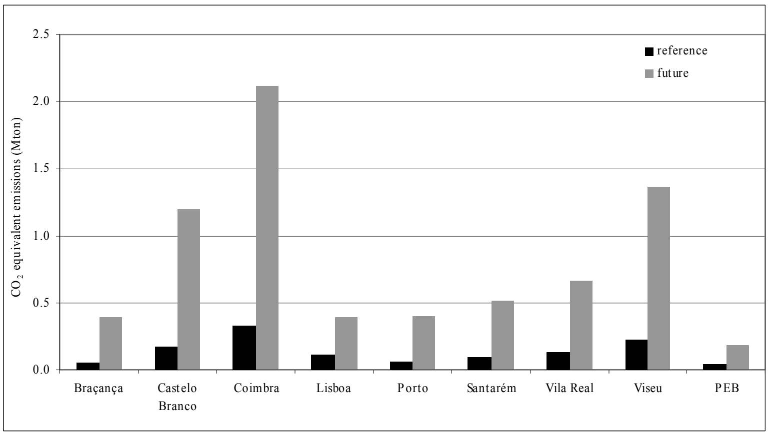


Figure 7—Annual CO_2 equivalent emissions (Mton) for a 2 x CO_2 scenario and for the reference scenario (1980-1990).

The annual CO_2 equivalent emissions derived from forest fires account for 1.2 Mton for the 1980-1990 period and 7.2 Mton in a 2xCO_2 scenario. This represents an overall increase of 500 percent.

The GHGs inventory that each EU Member State has to submit to the UNFCCC refers to six categories: energy, industrial processes, solvent and other product use, agriculture, land-use change and forestry (LUCF) and waste. According to the IPCC (2000), the LUCF category considers good practice to estimate CO_2 and non-CO_2 emissions from biomass burning on managed forestland. According to the methodology, in a large period of time (20 years) the net CO_2 flux may be zero, in the case the disturbed areas are reforested and the sink capacity restored. Although, in a shorter time period, the carbon release is not immediately recaptured by the forest re-growth, and the uptake of the quantity of carbon released in a fire by the forest re-growth may take several years. Such an estimate implies a better knowledge of the average carbon stocks and the evolution in time of the damaged areas. In this scope, the emissions from forest fires are still poorly accounted in the national inventories and this may represent a considerable error. Estimates of CO_2 equivalent emissions from LUCF show that this category was a net emitter in 1990 (3.8 Mton) and a carbon sink in 2004 (-2.5 Mton). The situation was temporarily inverted in 2003, when this source appeared as a net emitter (8.2 Mton), and which was due to the exceptional occurrences and extension, in that year, of forest fires (Ferreira and others, 2006).

There are some limitations in this study. Besides the climate change projections uncertainties, the land use patterns and main fuel characteristics were considered constant from reference to future scenario. Changes in fuel load were also not considered and thus not allowing for the carbon dioxide fertilization on vegetation. Only 11 of the 18 Portuguese districts were analysed.

Conclusions

This work investigates the relationship between forest fire activity and air quality in Portugal. 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 air pollutants concentrations in the atmosphere. The role of forest fires emissions in future climate scenario was another point of study. Projections of future area burned over Portugal point to increases from 238 percent to 643 percent, depending on the district. These projected increases can deeply impact future forest fire emissions. Estimates of CO_2, CO, CH_4, NMHC, $PM_{2.5}$, PM_{10} and NO_x emissions point to substantial increases in future climate. The estimated annual CO_2 equivalent emissions range from 0.5 to 2 Mton released to de atmosphere from forest fires activity. The potential impact of these emissions in climate change enhancement and air quality episodes constitutes an important research issue. Prevention strategies and adequate management plans will play a crucial role against the natural conditions, namely meteorology, that in future climate will favour forest fires activity. The understanding of future fire activity can help the Portuguese authorities and policy-makers to adapt and develop mitigation plans namely in what concerns forest fires emissions and its implications in international commitments, namely the Kyoto Protocol, and subsequent impacts on air quality and human health.

Acknowledgements

The authors thank the Portuguese Foundation for Science and Technology for the Ph.D. grant of A. Carvalho (SFRH/BD/10882/2002). Projects QUIMERA (POCTI/34346/CTA/2000) and INTERFACE (POCI/AMB/60660/2004) are also acknowledged. The authors are also thankful to Miguel Cruz at the General Directorate of Forestry Resources, Portugal, for the forest fire data provided. Acknowledges to SAS Portugal for the free software availability and to the Caloust Gulbenkian Foundation for financial support. ACCENT Network of Excellence (GOCE/CT/2004/505337) is also acknowledged.

References

Borrego, C.; Miranda, A.I.; Carvalho, A.C., Carvalho, A. 1999. **Forest fires and air pollution: A local and a global perspective.** In: Proceedings of the 'Air Pollution VII'. Eds C Brebbia, M Jacobson, H Power, WIT Press: Boston, 741-750.

Carvalho, A.; Flannigan, M.; Logan, K.; Miranda A.I.; Borrego, C. 2007. **Climate change impacts on area burned and number of fire starts in Portugal**. Climatic Change, submitted

Christensen, J.H.; Christensen, O.B.; Lopez, P.; van Meijgaard, E.; Botzet, M. 1996. **The HIRHAM4 Regional Atmospheric Climate Model**. Scientific Report 96-4, DMI, Copenhagen.

Decreto-Lei nº 320/2003, de 20 de Fevereiro, transposing the European Commission Directive 2002/3/EC relative to ozone in ambient air. Ministério das Cidades, Ordenamento do Território e Ambiente.

EC – European Commission, Schmuck, G.; San-Miguel-Ayanz, J.; Barbosa, Camia, A.; Kucera, J.; P., Libertà, G. 2006. **Forest Fires in Europe - 2005 fire campaign**. Official Publication of the European Communities; EUR 22312 EN.

EC – European Commission. 2002. **Guidance on the Annexes to Decision 97/101/EC on Exchange of Information as revised by Decision 2001/752/EC** for the European Commission, DG Environment, 2002.

Ferreira, V.G.; Pereira, T.C.; Seabra, T.; Torres, P.; Maciel, H. 2006. **Portuguese National Inventory Report on Greenhouse Gases, 1990-2004** Submitted under the United Nations Framework Convention on Climate Change. Eds. Institute for the Environment, Amadora, Portugal, 614 pp.

IPCC – Intergovernmental Panel on Climate Change. 2000. **Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.**

IPCC – Intergovernmental Panel on Climate Change. 1995. **Climate Change 1995, The Science of Climate Change: Summary for Policymakers and Technical Summary of the Working Group I Report.**

Miranda, A.I.; Ferreira, J.; Valente, J., Santos; P., Amorim, J.H.; Borrego, C. 2005a. **Smoke measurements during Gestosa 2002 experimental field fires**. International Journal of Wildland Fire 14, 107–116.

Miranda, A.I.; Borrego, C.; Sousa, M.; Valente, J.; Barbosa, P.; Carvalho, A. 2005b. **Model of Forest Fire Emissions to the Atmosphere**. Deliverable D252 of SPREAD Project

(EVG1-CT-2001-00043). Department of Environment and Planning, University of Aveiro AMB-QA-07/2005, Aveiro, Portugal, 48 pp.

Miranda, A.I.; Coutinho, M.; Borrego, C. 1994. **Forest fires emissions in Portugal: a contribution to global warming?** Environmental Pollution 83, 121-123.

Nakicenovic, N.; Alcamo, J.; Davis, G.; de Vries, B.; Fenhann, J.; Gaffin, S.; Gregory, K.; Grübler, A.; Jung, T. Y.; Kram, T.; La Rovere, E. L.; Michaelis, L.; Mori, S.; Morita, T.; Pepper, W.; Pitcher, H.; Price, L.; Raihi, K.; Roehrl, A.; Rogner, H-H.; Sankovski, A.; Schlesinger, M.; Shukla, P.; Smith, S.; Swart, R.; van Rooijen, S.; Victor, N.; Dadi, Z. 2000. **IPCC Special Report on Emissions Scenarios**, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 599 pp.

Peterson, J.; Sandberg, D. 1988. **A national PM10 inventory approach for wildfires and prescribed fires**. In: Proceedings of the PM10 implementation of standards: an APCA/EPA International Specialty Conference. Eds C Mathai; D Stonefield: San Francisco: CA.

Peterson, J. 1987. **Analysis and reduction of the errors of predicting prescribed burn emissions**. Seattle: University of Washington; Ph.D. Thesis.

PRUDENCE. 2005. **Prediction of regional scenarios and uncertainties for defining European climate change risks and effects**. Copenhagen. http://prudence.dmi.dk.

Reinhardt, E.; Ottmar, R.; Castilla, C. 2001. **Smoke Impacts from Agricultural Burning in a Rural Brazilian Town**. Journal of the Air & Waste Management Association 51, 443-450.

Santos, F.D.; Forbes, K.; Moita, R. 2002. **Climate Change in Portugal. Scenarios, Impacts and Adaptation Measures – SIAM Project**, Gradiva, Lisboa, Portugal, 454 pp.

SAS Institute Inc. 2004. SAS OnlineDoc®, Version 9.1.3, SAS Institute Inc., Cary, NC.

Simmonds, P.G.; Manning, A.J.; Derwent, R.G.; Ciais, P.; Ramonet, M.; Kazan, V.; Ryall, D. 2005. **A burning question. Can recent growth rate anomalies in the greenhouse gases be attributed to large-scale biomass burning events?** Atmospheric Environment 39, 2513-2517.

Van Wagner, C.E. 1970. **Conversion of Williams severity rating for use with the fire weather index**. Can. Dep. Fisheries and For., Petawawa Forest Expt. Stn., Information Report PS-X-21. Petawawa.

Ward, D.; Rothermel, R.; Bushey, C. 1993. **Particulate Matter and Trace Gas Emissions from the Canyon Creek Fire of 1988.** Proceedings of the 12th Fire and Forest Meteorology. Eds Society of American Foresters. pp. 62-76.