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Forest fires in a changing climate and their impacts on air quality

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ABSTRACT

In a future climate scenario forest fire activity over Portugal will substantially increase and consequently area burned and forest fire emissions to the atmosphere are also expected to increase. This study investigated the impact of future forest fire emissions on air quality over Portugal under the IPCC SRES A2 scenario. Reference and future climate change scenarios were simulated using the MM5/CHIMERE air quality modelling system, which was applied over Europe and over Portugal, using nesting capabilities. The initial and boundary conditions were provided by the HadAM3P model simulations for the reference and the future climate. The forest fire emissions were estimated using a methodology, which included the selection of emission factors for each pollutant, burning efficiency, fuel loads and the predicted area burned. These emissions were added to the simulation grid using specific parameterizations for their vertical distribution. Modelling results for Portugal pointed out that future forest fire activity will increase the O_3 concentrations of almost 23 μg m^{-3} by 2100 but a decrease of approximately 6 μg m^{-3} is detected close to the main forest fire locations. Future forest fire emissions will also impact the PM10 concentrations over Portugal with increases reaching 20 μg m^{-3} along the Northern coastal region in July. The highest increases are estimated over the north and centre of Portugal where the area burned projections in future climate are higher.

1. Introduction

Since the late 70s biomass burning has been recognized an important source of atmospheric pollutants (Crutzen et al., 1979) and in a changing climatic scenario this contribution can increase dramatically (Amiro et al., 2001) due to a larger area consumed by wildland forest fires. The impacts on air quality and human health can be relevant because large amounts of compounds are emitted into the atmosphere, namely carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x), ammonia (NH_3), particulate matter (PM), non-methane hydrocarbon (NMHC), and other chemical species (Crutzen and Andreae, 1990; Miranda et al., 2005a). The effects of these emissions are felt at different levels: from the contribution to the greenhouse effect (Miranda et al., 1994; Simmonds et al., 2005) to the occurrence of local atmospheric pollution episodes (Miranda, 2004; Hodzic et al., 2007; Miranda et al., 2009). Forest fire emissions can also affect the ecosystems, and in particular they can influence plant productivity downwind of fires through enhanced ozone (Sitch et al., 2007) and aerosol concentrations (Singh et al., 2010).

Fire activity is influenced by a number of factors including fuels, management, and climate/weather. Worldwide significant relationships between fire activity and weather have been established. The Intergovernmental Panel on Climate Change report (IPCC, 2007) suggests that, with global warming, forest fires frequency will increase all over the world. Moreover, several studies point that global warming is likely to increase fire frequency and severity (e.g., Flannigan et al., 2005; Moriondo et al., 2006). Over Portugal, where weather has been found to be the most important factor influencing forest fires (Carvalho et al., 2008; Hoinka et al., 2009), global warming will deeply impact fire activity namely area burned (Carvalho et al., 2010a). Projections indicate that by the end of the 21st century the area burned may increase almost 500% under the IPCC SRES A2 scenario (Nakicenovic et al., 2000). In this sense, in a changing climatic scenario forest fires may become an even larger source of air pollutants to the atmosphere (Carvalho et al., 2007).

The interaction between climate change, forest fires activity, air pollutant emissions and the associated impacts on air quality is still poorly studied. Spracklen et al. (2009) investigated the potential impacts of future area burned on aerosol concentrations over the United States. Using a global chemical transport model Spracklen

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et al. (2009) have estimated that climate change will increase summertime organic carbon (OC) aerosol concentrations over the western United States by 40% and elemental carbon (EC) concentrations by 20% from 2000 to 2050. Most of this increase (75% for OC and 95% for EC) is caused by larger wildfire emissions with the rest caused by changes in meteorology and for OC by increased monoterpene emissions in a warmer climate.

This study intends to assess the effects of future forest fire emissions on the air quality over Portugal. The MM5/CHIMERE (Grell et al., 1994; Schmidt et al., 2001) air quality modelling system has been applied. The climate change projections were driven by the HadAM3P (Jones et al., 2005) model simulations. Emissions of forest fires were estimated, for reference and future climate, using an already tested methodology (Miranda et al., 2005b) and included in the air quality simulation using specific parameterizations for their vertical distribution (Hodzic et al., 2007).

2. Methodology

The air quality modelling was performed, for a reference (year 1990) and a future climate scenario (year 2100), first at the European scale and then over Portugal. The HadAM3P simulation results for the reference and the IPCC SRES A2 climate scenario were used to drive the air quality modelling system. The global IPCC SRES A2 scenario family represents a differentiated world, in terms of social and political structures. It is considered to be the highest emission scenario and has been used in a previous work to forecast forest fire activity for Portugal under climate change conditions (Carvalho et al., 2010a). The forest fire emissions for both scenarios were estimated based on the 1990 area burned observations and on the 2100 area burned projections (Carvalho et al., 2010a) and included in the air quality simulations over Portugal.

2.1. Air quality modelling

The air quality modelling system is based on the chemistry-transport model CHIMERE (Schmidt et al., 2001; Bessagnet et al., 2004) forced by the mesoscale meteorological model MM5 (Grell et al., 1994). The MM5/CHIMERE modelling system has been widely applied and validated in several air quality studies over Portugal (Monteiro et al., 2005, 2007; Borrego et al., 2008), showing performance skills within the range found in several model evaluation studies using different air quality models (Vautard et al., 2007; Stern et al., 2008). This modelling system has also been applied during the summer of 2003 when severe forest fires have contributed to high ozone and particulate matter levels in the atmosphere over Portugal (Miranda et al., 2007) and over Europe (Hodzic et al., 2007). In addition, the MM5/CHIMERE modelling system has already been used in several studies that investigated the impacts of climate change on air pollutants levels over Europe (Szopa et al., 2006) and specifically over Portugal (Carvalho et al., 2010b).

The MM5 mesoscale model 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 selected MM5 physical options were based on the already performed validation and sensitivity studies over Portugal (Carvalho et al., 2006) and over the Iberian Peninsula (Fernández et al., 2007). A detailed description of the selected simulation characteristics is presented in Carvalho et al. (2010b). The MM5 model generates the several meteorological fields required by CHIMERE model, such as wind, temperature, water vapour mixing ratio, cloud liquid water content, 2 m temperature, surface heat and moisture fluxes and precipitation.

CHIMERE is a tri-dimensional chemistry-transport model, based on the integration of the continuity equation for the concentrations of several chemical species in each cell of a given grid. It was developed for simulating gas-phase chemistry (Schmidt et al., 2001), aerosol formation, transport and deposition (Bessagnet et al., 2004; Vautard et al., 2005) at regional and urban scales. CHIMERE simulates the concentration of 44 gaseous species and 6 aerosol chemical compounds. The aerosol model accounts for both inorganic and organic species, of primary or secondary origin, such as primary particulate matter (PPM), sulfates, nitrates, ammonium, secondary organic species (SOA) and water. The needed meteorological input variables driven by the MM5 model are linearly interpolated to the CHIMERE grid. In addition to the meteorological input, the CHIMERE model needs boundary and initial conditions, emission data, and the land use and topography characterization.

The modelling system was firstly applied at the European scale (with 50×50 km^2 resolution) and then over Portugal using the same physics and a simple one-way nesting technique, with 10×10 km^2 horizontal resolution. The European domain covers an area from 14°W to 25°E and 35°N to 58°N. Over Portugal the simulation domain goes from 9.5°W to 6°W and 37°N to 42.5°N (Carvalho et al., 2010b).

The vertical resolution of CHIMERE model consists of eight vertical layers of various thicknesses extending from ground to 500 hPa, with the first layer at 50 m. Lateral and top boundaries for the large-scale run were obtained from the LMDz-INCA (gas species) (Hauglustaine et al., 2005) and GOCART (aerosols) (Chin et al., 2002) global chemistry-transport models, both monthly mean values. The same boundaries conditions were used for both scenarios, since the objective is to only change the forest fire emissions and the meteorological driver forcing Transport of Saharan dust from the GOCART boundary conditions (Ginoux et al., 2001), as well as within-domain erosion, are considered using the formulation of Vautard et al. (2005). For the Portugal domain, boundary conditions are provided by the large-scale European simulation.

The CHIMERE model requires hourly spatially resolved emissions for the main anthropogenic gas and aerosol species. For the simulation over Europe, the anthropogenic emissions for NO_x, CO, sulphur dioxide (SO_2), NMHC and NH_3 gas-phase species, and for PM2.5 and PM10 are provided by EMEP (Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe) (Vestreng, 2003) with a spatial resolution of 50 km. The national inventory INERPA was used over the Portugal domain (Monteiro et al., 2007). This inventory takes into account annual emissions from line sources (streets and highways) using a bottom-up approach, large point sources with available monitoring data at each industrial plant and also area sources (industrial and residential combustion, solvents and others) estimated through a top–down methodology in order to obtain emission data with sub-municipality resolution (<5 km^2). Time disaggregation was considered through the application of monthly, weekly, and hourly profiles obtained in the scope of the GENEMIS Project (Monteiro et al., 2007).

Biogenic emissions were also included. The non-methane volatile organic compounds are disaggregated into 227 individual species. The methodology for biogenic emissions of isoprene and terpenes is described in Schmidt et al. (2001). The land use database comes from the Global Land Cover Facility (Hansen et al., 2000), providing the grid cell coverage of coniferous and broadleaf forests. The Stohl et al. (1996) methodology is used for biogenic emissions of nitrogen monoxide (NO) from fertilized soils. These biogenic emissions were kept constant for the reference and the future climate simulations, since the main purpose of this study is to evaluate the impact of forest fires emissions only.

Reference (year 1990) and the IPCC SRES-A2 climate scenario (year 2100) over Europe and over Portugal were simulated by dynamical downscalling using the outputs of HadAM3P (Jones et al., 2005), as initial and boundary conditions to the MM5 model. The Hadley Centre's HadAM3P (2.5° latitude by 2.5° longitude resolution) is a successor version of the HadAM3H model (Pope et al., 2000; Jones et al., 2001), that is an improved version of the atmospheric component of the latest Hadley Centre coupled Atmosphere-Ocean General Circulation Model (AOGCM), HadCM3 (Gordon et al., 2000). The sea surface temperatures (SSTs) used in the HadAM3P reference simulation were taken from a gridded data set of monthly mean observations covering the period 1960–1990 (Jones et al., 2003). The climate change simulation used SSTs from an existing HadCM3 simulation applying the obtained monthly anomalies to the 30 year averaged gridded monthly mean observed climatology. The HadAM3P simulations for reference and future climatic scenarios are freely available through the Met Office Hadley Centre, United Kingdom.

The MM5 model requires initial and time evolving boundary conditions for wind components, temperature, geopotential height, relative humidity, surface pressure and also the specification of SSTs. Carvalho et al. (2010b) discuss the global model HadAM3P and the MM5 ability to simulate the present climate. The HadAM3P was selected to drive the MM5 model because a previous work (Anagnostopoulou et al., 2008) has already concluded that the HadAM3P accurately reproduces the large-scale patterns namely the 500 hPa fields, The 500 hPa height reflects a broad range of meteorological influences on air quality. The authors concluded that the HadAM3P is able to capture the mean patterns of the circulation weather types. The obtained results give some confidence to use the HadAM3P outputs as initial and boundary conditions for regional simulations. In the scope of an air quality assessment it is important that the global model gives an accurate representation of the large-scale flow fields for the region of interest.

The MM5/CHIMERE simulations were conducted from May 1st to October 30th for 1990 and 2100. In Portugal, the peak season of wildfires takes place between June and September, with 93% of the annual area burned (Hoinka et al., 2009) occurring in this period. Under future climate, the forest fire activity will also be concentrated in these months (Carvalho et al., 2010a).

To better evaluate the influence of the future fire activity on air quality, the anthropogenic emissions were also kept constant in the simulations for the 2100 scenario and were not scaled in accordance to the IPCC SRES A2 scenario. The air quality simulations assumed no changes in regional anthropogenic emissions of the chemical species primarily involved in the chemical reactions of ozone formation and destruction, but only accounted for changes in the future forest fire emissions and climate. The forest fire emissions were just included in the simulation over Portugal, and not taken into account within the European domain simulation. Therefore, and aiming to analyse the impact of both climate change and future forest fire emissions over Portugal, the following simulations were carried out:

control simulation (C1) – 1990 climate and 1990 forest fire emissions;
scenario 1 (S1) – 2100 climate and 1990 forest fire emissions;
scenario 2 (S2) – 2100 climate and 2100 forest fire emissions.

2.2. Area burned under the IPCC SRES A2 scenario

Carvalho et al. (2010a) present the area burned projections for Portugal under the IPCC SRES A2 scenario. Here a brief summary of the main results that are relevant for this work is provided.

Daily climatic data for reference (1961–1990) and future (2071–2100) climate scenarios were collected from the Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects – PRUDENCE – project (Christensen and Christensen, 2007), considering the SRES A2 scenario. These data were used to assess the fire weather under the IPCC SRES A2 climate and to estimate future area burned in Portugal based on historical relationships (Carvalho et al., 2008). The forest fire activity in Portugal is strongly dependent on the weather conditions. So, it is expected that fire activity will increase with a changing climate. The projections over Portugal point to an increase of the mean temperature in all seasons especially in summer, reaching almost 6 °C in the inner districts of the country. The daily precipitation decreases in all seasons especially in spring. The north and central part of Portugal will register the highest reductions in rainfall amounts. These projections will deeply influence the fuel moisture conditions in future climate resulting in an increased fire weather risk over all the studied areas along with more severe and longer fire seasons.

Carvalho et al. (2008) established statistically significant relationships between the area burned and the weather for different Portuguese districts. The obtained statistical models were used to estimate the area burned for future (2071–2100) and reference climate (1961–1990). Ratios of change between future and reference annual area burned projections were estimated for each Portuguese district. In order to forecast future annual area burned the obtained ratios by district were multiplied by the observed averaged annual burned area between 1980 and 1990 (Carvalho et al., 2010a). The period between 1980 and 1990 has also been used for the validation of the reference climate simulation and considered for the area burned analysis. Fig. 1 shows the Portuguese districts identification and location.

According to Carvalho et al. (2010a), the estimated projections show a strong increase of the area burned, particularly in Bragança and Porto districts with values of 643% and 606%, respectively. All districts exhibit larger burned areas always higher than 200%. The results point to a North/South dichotomy with higher area burned increases in the North and Central part of Portugal and lesser in the South. Due to demographic, land use and structural conditions the districts in the North and Central part of Portugal already register the highest values of area burned and this is also forecasted under future climate conditions. In general future fire activity will increase dramatically across the entire country, with an averaged area burned increase of 478%.

2.3. Forest fire emissions estimation

Forest fire emissions depend on multiple and interdependent factors such as forest fuels characteristics, burning efficiency, burning phase, fire type, meteorology and geographical location. Models to estimate forest fire emissions are frequently based on a methodology, which includes emission factors, burning efficiency, fuel loads and area burned. Forest fire emissions can be estimated through Equation (1):

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

where, E_i – compound i emissions (g); A – area burned (m^2); B – fuel load ($kg\ m^{-2}$); β – burning efficiency; EF_i – compound i emission factor ($g\ kg^{-1}$).

Fuel type and load are one of the most important factors affecting forest fire emissions. Variations in fuel characteristics and consumption may contribute to uncertainties of 30% in estimates of wildfires emissions (Ottmar et al., 2009). This is a critical factor when describing forest fuels, because available fuel mass depends

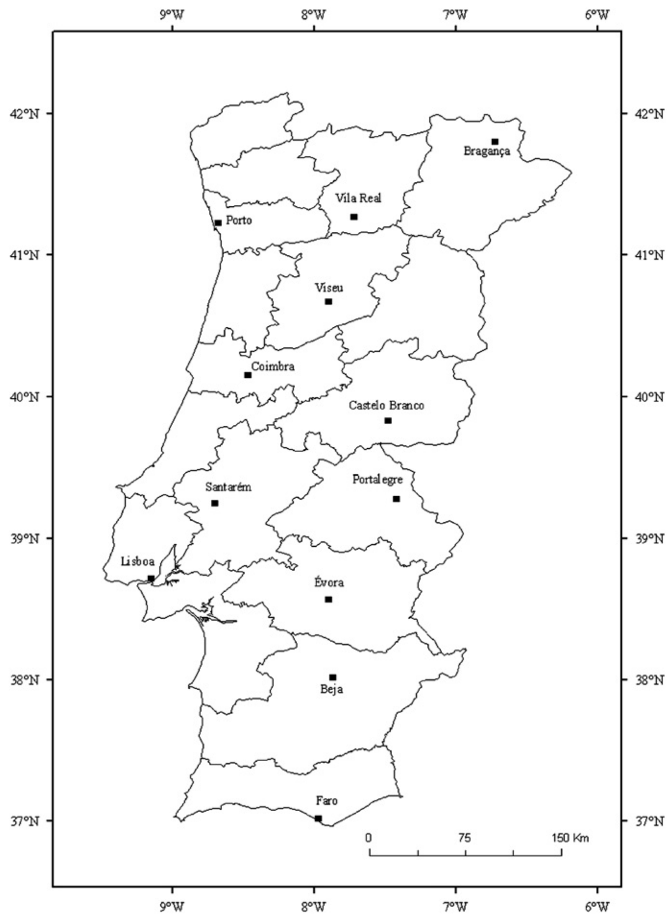

Fig. 1. Portuguese districts identification.

on the location, fuel type and time of the year. Burning efficiency is also an important fire emissions parameter, which is usually defined as the ratio of carbon released as CO_2 to total carbon present in the fuel. The selected fuel load, emission factors and combustion efficiency for CO_2, CO, CH_4, NMHC, PM2.5, PM10 and NO_x are the most adequate for the Portuguese land use types (Table 1). These data were gathered under the scope of the European Commission SPREAD Project (Miranda et al., 2005b) and the Gestosa experimental field fires (Viegas et al., 2002).

The ratio between the area burned in forest stands and shrubs has been estimated based on the 1980–1990 fire activity records at district level. These ratios were kept constant for the forest fire emissions estimation under future climate. Based on the national forestry inventory (DGRF, 2006) the forest stands percentage of resinous, deciduous and eucalypt by district was also considered. The area burned projections for the IPCC SRES A2, presented in Carvalho et al. (2010a) and explained in the previous section were used in this study.

Annual forest fire emissions were estimated for reference (1980–1990) and for future (2071–2100) climate scenarios and were uniformly distributed by district in accordance to the annual average area burned observed in reference and projected for the future climate. Monthly and hourly profiles of forest fire activity were considered in the fire emissions temporal disaggregation. For the reference simulation, the emissions monthly profiles were estimated based on the monthly area burned registered between 1980 and 1990 in Portugal. The monthly area burned estimates for the future climate were used to calculate the emissions monthly profiles under the IPCC SRES A2 scenario. Table 2 presents the monthly distribution of area burned for both climate scenarios.

Table 2
Monthly distribution of the area burned for both climate scenarios used to distribute the annual forest fire emissions.

Month	1980–1990 (%)	2071–2100 (%)
1	0.2	0.0
2	0.2	0.1
3	0.3	0.2
4	0.4	0.4
5	0.4	2.6
6	2.7	12.5
7	28.3	35.2
8	34.9	34.4
9	28.8	13.0
10	3.8	1.4
11	0.1	0.2
12	0.0	0.0

The hourly smoke emissions were estimated using the Western Regional Air Partnership – WRAP diurnal profiles (WRAP, 2005) that are based on the fuel consumption data registered for forest fires events in the USA. This type of information is still absent for Portugal, but data gathered for specific forest fire events indicate peak ignitions between 14 and 17 LST (Local Standard Time), which agree with the pronounced diurnal cycle with peak emissions during the afternoon and very low emissions during the night suggested by the WRAP study (Eck et al., 2003; WRAP, 2005). According to the WRAP (2005) analysis the daily emissions peak is attained at 16 LST and the minimum values are registered during the night. To estimate the hourly forest fire emissions the same diurnal profile was applied for the reference and future scenarios. It is important to note that any differentiation among working days and weekends was not considered since no reliable information was available for forest fire activity on this subject. These hourly emissions were finally added to the anthropogenic and biogenic gridded emissions in order to proceed with the air quality simulations.

The simulation of forest fire effects on air quality requires, nevertheless, the analysis and integration of additional factors: fire progression, atmospheric flow, smoke dispersion and chemical transformation (Miranda, 2004; Pouliot et al., 2005; Hodzic et al., 2006, 2007). The representation of emissions vertical distribution within the model is one key parameter because the injection height of the fire plume will determine the transport of the emitted pollutants and therefore their impacts on local and regional concentrations and effects. In particular, wildfires under future warmer climate are expected to be much larger (as shown from the

Table 1
Fuel load, emission factors and combustion efficiency suitable for Portuguese forest and shrub characteristics (Miranda et al., 2005b).

Fuel	Fuel load (kg m^{-2})	Combustion efficiency	Emission factor (g kg^{-1})						
			CO_2	CO	CH_4	NMHC	PM2.5	PM10	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
Eucalypt	3.90	0.25	1414	117	6	7	11	13	4

Table 3
Comparison between anthropogenic and forest fire emissions (Gg) for the year 1990.

Source	CO_2	CO	CH_4	NMHC	PM2.5	PM10	NO_x
Forest fires	1007.4	62.4	3.7	4.4	6.8	7.4	3.1
Industry	33 513.4	69.2	23.9	147.2	35.5	51.2	111.0
Transport	9827.7	511.0	3.5	118.1	8.5	8.5	111.7
Forest fires/ (transport + industry) (%)	2.3	9.7	11.9	1.6	13.4	11.1	1.4

estimates of area burned for 2100) and to release more energy into the atmosphere creating pyro-convective vertical transport of pollutants. In this sense, the determination of the injection altitude of the fire emissions involved specific parameterizations to locate the emissions into the various model vertical layers, following Hodzic et al. (2007) and the WRAP method (WRAP, 2005). The injection height is calculated based on fire characteristics and atmospheric conditions. The bottom (H_{bot}) and top (H_{top}) altitudes of the fire plume are calculated as a function of the fire buoyant efficiency (BE) that is derived from the area burned (typical values for BE range from 0.5 for small fires to 0.95 in the presence of large fires). In this sense, the emissions injection height changed in the future climate change scenario according to the increase of the projections of the area burned.

3. Results and discussion

In the following analysis, we present the main results regarding the future forest fire emissions and its impacts on O_3 and PM10 concentrations over Portugal. All the spatial concentration patterns presented in this section are exhibited as differences between the future and the reference scenarios. In addition, the monthly patterns will only be presented for the months where the changes were highest.

3.1. Forest fire emissions in a future climatic scenario

Forest fire emissions were estimated and compared against the anthropogenic pollutant emissions data for Portugal. Table 3 shows the comparison between the annual averaged forest fire emissions and industry and transport emissions for the period between 1980 and 1990.

Forest fires represent a considerable percentage of the total (industry and transport) emissions, reaching up to 12% for CH_4 and 13% for PM2.5. Miranda et al. (2007) estimated for the year 2003, which included one of the most critical fire seasons in terms of area burned, a forest fire emissions contribution of 40% of the CO and CH_4 total emissions.

Fig. 2 presents the estimated annual emissions from forest fires for the reference scenario (1980–1990) and for the future scenario (2071–2100).

Due to the projected area burned increases higher emissions of all the analysed pollutants are also estimated. CO, CO_2, and CH_4 emissions were converted into CO_2 equivalent emissions based on the global warming potential (GWP) for a 100 years' time horizon. The annual CO_2 equivalent emissions from forest fires account for 1.27 Mt for the annual averaged 1980–1990 period and 7.44 Mt under the IPCC SRES A2 scenario. This represents an overall increase of approximately 500%.

3.2. Forest fire impacts on air quality under the IPCC SRES A2 scenario

In Carvalho et al. (2010b) a detailed analysis of the MM5/CHIMERE modelling system application under climate change has been presented. The validation of the MM5/CHIMERE modelling system has also been performed with good simulation skills.

According to Carvalho et al. (2010b) the simulated temperature increases under future climate, between May and October, almost reaching 8.5 °C over mid and southern Europe. These projections are in accordance to Rowell (2005) who predicted that in winter the largest warming occurs over eastern Europe, up to 7 °C, and in summer temperatures rise by 6–9 °C south of about 50°N. Ozone is strongly positively correlated with high temperatures and solar radiation, as this enhances the photochemical conditions that lead to ozone formation (Comrie, 1996).

Fig. 3 shows the monthly mean O_3 changes over Portugal due to climate change alone and to climate change and future forest fire emissions for July, August, and September. The O_3 levels are exhibited as differences between future and reference scenarios (S1-C1 and S2-C1).

The highest increases in O_3 concentrations are detected in July in the north of Portugal, because of the air quality boundary conditions settled by the European domain simulation (Carvalho et al., 2010b). The increase of the average temperature, the decrease of the average boundary layer (BL) height and of the average wind speed contributes to the ozone enhancements in July (Carvalho et al., 2010b). In July there is an increase of approximately 20 $\mu g\ m^{-3}$ in the O_3 levels in the north and central region of Portugal only due to climate change. This represents 23% augment

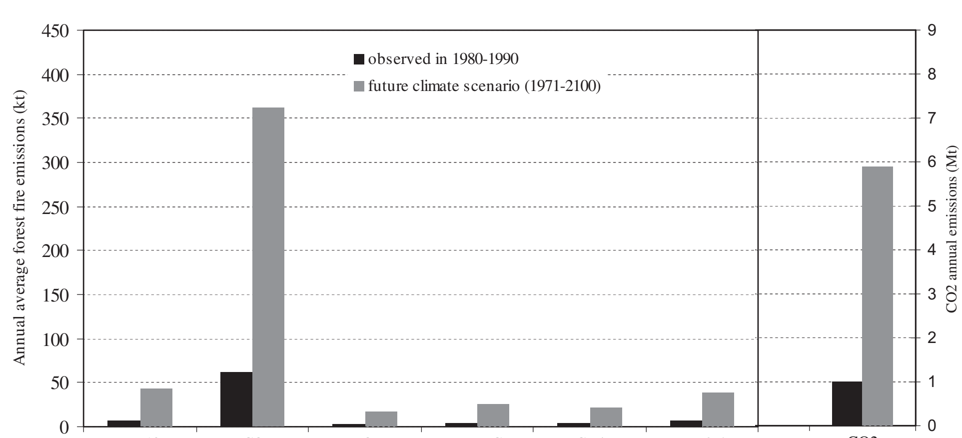

Fig. 2. Annual average forest fire emissions for the reference period (1980–1990) and for the future climate (1971–2100) under the IPCC SRES A2 scenario.

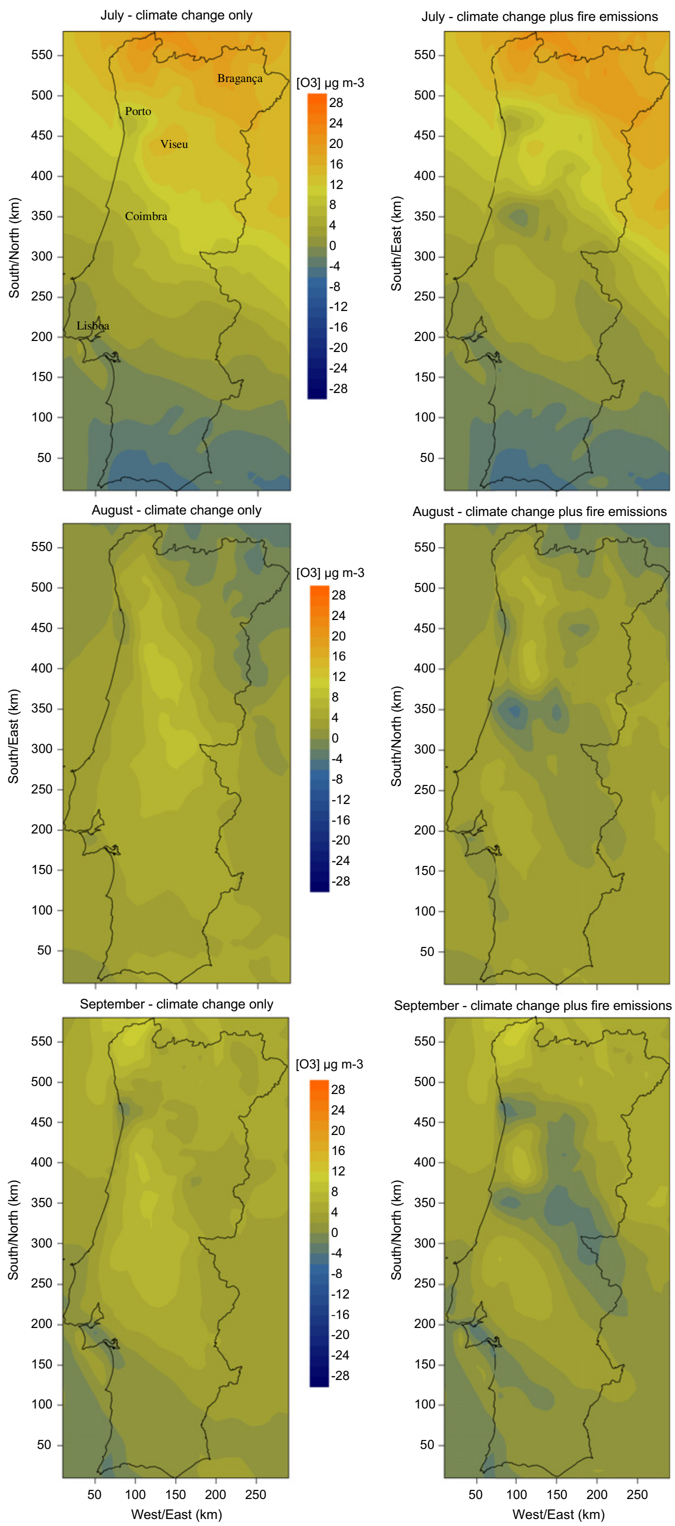

Fig. 3. Monthly mean surface O_3 changes simulated over Portugal considering only climate change (S1-C1) and climate change and future fire emissions (S2-C1) for July, August, and September.

in the ozone levels over this region. If future forest fire emissions are also considered the centre and northern regions of Portugal, especially over Coimbra and Porto, experience a smaller increase or even a reduction in the O_3 concentrations (-1.2 µg m^{-3} in July, -4.9 µg m^{-3} in August and -3.8 µg m^{-3} in September). This pattern is related to the O_3 consumption promoted by the O_3 precursor's emitted by the forest fires in these regions.

Due to the area burned projections that pointed the district of Coimbra as the main affected under future climate the forest fire emissions are highest in this region. These high levels of O_3 precursor's emissions may also lead to its depletion (e.g., through NO titration) and the overall balance may conduct to the diminishing of the O_3 levels in the atmosphere. It is also expectable an increase of the O_3 concentrations downwind of the fire due to the dispersion of the emitted pollutants and their chemical transformation (Sitch et al., 2007; Singh et al., 2010). In Fig. 3 it is possible to see the depletion of the O_3 levels in July, August, and September, although the monthly average analysis does not allow verifying a clear increase of the O_3 concentrations downwind of the fire locations. The ozone levels in the atmosphere present a marked daily profile closely related to the photochemical activity that reaches its maximum during the afternoon. In this sense and in order to make a more detailed discussion of the O_3 concentrations trend along the diurnal cycle the O_3 averaged values at 12, 15, and 18 UTC (Coordinated Universal Time) were computed for August (Fig. 4).

At noon, considering the future forest fires emissions and the climate change impacts, it is possible to see an increase of the O_3 concentrations and its plume extension in the districts of Porto and Coimbra.

The highest levels of O_3 in the atmosphere are observed at 15 UTC. A larger plume with higher concentrations is spreading towards the centre and the southern regions of the country. At this time Coimbra district registers a decrease on the ozone levels (S2-C1) (-10 µg m^{-3}) that may be related with the higher amounts of forest fire emissions in this region. It is also possible to see a clear increase on the O_3 plume concentrations northern and southern of Coimbra. The increase on the O_3 levels reaches 28 µg m^{-3} under future climate and forest fire emissions.

By the end of the afternoon, at 18 UTC, the extension of the ozone plume differences (scenario S2-C1) with higher concentrations diminishes and a decreasing pattern can be clearly identified in the centre of Portugal (districts of Viseu, Coimbra, and Castelo Branco). The ozone precursor's emissions due to forest fire activity are consuming the ozone that was previously produced. This decrease can reach up to -30 µg m^{-3}. It can also be observed the decrease of the ozone concentrations over a larger extension in the surroundings of the main Portuguese cities like Porto and Lisboa.

The interaction between the emitted pollutants and the overall chemical reactions in the atmosphere under a changing climate may lead to increases and decreases of ozone values depending on the region. The hourly average of the ozone daily profile gives important information regarding the pollutant patterns distribution in the vicinity of the fires and distant from their main locations. It is clearly that there is a decrease of the ozone concentrations just close to the forest fires and an increase in the surrounding areas. The diurnal evolution of the obtained ozone differences is also closely connected to the forest fire emissions hourly profiles considered in the numerical modelling that allocates the highest percentage of the released emissions from noon to 18 UTC. After 18 UTC the forest fire pollutants emitted to the atmosphere are leading to the O3 consumption.

The monthly and the hourly analysis of the average ozone patterns over Portugal allow verifying that climate change alone may significantly impact the pollutant levels in the atmosphere especially in July and August. For instance, the projected increases on temperature in summer may deeply influence the kinetic rates of the atmospheric chemical cycles. The projected impacts of climate change on the BL height, wind speed and relative humidity may also influence the obtained ozone concentration patterns.

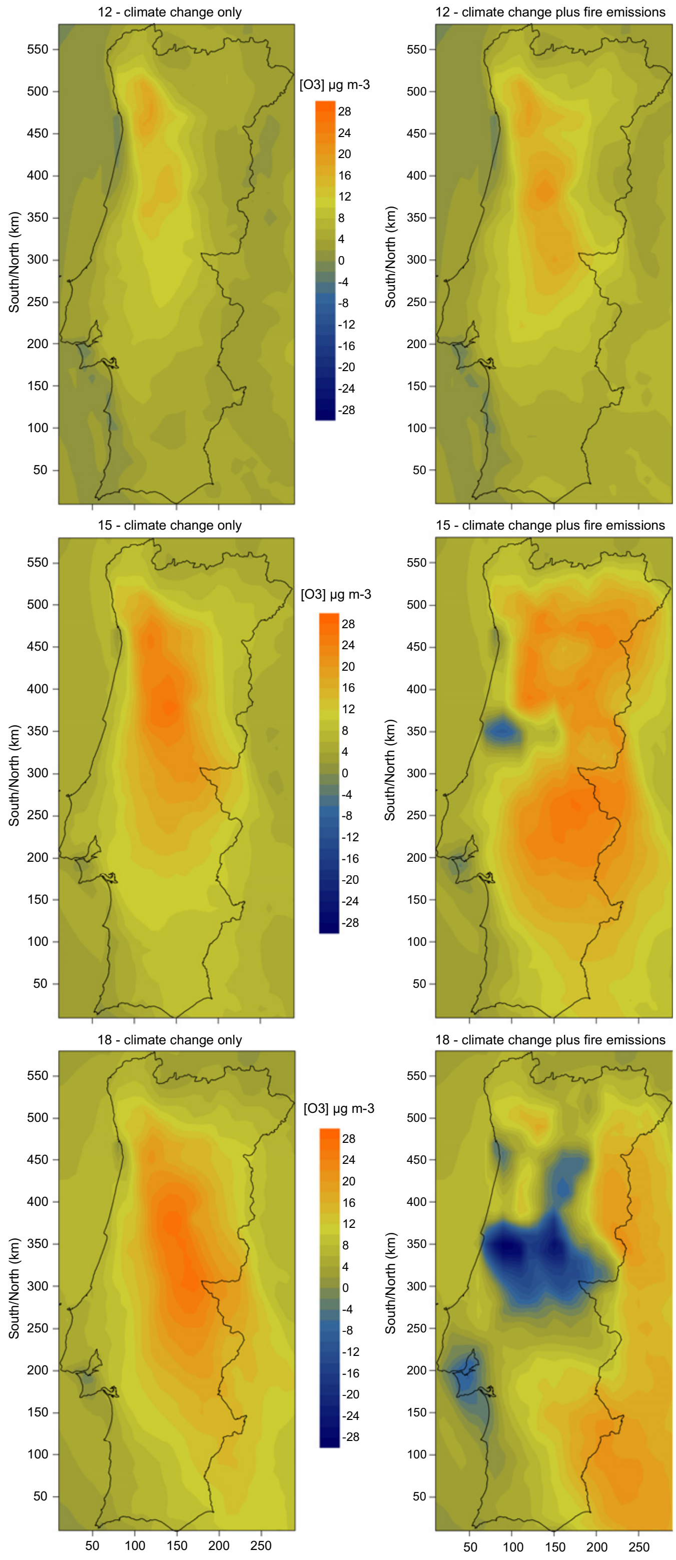

Fig. 4. Hourly mean surface O_3 concentrations for August at 12, 15, and 18 UTC considering climate change only (S1-C1) and climate change and future forest fire emissions (S2-C1).

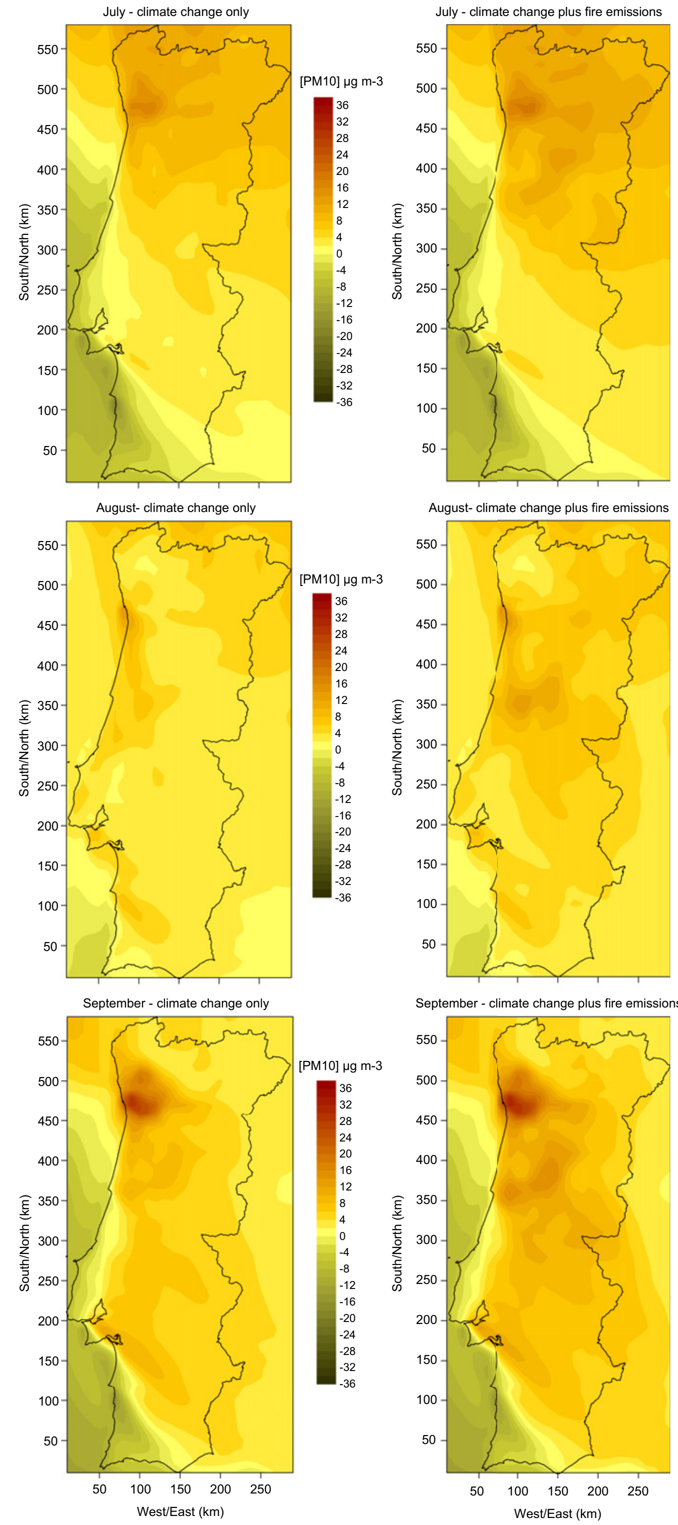

Fig. 5. Monthly mean surface PM10 concentrations over Portugal considering climate change only (S1-C1) and climate change and future fire emissions (S2-C1) for July, August and September.

Regarding particulate matter, Fig. 5 depicts the monthly mean of surface PM10 changes for July, August and September between the 2100 climate and the 1990 climate over Portugal (considering or not the forest fire emissions) estimated with the MM5/CHIMERE modelling system.

Only due to climate change, the PM10 concentrations increase almost 18 μg m^{-3} in July, over the North coastal region of Portugal. This represents a 40% increase in the PM10 concentrations between the reference and the future climate scenarios. In August this increase reaches 15 μg m^{-3}. For both months, the BL average height registers a decrease from the reference to the future climate (Carvalho et al., 2010b). Climate change deeply impacts the PM10 levels in the atmosphere. The projected impacts are related to changes in the climate/meteorological characteristics that influence the PM10 chemical and physical mechanisms. Changes in the boundary layer height, relative humidity, wind speed, temperature and precipitation deeply impact the advection, deposition, coagulation and absorption processes that lead particulate matter transformation and transport in the atmosphere (Carvalho et al., 2010b).

From Fig. 5 it is also possible to see the different PM10 concentration patterns between simulations considering or not the future forest fire emissions. In July, the PM10 levels increase +20 μg m^{-3} over Porto region due to climate change and future forest fire emissions. The influence of future forest fire emissions is visible in the PM10 plume extension presenting higher concentrations over Porto, Coimbra, and Viseu districts. The estimated increases are located in the north and central part of Portugal because these are the regions most affected by forest fire emissions.

In August the PM10 plume shows again its highest concentrations over the central part of Portugal and in Bragança district for the simulation considering climate change and future forest fire emissions. The maximum increase in PM10 values is +15 μg m^{-3} considering only climate change and +16 μg m^{-3} under climate change and future forest fire emissions. Notwithstanding the small influence of forest fire emissions in the monthly averaged values, the PM10 concentration plume clearly shows the contribution of the forest fire emissions to the atmospheric concentrations of this pollutant.

September registers the highest increases on the PM10 concentrations reaching 30 μg m^{-3} just due to climate change (Carvalho et al., 2010b). The increase on the PM10 levels due to climate change and future forest fire emissions is visible in the pollution dispersion plume with higher values over Coimbra, Viseu, and Castelo Branco districts, which can go up to 32 μg m^{-3}.

4. Summary and conclusions

This study investigated the impact of climate change and future forest fire emissions on air quality over Portugal under the IPCC SRES A2 scenario. Natural and anthropogenic emissions were kept constant and only forest fire emissions changes were considered between a current and a future climate scenario. Only with this hypothetic and isolated scenario the evaluation of the impact of forest fires in a climate changing environment was possible.

Estimates of CO_2, CO, CH_4, NMHC, PM2.5, PM10 and NO_x emissions from forest fires under a future climate scenario indicate substantial increases that are related to larger area burned projections.

Numerical simulations performed with the MM5/CHIMERE modelling system over Portugal pointed out an important impact of O_3 and PM10 levels in the atmosphere under future forest fire conditions. Ozone concentrations may rise 23 μg m^{-3} by 2100 but a decrease of almost 6 μg m^{-3} is also estimated over the main forest fire locations. Hence the increase of forest fire emissions to the atmosphere does not necessarily mean that ozone levels will rise as shown by the obtained ozone change spatial distributions; the O_3 levels may decrease over the fire activity locations and increase downwind of these regions. The diurnal patterns of the O_3 changes clearly show the production and consumption behaviours that may be established under future climate and forest fire conditions.

Concerning PM10 the months of July, August, and September exhibit the influence of the forest fire emissions in the concentration plume over Portugal. The impact of future forest fire emissions is visible in the PM10 plume extension presenting higher concentrations in the north and centre of Portugal that reach almost 32 μg m^{-3} over the centre of Portugal.

These findings may support the Portuguese authorities and policy-makers into the design and implementation of mitigation and adaptation plans in the scope of forest fire emissions reduction and air quality management due to the potential implications in international commitments, e.g., the Kyoto Protocol, and subsequent impacts on human health and environmental resources.

The modelling of climate change and future forest fire activity impacts on air quality constitutes an adequate tool to better assess the relationships among these topics. Nevertheless, the obtained results must be seen as preliminary since the impacts of climate change and forest fires on air quality involve multiple and long-term feedbacks between meteorological, chemical processes ad vegetation dynamics, and not all the interactions were addressed. Moreover, the lack of scaled emissions based on the IPCC SRES A2 scenario bounds the main findings of this study and all the forecasted changes in the pollutant concentrations must be understood as trend indicators due to the uncertainty inherent to this type of studies. However this paper further discusses and quantifies some of the most important trends, showing the effects of forest fires under a future climate scenario.

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