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Climate change, forest fires and air quality in Portugal in the 21st century

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1. Introduction

There are regions of the world more vulnerable to climate change and some of those regions are also sensitive to forest fire occurrences. The way climate change interacts with the forests of the world and consequently with forest fire activity is a point of debate among the scientific community.

Several features dominate the forest fires of a given region and these can be described in terms of the main temporal and spatial scales of variation. From a fire event to the definition of the fire regime of a given region several drivers are determinant in the characterization of these dynamics. From the local weather conditions to the large scale weather patterns the forest fires evolve from simple events to the definition of the fire regime of a given region. The short temporal scale and the local characteristics that dominate a fire event are ruled by the local weather conditions that drive the forest fires daily variability. Additionally, the physiographic and the topographic variability that characterize the large temporal and spatial scales variations represent the broader influence of these scales on the fire regime definition.

To correctly assess the inter-connection between all analysed drivers human influence must also be considered. One of the best definitions of this relationship is given by Stephen Pyne (Pyne, 2007) who describes the area burned of a region as "a proxy of climate interacting with people". At a larger temporal and spatial scale human activities may deeply influence climate and subsequently the fire regime of a region. At local scale human activities have a remarkable impact on forest fires mainly through changes in land-use, negligent actions or simply by arson.

Wildland fire is a global phenomenon, and a result of interactions between climate–weather, fuels and people (Flannigan et al., 2009). The influence of the human activities on climate is leading to worldwide forest fire changes and disruptions. The most recent report of the IPCC (IPCC, 2007) discusses the changing of the vegetation structure and composition due to intensified wildfire regimes driven at least partly by the 20th century climate change. Worldwide the wildfire regime is changing. In the United States of America (USA) the number of forest fires is decreasing due to fire prevention strategies but they are becoming larger and consequently more severe. In this sense the fire suppression efforts are escalating (Miller, 2007).

Recently, Europe has experienced a large number of forest fires that have caused enormous losses in terms of human lives, social disturbances, environmental damage and economic disruptions. Most of the fires in Europe take place in the Mediterranean region where over 95% of the forest fire damage occurs (EC, 2003). There are several features that make the landscapes of the European Mediterranean Basin different from those of the rest of Europe. These differences are mainly related to the climate, the long and intense human impact, and the role of fire. The latter is, in turn, influenced by the other two (Pausas and Vallejo, 1999). The interaction between the human activity and the fire is a complex question that drives the majority of fire activity in southern Europe.

Since 1980, the statistics of the annual area burned in Portugal, Spain, France, Italy and Greece, have varied considerably from one year to the next, which can be an indication of how strongly the area burned depends on weather conditions. Fire occurrence increased during the 1990s, but since 2001 the number of fires has remained more or less stable (EC, 2005). This stabilization was possibly due to public information campaigns and improvements in the prevention and fire-fighting abilities of these countries. In Portugal, out of the last 30 years 2003 had the worst fire season, which resulted in the burning of almost 430,000 ha of forested lands and scrublands with global economic losses of 1,200 million Euros (DGRF, 2006). In that year the social costs were most significant with the loss of 20 human lives and the destruction of 117 houses. Due to extreme fire weather conditions (Viegas et al., 2006) the year 2005 also recorded a very high value of area burned, approximately 325,000 ha.

Even the main reason for fire increase is probably changes in land use, climatic factors should be considered as a contributing factor. Fires tend to be concentrated in summer when temperatures are high, and air humidity and fuel moisture are low (Pausas and Vallejo, 1999). Over Portugal and since 1972, there is a general trend towards an increase in the mean annual surface air temperature. Additionally, spring accumulated precipitation has registered a systematic reduction, accompanied by slight increases in the other seasons (Santos et al., 2002). Predictions of climate warming in the Mediterranean basin indicate an increase in air temperature and a reduction in summer rainfall (Christensen and Christensen, 2007)). Although there is uncertainty on the mean and variance of the precipitation changes, all predictions suggest a future increment in water deficit. These changes would lead to an increase in water stress conditions for plants, changes in fuel conditions and increases in fire risk, with the consequent increase in ignition probability and fire propagation (Pausas and Vallejo, 1999).

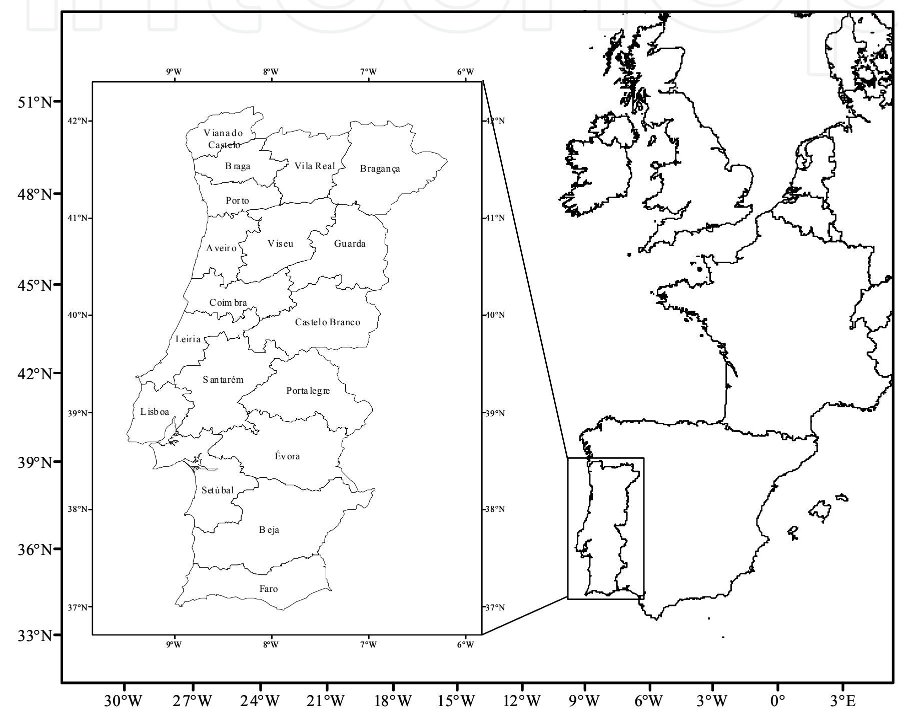
Since the late 70s biomass burning has been recognized as an important source of atmospheric pollutants (Crutzen et al., 1979). Several works have already discussed the importance of forest fires as a source of air pollutants (Amiro et al., 2001a; Miranda et al., 2005a) and in a changing climatic scenario this contribution can increase dramatically (Amiro et al., 2001b) due to larger area burned. Forest fire emissions, namely particulate matter (PM), ozone (O_3) precursor gases (like nitrogen oxides – NO_x and volatile organic compounds – VOC) and carbon dioxide (CO_2), can significantly impact the ecosystems and the air quality and consequently human health (Riebau and Fox, 2001). Particularly, they can influence plant productivity downwind of fires through enhanced ozone and aerosol concentrations (Sitch et al., 2007). In a changing climate the forest fire emissions can play an important role in all these interactions.

Air quality and its potential impacts namely in the ecosystems, structures and human health is currently one of the main concerns at global, regional and local scales. In Dentener et al. (2006) the troposphere composition change to be expected in the near future (year 2030) is investigated using 26 state-of-the-art global atmospheric chemistry transport models (CTMs) and three different emissions scenarios. Based on the ensemble mean model results, by 2030 global surface ozone is estimated to increase globally by 4.3 ± 2.2 ppb for the IPCC SRES A2 scenario (Nakicenovic et al., 2000). This study shows the importance of enforcing current worldwide air quality legislation and the major benefits of going further. Nonattainment of these air quality policy objectives, such as expressed by the IPCC SRES A2 scenario, would further degrade the global atmospheric environment.
The analysis of the climate change impacts on air quality and its feedback mechanism is nowadays a well recognised approach at the global scale. Nonetheless, studies from the regional to a country scale are not so widespread. The highest number of studies can be found for USA (e.g. Hogrefe et al., 2005). Over Europe some studies have addressed this issue (e.g. Szopa et al., 2006) pointing that by 2030 estimated ozone levels, in July, may increase up to 5 ppb. In Europe and at country level these studies are still reduced and only applied for episodic situations (e.g. Borrego et al., 2000). Additionally, the interaction between climate change, forest fire emissions and air quality is still poorly discussed. Spracklen et al. (2009) firstly investigated the potential impacts of future area burned on aerosol concentrations over the United States. In this scope, the main objective of this chapter is to investigate the role of climate change in forest fire activity and its impacts on air quality patterns over Portugal through the projection of future area burned and pollutants emissions under the IPCC SRES A2 climatic scenario.

2. Fire activity data in Portugal

Forested lands in Portugal occupy 5.4 millions of hectares and represent two-thirds of Portugal's surface area (DGRF, 2006). Eleven percent of the Portuguese territory is occupied by Maritime Pine stands or lands (*Pinus pinaster*), followed by Eucalypt (*Eucalyptus globulus*) (8 %) and Cork Oak (*Quercus suber*) (8 %). The Holm Oak (*Quercus rotundifolia*) represents 5 %, and the oak tree (*Quercus faginea*) and Stone Pine (*Pinus pinea*) exhibit 1 % each. Figure 1 shows the Portuguese districts identification and the dominant forest types. Maritime Pine is mostly common in the Castelo Branco, Coimbra, Leiria and Viseu districts. Castelo Branco, Aveiro and Santarém districts have higher forest lands of Eucalypt. On the other hand, the southern districts of Évora, Portalegre, Santarém and Setúbal have the majority of the Cork Oak in Portugal. The oak tree is most common in the northern districts of Vila Real, Bragança, and Guarda.
The Portuguese population is mainly concentrated in the urban and sub-urban areas of the coastal regions. The north region contains 35 % of the population, the Lisbon area 26 % and the central part 23 %. The remaining Portuguese regions have occupation levels below 8 % (INE, 2003). This represents a considerable population asymmetry that certainly influences forest fire ignitions and spreading.
Some aspects of the property regime in the north and centre of Portugal, namely the high number of land owners (most of them unknown) and the absence of adequate property records, have important negative consequences concerning forest management. An increase of population within the forested lands greatly enhances the forest fire risk and,

consequently, the destruction of goods and human lives and creates difficulties for the fire fighting operations. Land abandonment, due mainly to the aging of the land owners, also creates difficulties in the management of forested properties, leading to an increase in the fuel load and consequently in forest fire risk. In the southern part of the country the districts of Beja, Évora and Portalegre have a different demographic pattern. The populations are more concentrated and not spread among the forested areas, additionally the dominant forest types are resistant to forest fires. These are the regions of Portugal which reach the highest temperatures during the summer period and have lower precipitation rates throughout the year.



District name	Dominant forest type (% district area)
Bragança	Maritime Pine (5%)
Vila Real	Maritime Pine (17%)
Viana do Castelo	Maritime Pine (17%)
Braga	Eucalyptus (16%)
Porto	Eucalyptus (18%)
Aveiro	Eucalyptus (25%)
Viseu	Maritime Pine (23%)
Guarda	Maritime Pine (12%)
Coimbra	Maritime Pine (30%)
Castelo Branco	Maritime Pine (24%)
Leiria	Maritime Pine (30%)
Santarém	Cork Oak (18%)
Portalegre	Cork Oak (23%)
Lisboa	Eucalyptus (10%)
Setúbal	Cork Oak (25%)
Évora	Holm Oak (20%)
Beja	Holm Oak (16%)
Faro	Cork Oak (8%)

Fig. 1. – Location of Portugal in the Iberian Peninsula, Portuguese districts identification and dominant forest types as a percentage of district area.

The forest fire database for Portugal is provided by the Autoridade Florestal Nacional-AFN. This database constitutes the national component of the European Forest Fire Information System (EFFIS) created by the European Commission in 1994. The Commission Regulation (EC) 804/94 (now expired) established a Community system of information on forest fires for which a systematic collection of a minimum set of data on each fire occurring, the so-called "Common Core", had to be carried out by the Member States participating in the system. According to the currently in force Forest Focus, Regulation (EC) 2152/2003, concerning monitoring of forests and environment interactions in the community, the forest fire common core data should continue to be recorded and notified in order to collect comparable information on forest fires at the Community level.

At national level, the recorded information includes daily area burned and daily number of fires per district, among other variables. From 1980 to 2009, the dataset record illustrates a total of 3.1×10^6 ha of area burned, approximately 30 % of Portugal's total area, and 487,000 of forest fire occurrences. The AFN database is based on *in situ* information provided by the

Ministry of Agriculture and the National Civil Protection Service. Since 1990, the annual area burned is mapped based on satellite information.
Simple statistics for forest fire activity in Portugal were performed in order to better understand its main characteristics in terms of spatial and temporal distribution. Figure 2 represents the annual area burned and number of fires between 1980 and 2009. The maximum number of annual forest fires occurred in 1995, 1998, 2000 and 2005, reaching 35,000 occurrences. In terms of area burned the year of 2003 reached the highest value ever registered – 430,000 ha, followed by 2005 with 337,000 ha. It is interesting to observe that between 1980 and 2000 the annual number of forest fires registered an increase from year to year except in some specific years. In addition to this and according to the Portuguese Meteorological Institute since 1974 there is a clear increase in the average temperature values in Portugal. The years of 1995, 1997, 1998 and from 2000 to 2006 present higher average temperatures than the normal. From 1995 to 2000 the number of forest fires registered a clear increase, although since 2001 they tend to remain almost constant except in 2005 and 2009.

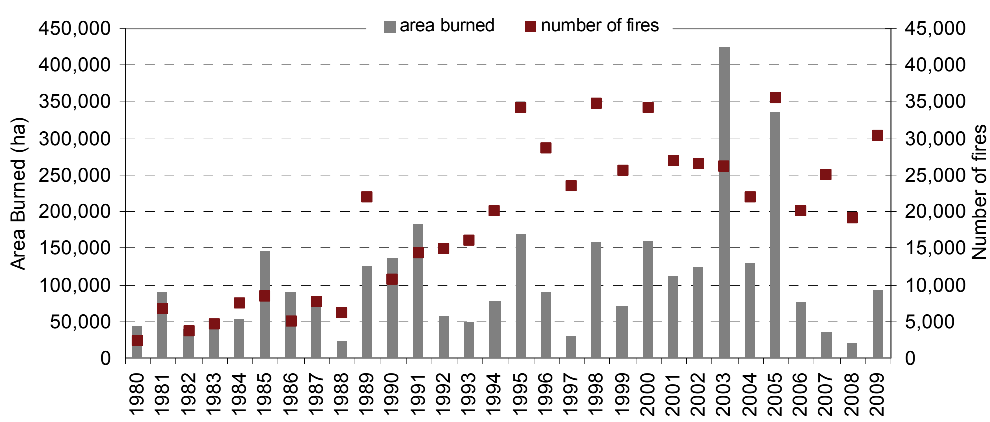


Fig. 2. Annual area burned (bars) and number of fires (square points) in Portugal between 1980 and 2009.

The number of fire occurrences in the months of June (8 %), July (22 %), August (32 %), and September (20 %) represent 82 % of the yearly total (not shown). The area burned peak is observed in August accounting for 45 % of the yearly total (not shown) with the districts of Guarda, Castelo Branco, Viseu, and Coimbra presenting the highest area burned values in Portugal (not shown). According to the National Plan for Forest Fires Prevention, the ignitions peak occurs along the weekend, and especially during the afternoon, denoting an important human influence on fire starts (APIF, 2005).
The annual number of forest fires is higher in the most urban and sub-urban districts (Aveiro, Braga, Lisboa, Porto, Viana do Castelo, and Setúbal) (not shown). In terms of forest fire occurrences, the Porto district (urban/sub-urban region) represents the highest percentage of fire occurrences reaching almost 22 % of the total. Additionally, the Guarda district (rural region) accounts for almost 18 % of the area burned in Portugal, followed by Castelo Branco with 11 % (not shown).
An analysis performed for the period between 1993 and 2003 revealed that 97 % of the forest fire ignitions were due to human influence with 37 % to arson, 28 % to negligence, and 32 % to unknown causes (APIF, 2005). Arson is mainly related to fraud, hunting conflicts, and

building construction interests, and is most notorious in the northern part of the country especially in the coastal regions. Negligence is the most important cause in the south mainly due to clearance activities. In the southern districts of Beja, Évora, and Portalegre the principal cause of negligence is related to agricultural machinery use. Specific regional characteristics are also responsible for forest fires starts such as fireworks activity in the northern districts of the country (APIF, 2005). Portugal, like the majority of the southern European countries, has fewer forest fires due to natural causes because phenomena such as lightning have a low frequency of occurrence during the summer period.

3. Observed fire weather risk in Portugal

The Canadian Forest Fire Weather Index (FWI) System is a system that monitors forest fire risk and supplies information to support fire management. The components of the FWI System can be used to predict fire behaviour and can be used as a guide to policy-makers in developing actions to protect life, property and the environment.

The FWI system was developed for Canadian forests but has also been applied in other countries and environments such as Mexico, Southeast Asia, Florida and Argentina (Moriondo et al., 2006). For the Mediterranean basin, several studies showed that the FWI system and its components were well suited to the estimation of fire risk for the region (Viegas et al., 1999). Moreover, the FWI is currently the fire risk index used by the Joint Research Centre (JRC) to map fire risk at the European Union level (JRC, 2006). The success of this system is due both to the simplicity of its calculation procedures and to the simulation of the moisture of a generalized fuel type, which has been successfully applied to model fire potential in a broad range of fuel types (Van Wagner, 1987).

The FWI System (Figure 3) is a weather-based system that models fuel moisture using a dynamic bookkeeping system that tracks the drying and wetting of distinct fuel layers in the forest floor. There are three moisture codes that represent the moisture content of fine fuels (fine fuel moisture content, FFMC), loosely compacted organic material (duff moisture code, DMC), and a deep layer of compact organic material (drought code, DC). The drying time lags for these three fuel layers are 2/3 of a day, 15 days, and 52 days respectively for the FFMC, DMC, and DC under normal conditions (temperature 21.1ºC, relative humidity 45%). These moisture indexes are combined to create a generalized index of the availability of fuel for consumption (build up index, BUI). The FFMC is combined with wind speed to estimate the potential spread rate of a fire (initial spread index, ISI). The BUI and ISI are combined to create the FWI which is an estimate of the potential intensity of a spreading fire. The daily severity rating (DSR) is a simple exponential function of the FWI intended to increase the weight of higher values of FWI in order to compensate for the exponential increase in area burned with fire diameter (Van Wagner 1970).

For the purposes of this study, the FWI System components were computed using daily mean values of temperature, relative humidity, wind, and daily total precipitation. The Statistical Analysis System (SAS) version 9.1.3 (SAS, 2004) was used for the FWI System components estimation. The FWI System components have been estimated for the period between 1980 and 2005 were meteorological data was available at 12 synoptic sites across Portugal.

Figure 4 presents the daily mean fire weather index (FWI) from 1980 to 2005. Porto district exhibits the lowest values. The southern region formed by Portalegre, Évora, and Beja districts presents the highest interquartilic interval (interquartile range from 25th percentile to 75th percentile) of FWI values. In terms of yearly distribution, 2005 (Figure 4b) presents the highest interquartilic interval of values but the maximum FWI index was attained in 2004. According to the monthly distribution (Figure 4c), July presents the maximum FWI value but the interquartilic interval remains almost the same between July and August. As expected, the period between May and October presents the highest FWI values.

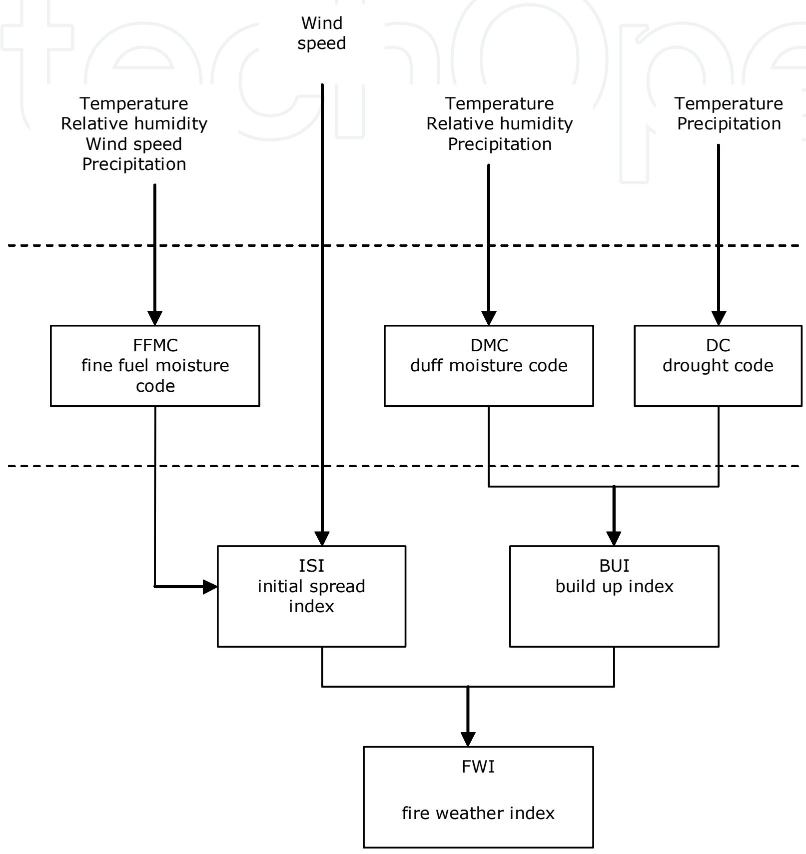
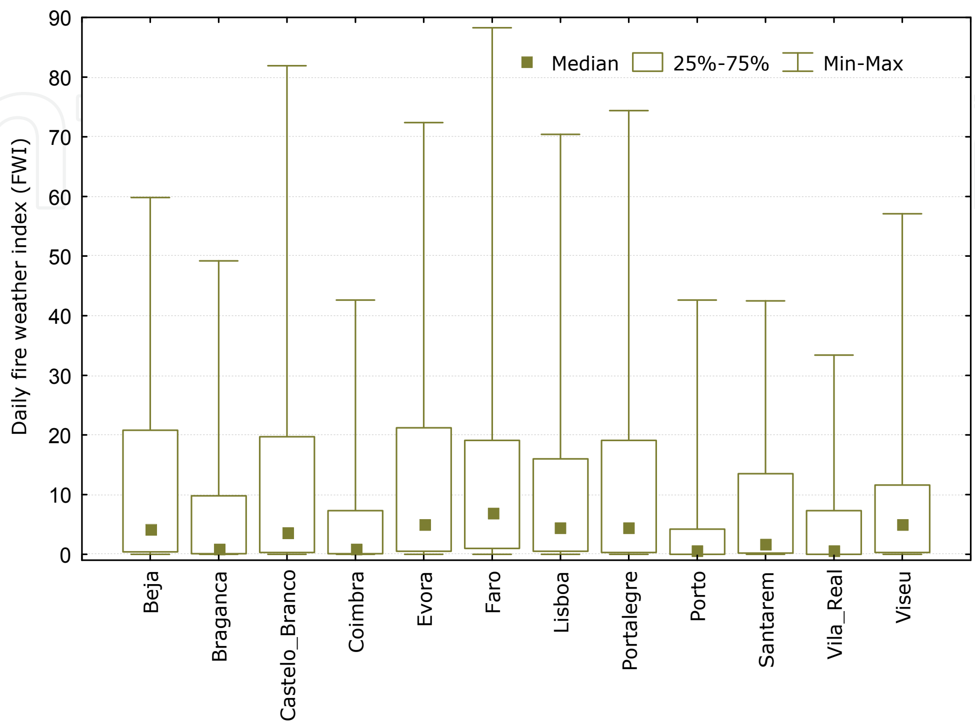


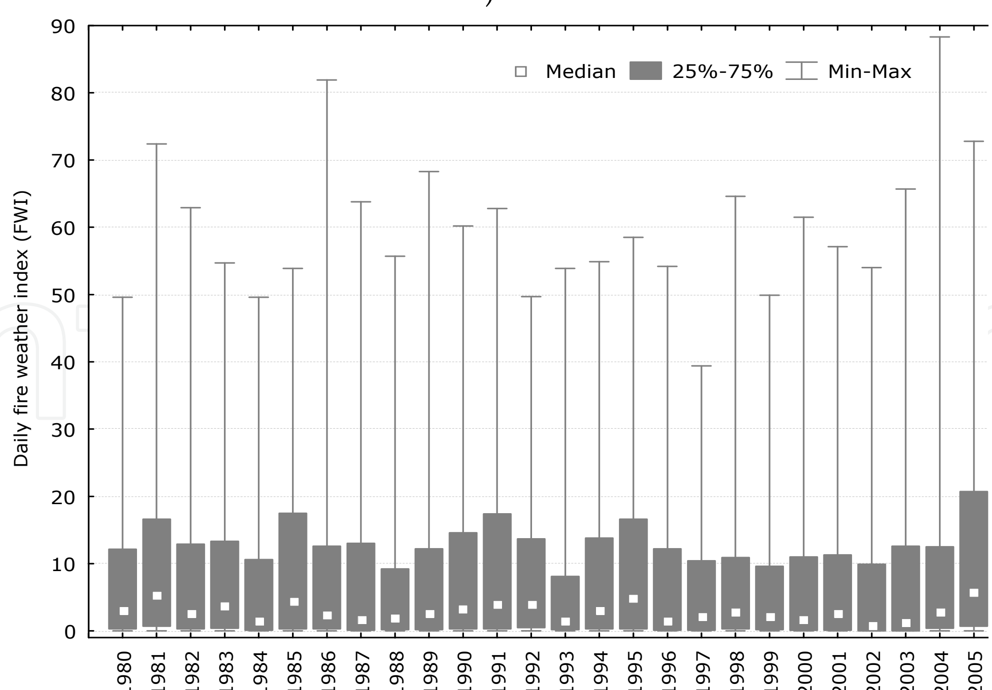
Fig. 3. Canadian Fire Weather Index (FWI) System components (adapted from Van Wagner, 1987).

The 12 stations fire weather data was used to estimate the FWI spatial pattern for Portugal. A Geographic Information System (GIS) software was used to compute a spline interpolation (Schumaker, 1981) over the monthly means of the FWI daily values estimated between 1980 and 2005. Figure 5 presents the FWI spatial distribution over Portugal, from May to October, between 1980 and 2005. According to Figure 5 July and August register the highest values and the southern regions are also the main affected. The monthly mean FWI values range from 1 to 32 depending on the region giving an indication on the associated fire danger. According to Viegas et al. (2004) the highest FWI values registered in the southern region are associated to low fire danger classes. On the contrary, in July and August the districts of the centre and north interior present FWI values ranging from 13 to 29, which are related to moderate to high level of, fire danger. The coastal regions in the north and Centre show the lowest FWI values ranging from 1 to 12. In these regions the obtained FWI values are related to a low to moderate level of fire danger.

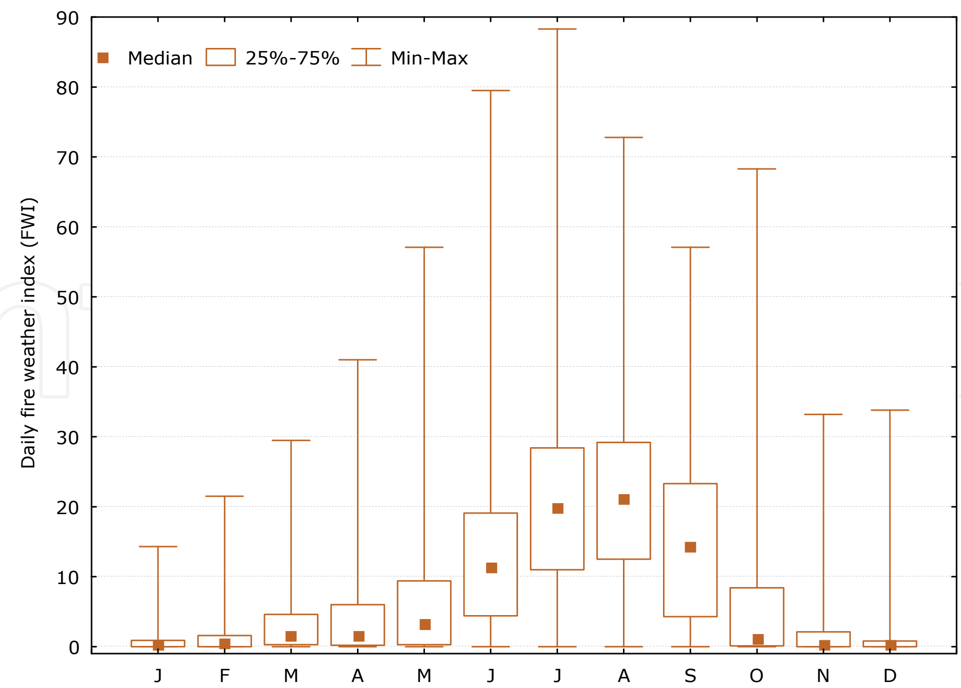
The FWI index spatial distribution has a markedly NW-SE gradient. The NW region of Portugal exhibits the lowest FWI values and the SE the highest. This gradient is in agreement with the temperature patterns and the mean sea level pressure field of the summer climatology observed over the Iberian Peninsula (Hoinka et al., 2009).



a)

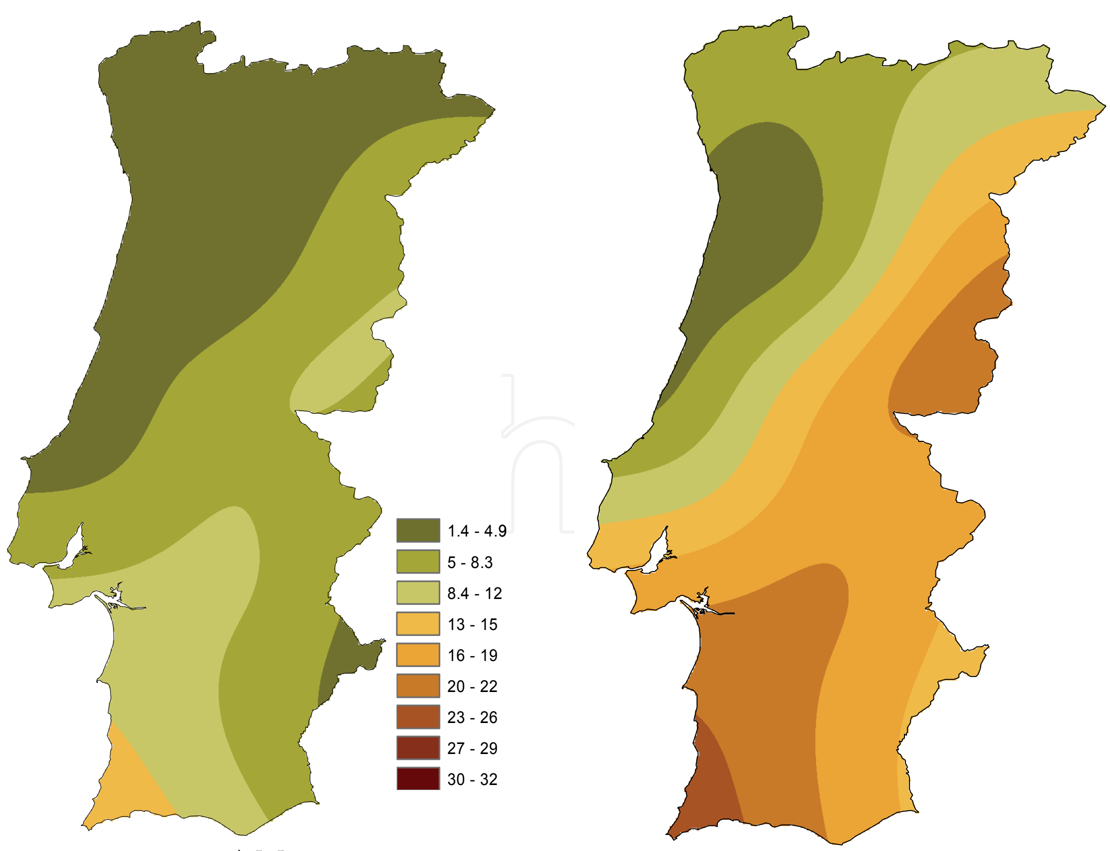


b)



c)

Fig. 4. Daily fire weather index (FWI) between 1980 and 2005 by a) district, b) year and c) month.



a) May

b) June

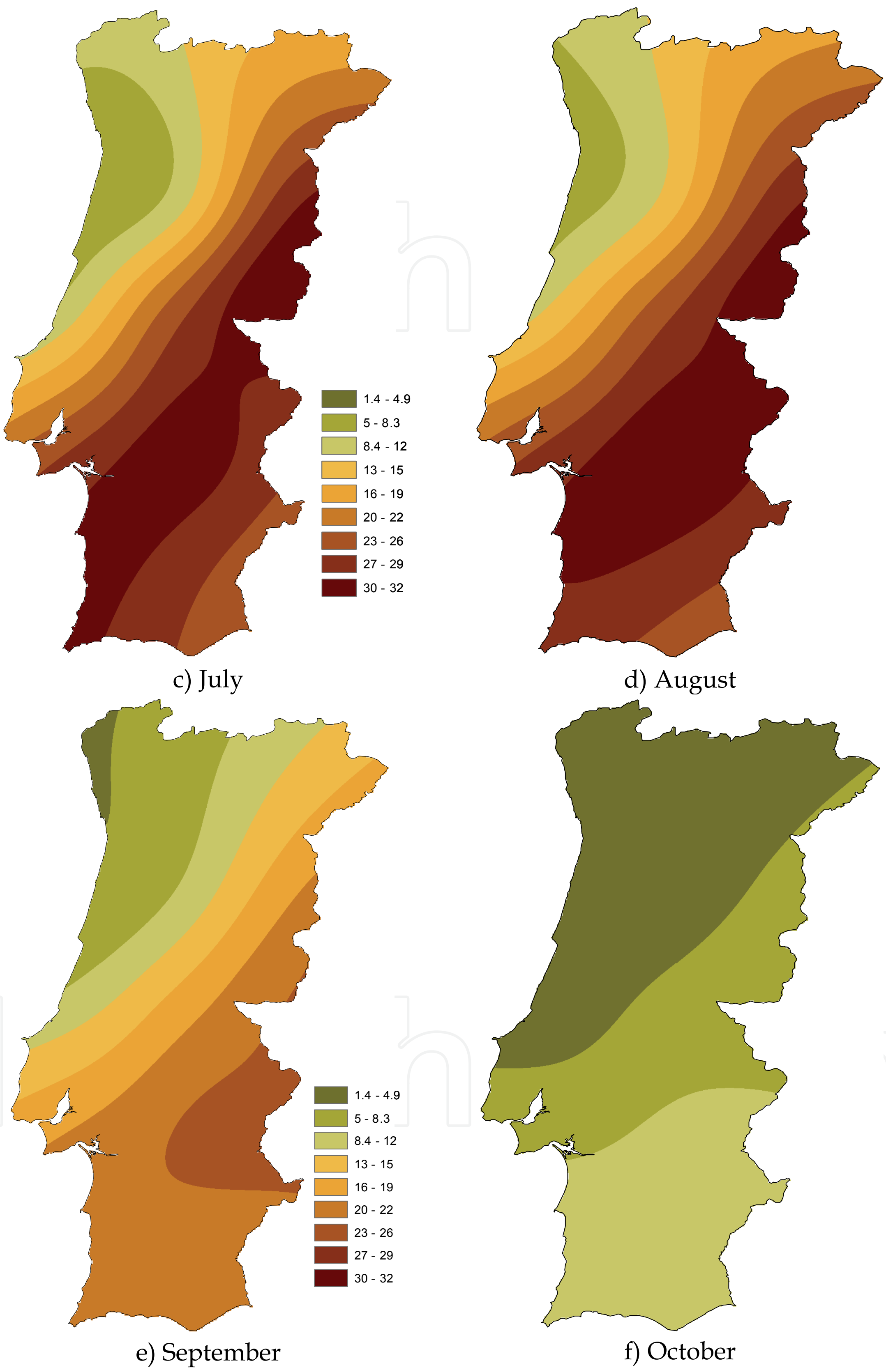


Fig. 5. Monthly mean fire weather index (FWI) between 1980 and 2005 for a) May, b) June, c) July, d) August, e) September, and f) October.

4. Climate change impacts on fire weather risk

To estimate the impacts of climate change on the fire weather risk, daily climatic data were collected from the regional climate model HIRHAM (Christensen et al., 1996), at 12 km spatial resolution from the Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects – PRUDENCE – project (Christensen and Christensen, 2007) considering the IPCC Special Report on Emissions Scenarios (SRES) A2 scenario. The IPCC SRES A2 scenario is characterized by a very heterogeneous world with a continuously increasing global population. The economic development is primarily regionally oriented and per capita economic growth and technological change is more fragmented and slower than in other IPCC scenarios. In this sense, the A2 is considered a high emission scenario. For the analysed time slices the IPCC SRES A2 is consistent to a 2 x CO_2 climatic scenario.

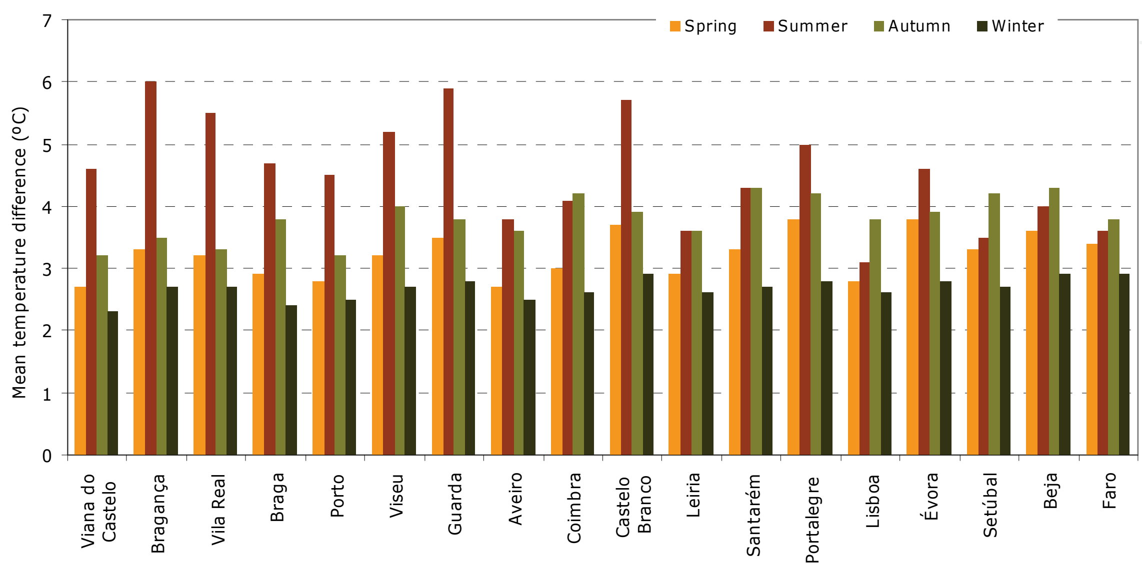
A detailed validation of the HIRHAM outputs was performed for 12 sites across Portugal between 1980 and 1990 (11 year period for which observed data were available). Using SAS version 9.1.3 monthly mean values of the simulated daily mean temperature, daily maximum temperature, daily mean wind speed, total precipitation, and daily mean relative humidity and fire weather risk variables were evaluated. According to the validation procedure the relative humidity presented significant differences against the observed data (Carvalho et al., 2010a). Concerning relative humidity the HIRHAM model presents drier values than the observed at the weather stations. In order to correct the relative humidity field the dew point temperature was evaluated and statistical significant differences were found. The HIRHAM model presents a cold bias in the dew point temperature fields and especially in the south of Portugal and in autumn. A correction factor was applied based on a monthly discrimination (Carvalho et al., 2010a). The correction factor was applied to the reference and to the future climate simulations. This approach has already been used in other works and is considered an adequate calibration procedure (e.g., Flannigan et al., 2005). The corrected climatic fields were used to estimate the FWI System components for reference (1961-1990) and future (2071-2100) scenarios.

The HIRHAM projections over Portugal point to an increase of the mean temperature in all seasons especially in summer, reaching almost 6 ºC in the inner districts of the country ($p<0.0001$) (Figure 6a). 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 (Figure 6b). These projections will deeply influence the fuel moisture conditions in future climate.

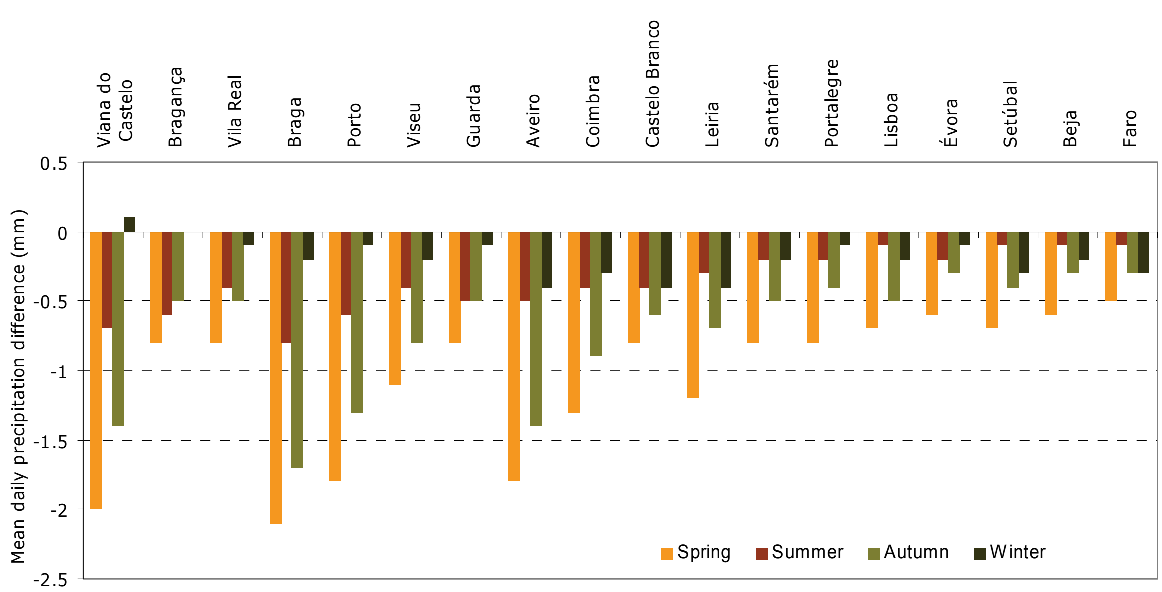
Concerning fire severity, all seasons experience an increase in the FWI component by the end of 21st century. The summer months of June, July and August show the highest FWI values. May registers the highest relative increases, October and November also exhibit high increases in the FWI index. This could lead to a clear anticipation of the fire season starting and an increase in its length. There is also a clear FWI increasing trend from north to south (Carvalho et al., 2010a).

Figure 7 exhibits the FWI cumulative frequency distribution for each scenario by district. To help on the discussion the districts are organized by north, centre and south of Portugal.

The obtained cumulative distribution functions clearly show the FWI shift to attain higher values in a future climatic scenario. The districts of the north formed by Viana do Castelo, Bragança, Vila Real, Braga, and Porto show an increase of the maximum FWI range of values from 26-53 to 45-76. The 50th percentile also shows an increase but not so pronounced. The districts in the Centre like Viseu, Guarda, Aveiro, Coimbra, Castelo Branco and Leiria, also present an increase in the FWI maximum values ranging from 39-55 to 55-71 from the reference to the future climatic scenario. The southern districts of Santarém, Portalegre, Lisboa, Évora, Setúbal, Beja and Faro present the highest FWI maximum values in the reference scenario and the same is verified in the future climate. The FWI values between the 25th percentile and the maximum show a clear increase in all southern districts. In this part of the country the FWI ranges from 50-71 and in future climate these values increase to 57-76.

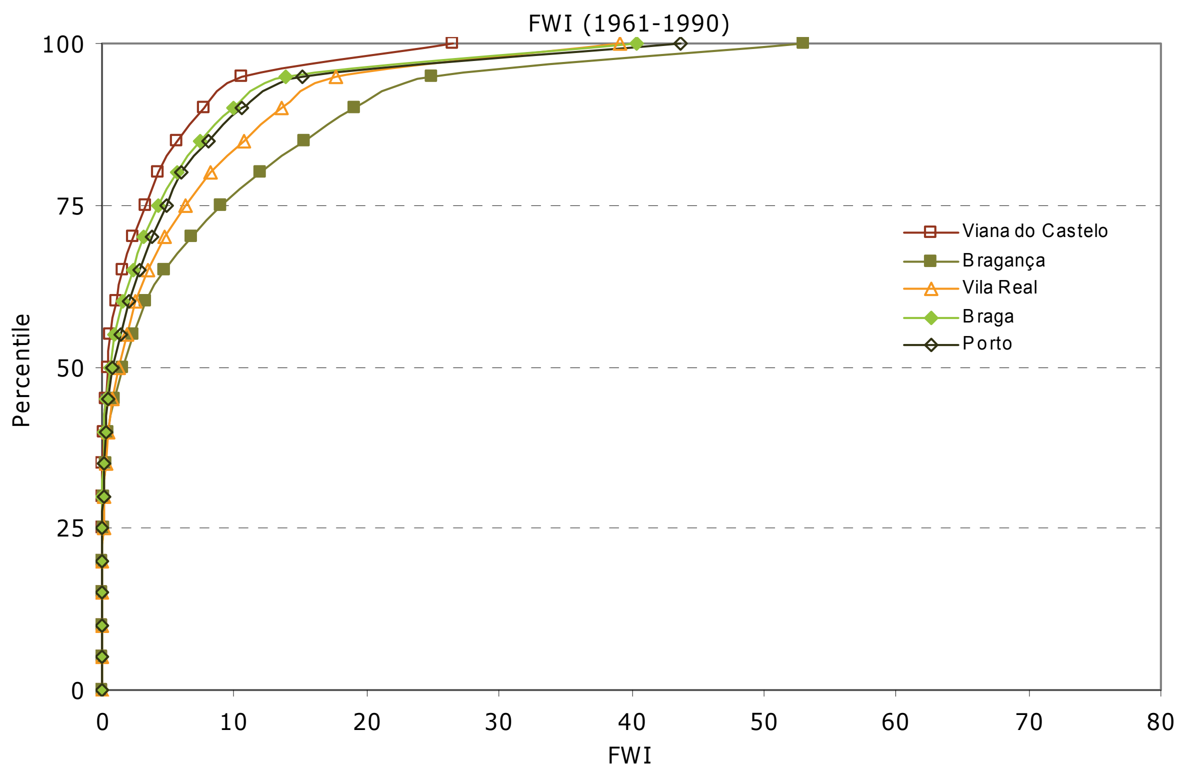


a)



b)

Fig. 6. Differences between future (2071-2100) and reference (1961-1990) climatic scenarios for a) daily mean temperature and b) daily precipitation, by season and for each Portuguese district.



FWI (1961-1990)
100
75
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25
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Percentile
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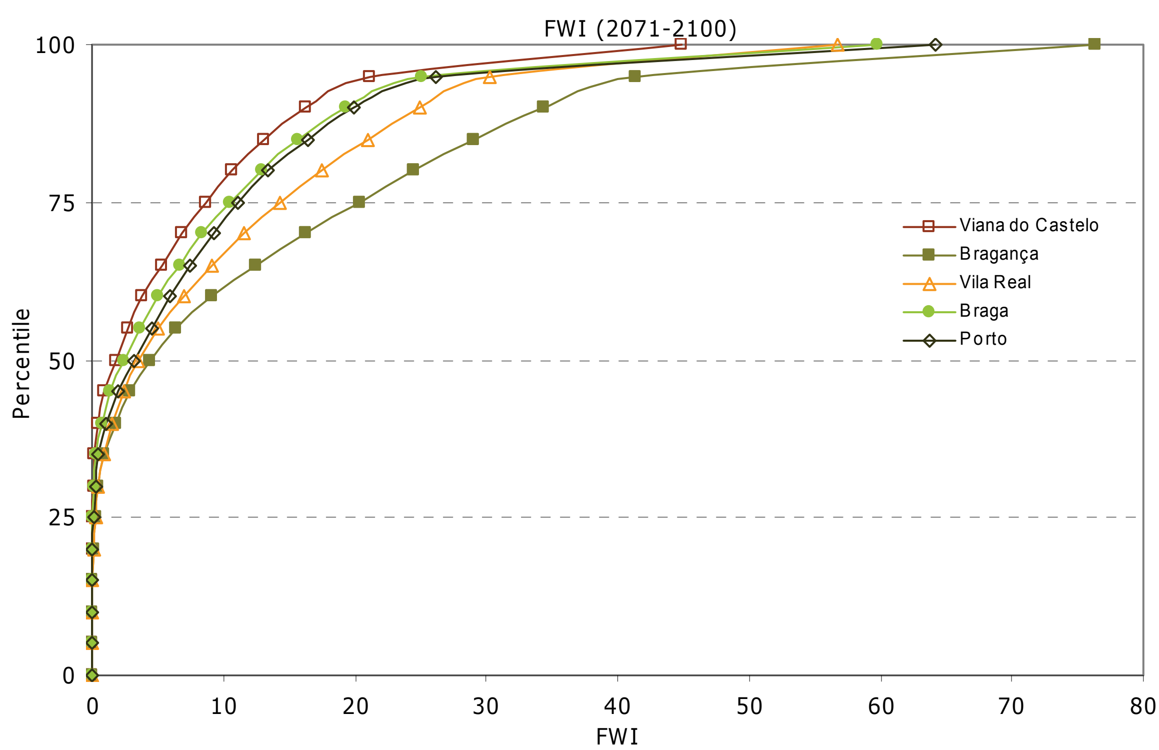
70
80
FWI
Viana do Castelo
Bragança
Vila Real
Braga
Porto



FWI (2071-2100)
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75
50
25
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Percentile
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Viana do Castelo
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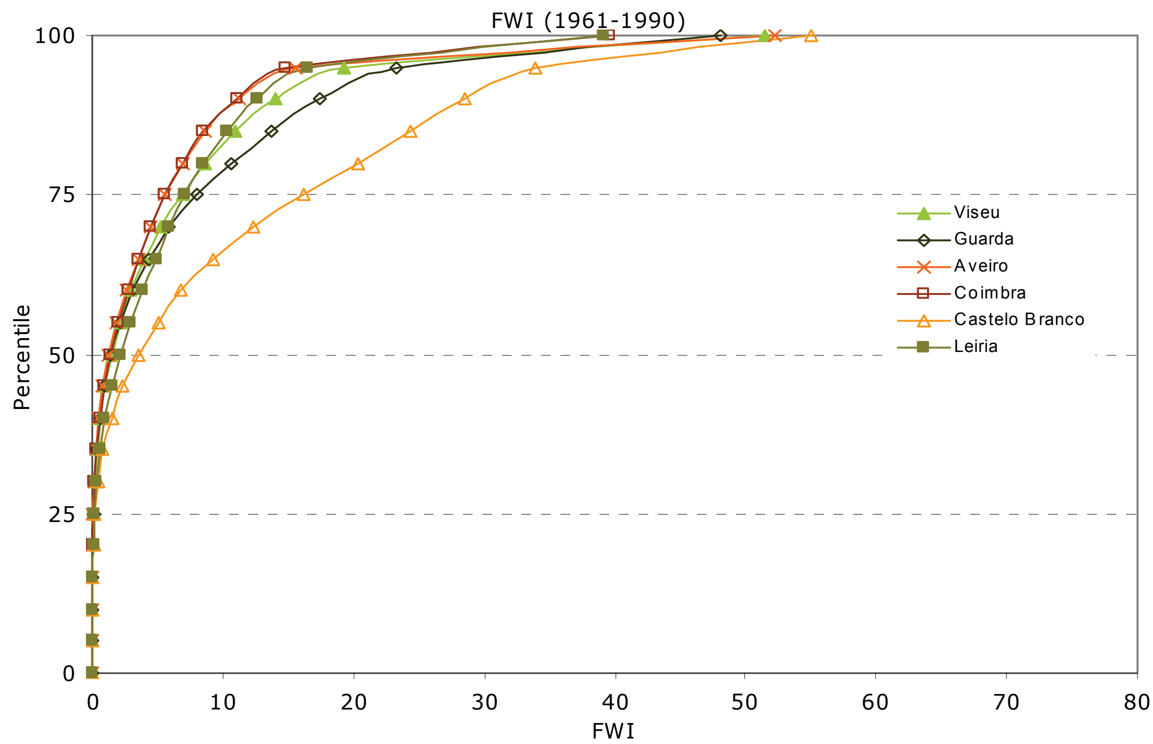
Porto


FWI (1961-1990)
Percentile
FWI
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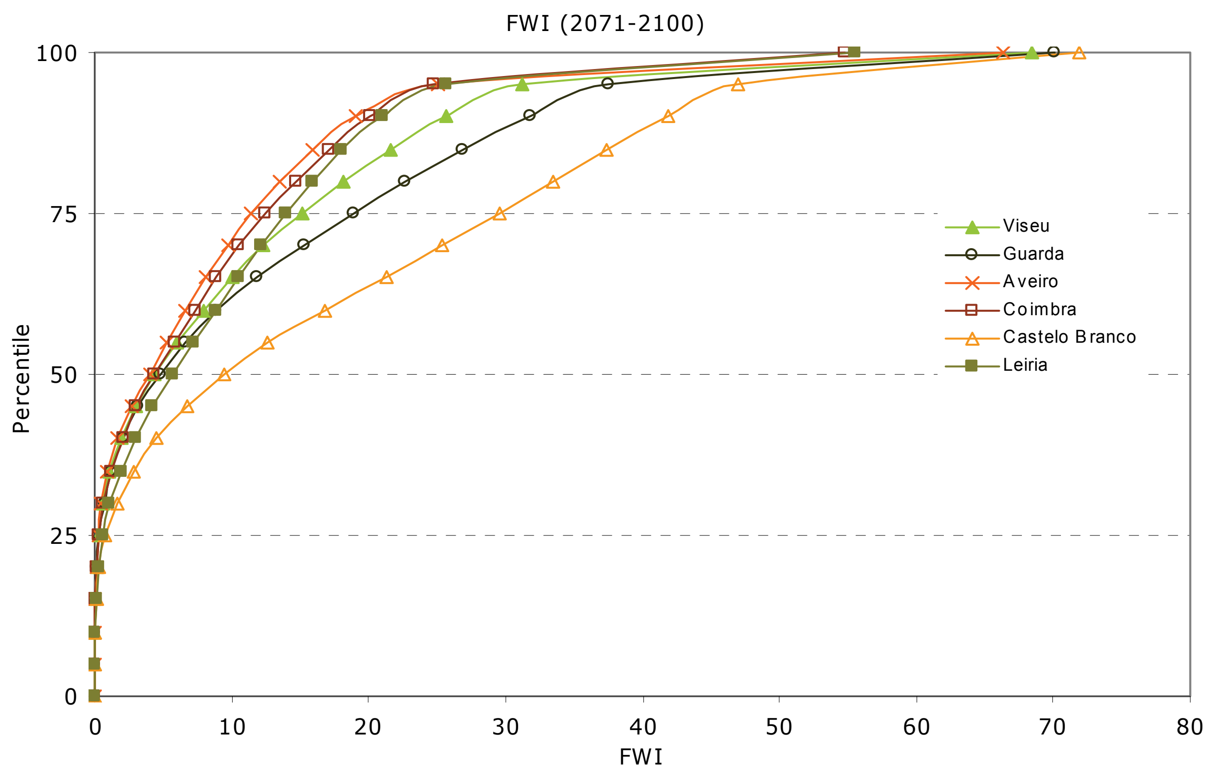
Leiria


FWI (2071-2100)
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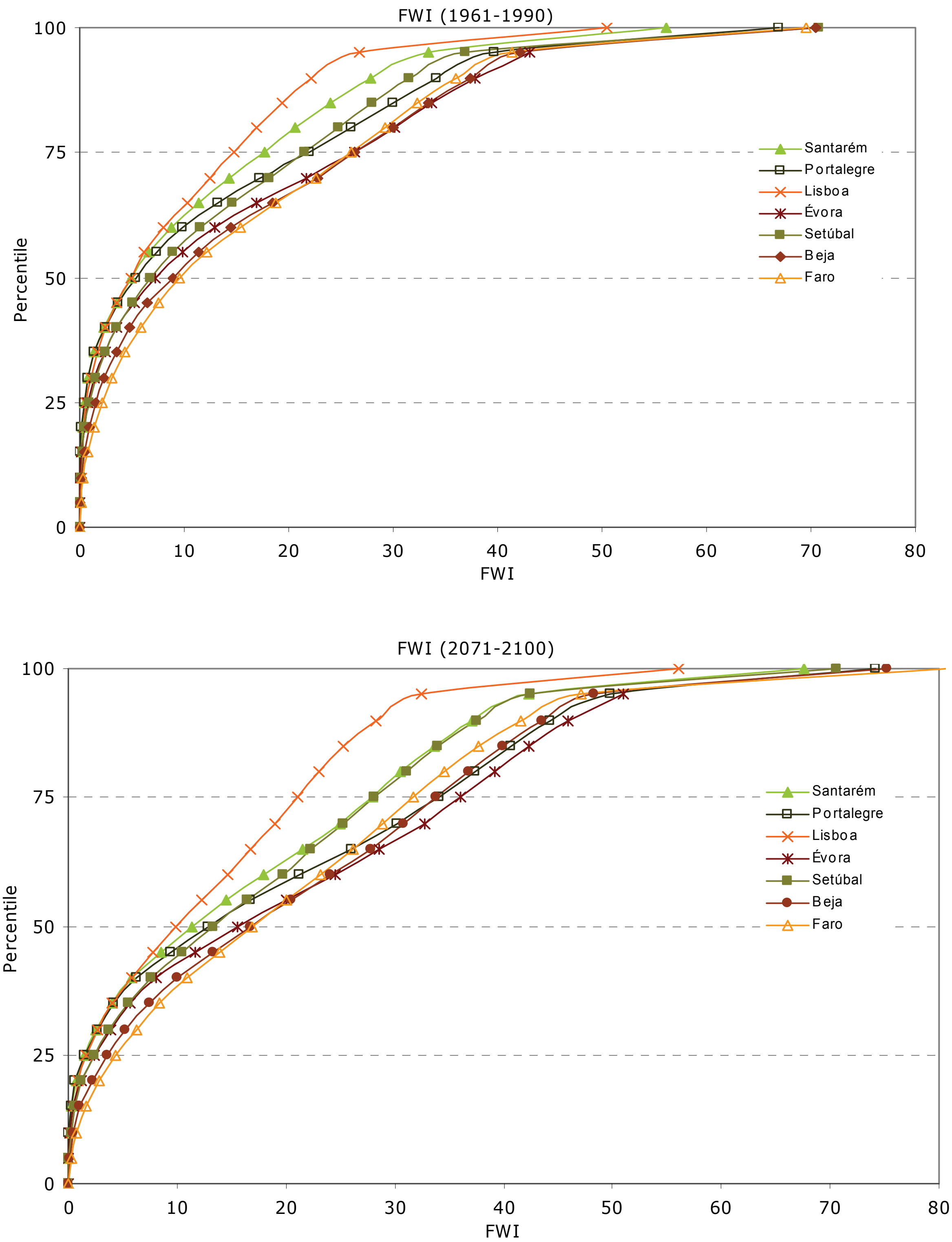


Fig. 7. Cumulative frequency distribution of the daily FWI component by district and for each climatic scenario (reference and 2 x CO_2). The districts are organized by north, centre and south of Portugal.

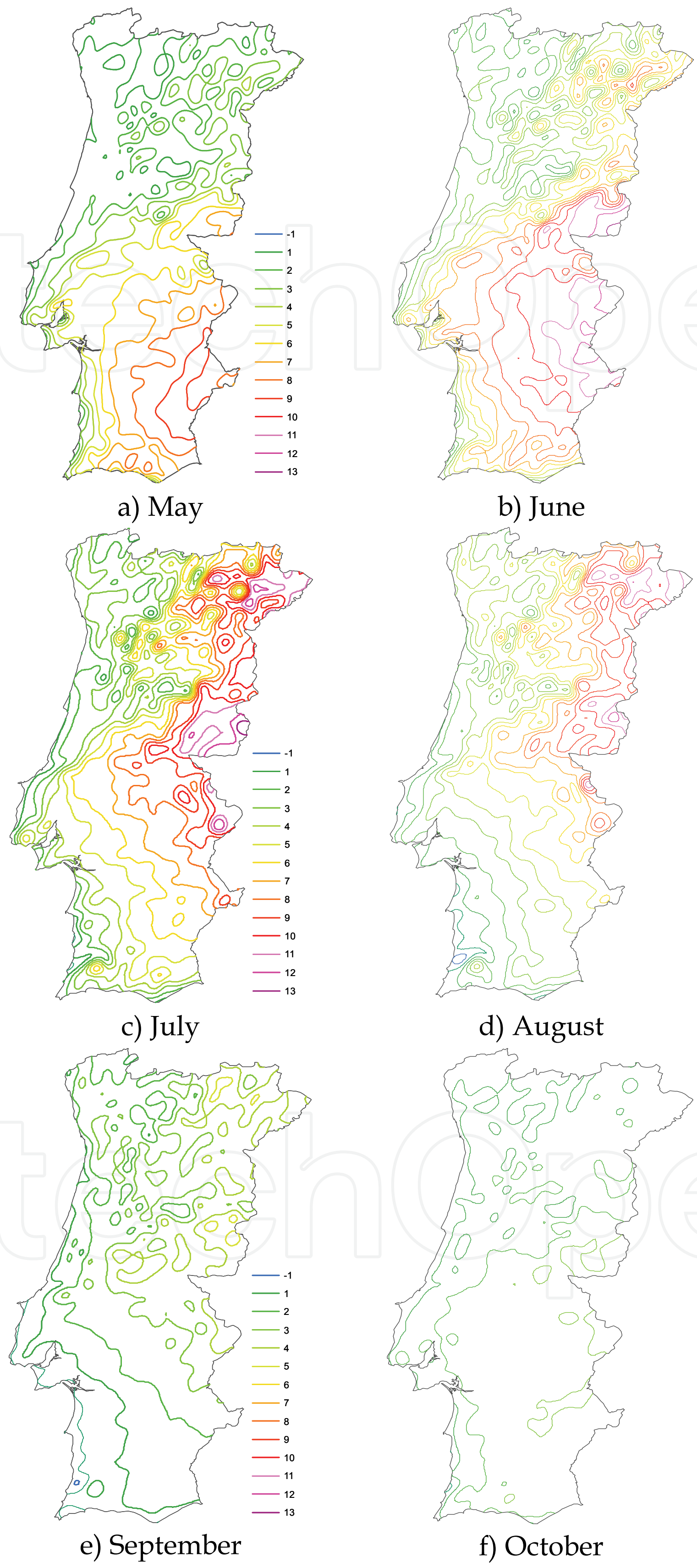


Fig. 8. FWI changes between future and reference scenarios for a) May, b) June, c) July, d) August, e) September, and f) October.

Figure 8 presents the differences on the FWI patterns for May, June, July, August, September, and October between future and reference climatic scenarios. As previously noted, all the districts across Portugal experience an increase on the FWI component but this is more pronounced in the inner regions. July and August show the highest increases namely in the districts of Bragança, Guarda, and Castelo Branco. These districts form a regional elongated pattern that goes from north to the centre just close to the Spanish border. September and October exhibit a very homogeneous pattern of increase from north to south.

The area burned and the number of fires in Portugal is strongly dependent on the weather conditions. So, it is expected that fire activity will increase with a changing climate. In Carvalho et al. (2008) statistically significant relationships were established between the area burned, the number of fires and the weather for different Portuguese districts. The authors have concluded that the weather explains the majority of the variance of the area burned and of the number of fires in Portugal. The obtained statistical models were used to estimate the area burned and the number of fires for future climate. The results point to a substantial increase in the area burned and on the number of fires ranging from 238 % to 643 % and 111 % to 483 %, respectively, depending on the Portuguese district (Carvalho et al., 2010a). The regions in the central part of the country will be the most affected. The monthly distribution of the area burned and number of fires indicates that an earlier fire season starting may be expected under future climate.

5. Forest fires and climate change impacts in particulate matter and ozone levels

The impact of climate change and future area burned on forest fire emissions and consequently on regional air quality was assessed through the application of the MM5/CHIMERE numerical modelling system. This numerical system has been widely tested and successfully used over Portugal (Monteiro et al., 2005; Monteiro et al., 2007; Monteiro, 2007). The HadAM3P (Jones et al., 2005) simulations for the reference and the IPCC SRES A2 climatic scenario were used to driven the MM5/CHIMERE modelling system. The forest fire emissions for both scenarios were estimated and considered in the air quality simulations over Portugal.

The air quality modelling application was performed using the chemistry-transport model CHIMERE (Schmidt et al., 2001; Bessagnet et al., 2004), forced by the musicale model MM5 (Grell et al., 1994). The MM5 model has been used worldwide in several regional climate studies (e.g., Boo et al., 2004; Van Dijck et al., 2005). 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 Fifth-Generation Penn State University/National Center for Atmospheric Research (PNU/NCAR) Mesoscale Model, known as the MM5, is a no hydrostatic, vertical sigma-coordinate model designed to simulate musicale 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 (Ferreira et al., 2004; Aquilina et al., 2005; Carvalho et al., 2006) and over the Iberian Peninsula (Fernandez et al., 2007). A detailed description of the selected simulation characteristics is presented in Carvalho et al. (2010b). The MM5 model generated 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 European and urban scales. The 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 non-methane volatile organic compounds (NMVOCs) are disaggregated into 227 individual VOCs according to the speciation suggested by Passant (2002) for each activity sector. The methodology for biogenic emissions of isoprene and terrenes 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. The gas-phase chemistry scheme, derived from the original complete chemical mechanism MELCHIOR (Lattuati, 1997), has been extended to include sulphur aqueous chemistry, secondary organic chemistry and heterogeneous chemistry of HONO and nitrate (Hodzic et al., 2005). The model simulates the concentration of 44 gaseous species and 6 aerosol chemical compounds.

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, SO_2, NMVOC and NH_3 gas-phase species, and for PM2.5 and PM10 are provided by the 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., 2005). This inventory takes into account annual emissions from line sources (streets and highways), area sources (industrial and residential combustion, solvents and others) and large point sources (with available monitoring data at each industrial plant). Time disaggregation was calculated by the application of monthly, weekly, and hourly profiles obtained in the scope of the GENEMIS Project (GENEMIS, 1994).

In the present analysis, the CHIMERE model was applied first at the European scale (with 50 x 50 km^2 resolution) and then over Portugal using the same physics and a simple one-way nesting technique, with 10 x 10 km^2 horizontal resolution. The vertical resolution 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., 2004) and GOCART (aerosols) (Ginoux et al., 2001) global chemistry transport models. Transport of Saharan dust from the GOCART boundary conditions, 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 European scale simulation.

In order to simulate the impact of climate change on air quality the MM5/CHIMERE modelling system was forced by the Hadley Centre global atmospheric circulation model HadAM3P (Jones et al., 2005). Reference (1990) and the IPCC SRES-A2 climatic scenario

(2100) over Europe and over Portugal were simulated by dynamical downscalling using the outputs of HadAM3P, as initial and boundary conditions to the MM5 model. The MM5 model requires initial and time evolving boundary conditions for wind components, temperature, geopotential height, relative humidity and surface pressure. MM5 also requires the specification of SSTs Carvalho et al. (2010b).

The integration between the HadAM3P outputs and the MM5 model was set through a programming stage that was implemented in order to convert, interpolate and generate the pressure levels and the data formats requirements needed for the MM5 simulations. The downscaling of the global model outputs to the MM5 model has already been carried out for the regional climate change simulations over South America (Solman et al., 2007).

To better evaluate the influence of the future fire activity on air quality, the anthropogenic emissions were kept constant in the simulations for the 2100 scenario. The emissions 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 climate. This idealized regional model simulation provides insights into the contribution of possible future climate changes on ozone and particulate matter concentrations. The forest fire emissions were just included in the simulation over Portugal. The European domain simulation did not take into account these emissions.

Based on future area burned projections (Carvalho et al., 2010a) it was possible to estimate forest fire emissions. Forest fire emissions depend on multiple and interdependent factors like forest fuels characteristics, burning efficiency, burning phase, fire type, meteorology, and geographical location. The forest fire emissions concerning CO_2, CO, methane (CH_4), non methane hydrocarbons (NMHC), PM2.5, PM10 and NO_x were estimated based on the methodology investigated in previous studies over Portugal (Miranda et al., 2004; Miranda et al., 2005b). The annual forest fire emissions were estimated for 1990 and for 2100 climates and then included in the CHIMERE model application over Portugal (Carvalho, 2008). Monthly and hourly profiles of forest fire activity were considered in the emissions temporal disaggregation for both climates. All Portuguese districts suffer a substantial increase in emissions due to the projected increases on the area burned (Carvalho, 2008). This increase on the forest fire emissions is proportional to the area burned projections. The annual CO_2 equivalent emissions derived from forest fires account for 1.27 Mton for the 1980-1990 period and 7.44 Mton in a 2 x CO_2 scenario. This represents an overall increase of approximately 500 %.

The MM5/CHIMERE simulations were conducted from May 1st to October 30th for 1990 and 2100. Over Portugal the simulation design comprised three approaches:

- 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.

In this sense and in order to assess the impact on air quality it is possible to analyse the changes only due to climate change and the impact of both climate change and future forest fire emissions.

Figure 9 exhibits 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).

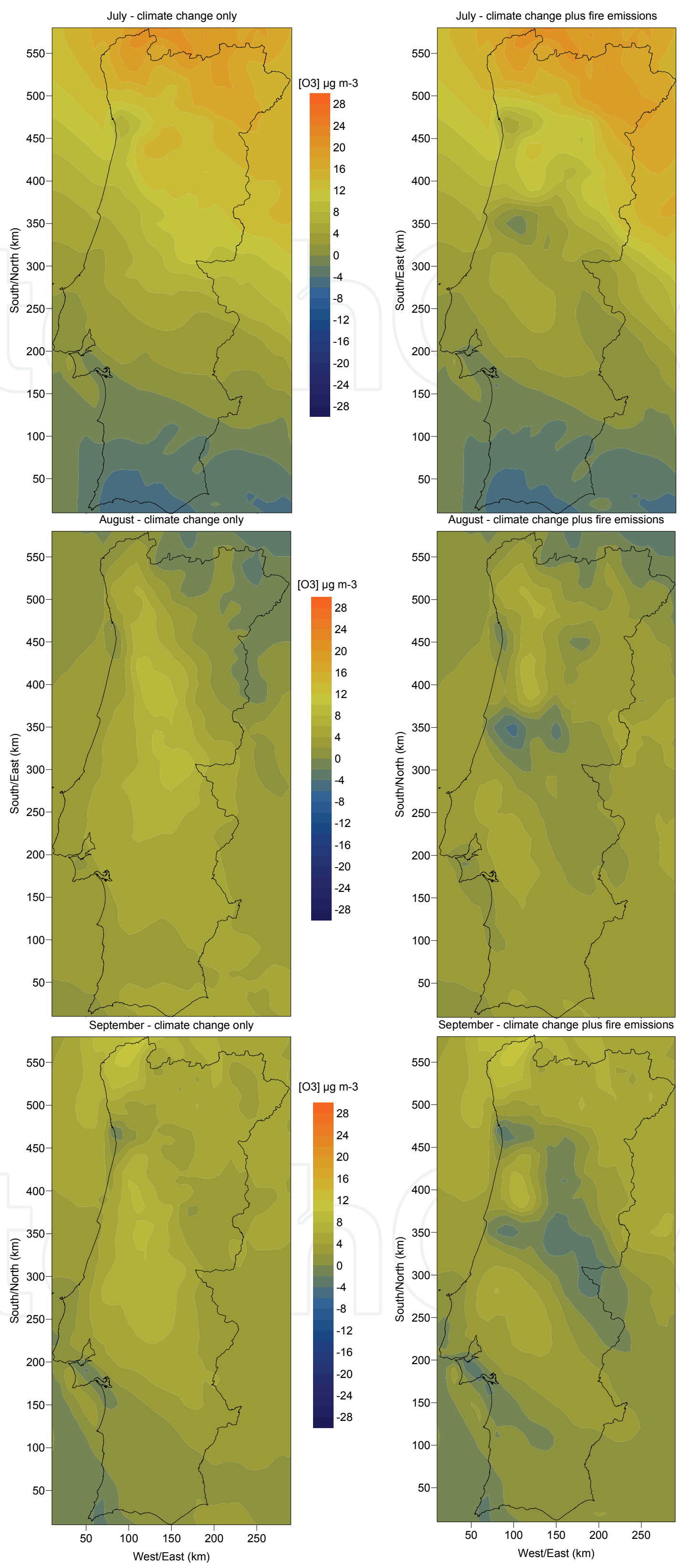


Fig. 9. Monthly mean surface O_3 changes simulated over Portugal considering only climate change (S1 – C1) and climate change and future fire emissions (S2 – C1) for July, August, and September.

The highest increase in O_3 concentrations are detected in July but this is clearly influenced by the air quality boundary conditions settled in the north of Portugal by the European domain (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 Carvalho et al. (2010b). If future forest fire emissions are considered the regions in the centre of Portugal especially over Coimbra and Porto in the north experience a smaller increase or even a reduction in the O_3 concentrations (-1.2 $\mu g.m^{-3}$ in July, -4.9 $\mu g.m^{-3}$ in August and -3.8 $\mu g.m^{-3}$ in September). This feature is probably due to the O_3 consumption promoted by the O_3 precursor's emissions (like NO_x, CO and VOC) released by the forest fires in these regions.

The area burned projections (Carvalho et al., 2010a) highlight the district of Coimbra as the main affected. Consequently the future forest fire emissions are highest in this region. The 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 (Stich et al., 2007). In Figure 9 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 markedly daily profile closely connected to the photochemical activity that reaches its maximum during the afternoon. In this sense and in order to make a more detailed discussion on the O_3 concentrations change along the diurnal cycle the O_3 average values at 12, 15 and 18 UTC are discussed for August (Figure 10).

At noon, the highest O_3 level is observed for the S2 scenario reaching 108 $\mu g.m^{-3}$ in the inner part of the country (not shown). Considering the climate change impacts only, 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 ozone in the atmosphere are observed at 15 UTC, reaching almost 130 $\mu g.m^{-3}$ in the S2 scenario (not shown). It can also be detected the increase of the pollutant plume with higher concentrations and its spreading towards the centre and the southern part of the country. At this time Coimbra district registers a decrease on the ozone levels (S2-C1) (-10 $\mu g.m^{-3}$) that may be related with the higher amounts of forest fire emissions released 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 approximately 27 $\mu g.m^{-3}$ and 28 $\mu g.m^{-3}$ for the S1 and S2 scenario, respectively.

By the end of the afternoon, at 18 UTC, the ozone plume differences (scenario S2-C1) with higher concentrations diminish its extension and a decrease 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 $\mu g.m^{-3}$. 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 Lisbon.

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 boundary height, wind speed and relative humidity may also influence the obtained ozone concentration patterns (Carvalho et al., 2010b).

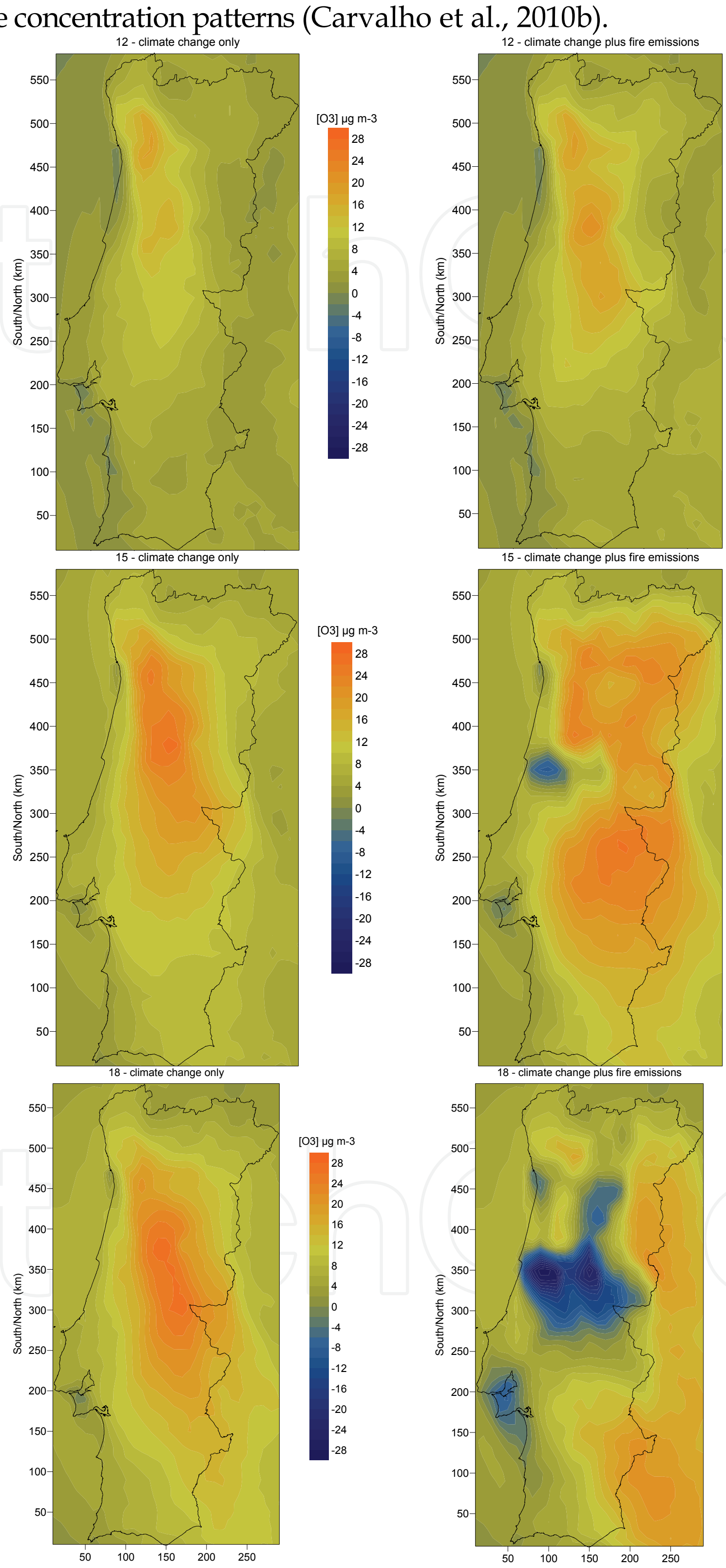


Fig. 10. Hourly average O_3 concentrations changes for August at 12, 15 and 18 UTC considering climate change only (S1-C1) and climate change and future forest fire emissions (S2-C1).

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 modeling that allocates the highest percentage of the released emissions from noon to 18 UTC (Carvalho, 2008). After 18 UTC the forest fire pollutants emitted to the atmosphere are leading to the O_3 consumption.

Particulate matter is an important pollutant emitted from forest fires that can lead to severe air pollution episodes and visibility impairment (Valente et al., 2007). Figure 11 depicts the monthly average of the PM10 changes for July, August, and September considering only climate change and climate change and future forest fire emissions.

Only due to climate change impact the PM10 concentrations diminish almost 36 $\mu g.m^{-3}$ over Porto region in May. In the rest of the country the values register a maximum increase of 4 $\mu g.m^{-3}$. In June the range of variation of the PM10 concentrations goes from -10 $\mu g.m^{-3}$ over Porto region to +10 $\mu g.m^{-3}$ along the coastal regions (Carvalho et al., 2010b).

In July it is possible to see the different plume patterns between simulations considering or not the future forest fire emissions. The PM10 levels increase 20 $\mu g.m^{-3}$ over Porto region due to climate change and future forest fire emissions. Only due to climate change the PM10 levels in July may raise up to 18 $\mu g.m^{-3}$. The influence of future forest fire emissions is visible in the PM10 plume extension presenting higher concentrations over Porto, Coimbra, and Viseu districts. It is clearly visible that the registered increases are located in the north and centre part of Portugal. The PM10 values diminish over the Atlantic Ocean and over the coast in Sines region.

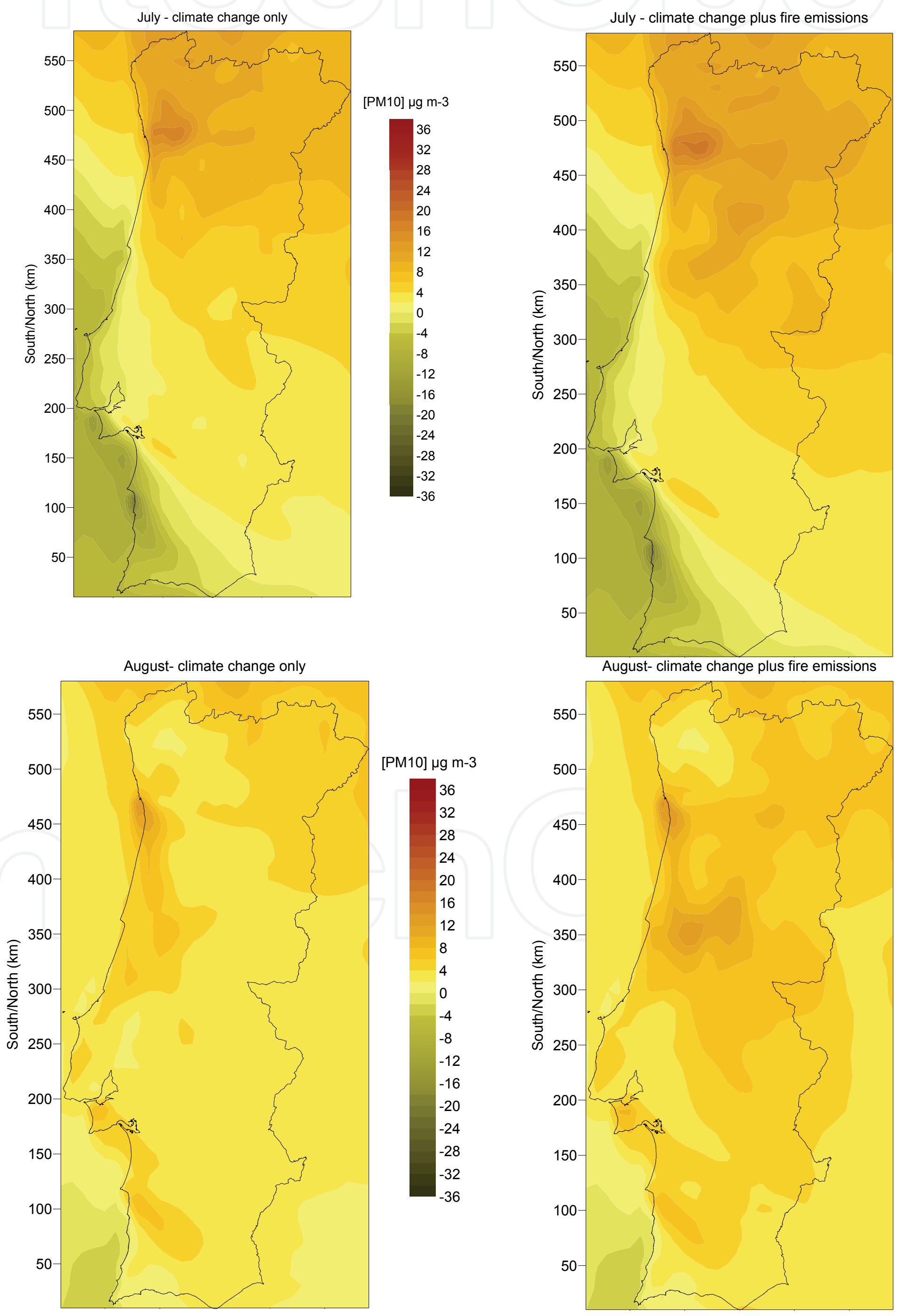
In August the PM10 plume shows its highest concentrations again over the centre of Portugal and in Bragança district for the simulation considering climate change and future forest fire emissions. The maximum increase in PM10 values is 15 $\mu g.m^{-3}$ considering only climate change and 16 $\mu g\ m^{-3}$ under climate change and future forest fire emissions. The PM10 dispersion plume clearly shows the influence of the forest fires emissions on the atmospheric concentrations of this pollutant.

September and October register the highest increases on the PM10 values reaching 30 $\mu g.m^{-3}$ and 26 $\mu g.m^{-3}$, respectively, just due to climate change (Carvalho et al., 2010b). The maximum increases are always observed over Porto region. In September, the increase on the PM10 values due to climate change and future forest fire emissions are visible in the pollutants dispersion plume with higher values over Coimbra, Viseu, and Castelo Branco districts with a maximum increase of 32 $\mu g.m^{-3}$.

In summary, the monthly PM10 average values revealed that climate change may deeply impact its levels in the atmosphere. The Porto region is the most affected one in terms of PM10 increases (Carvalho et al., 2010b). Nowadays Porto region faces specific air quality problems closely related to the high levels of PM10 that are registered at the monitoring network (Borrego et al., 2010).

The months of July, August, and September present a clear increase in the PM10 levels due to climate change and the inclusion of future forest fire emissions reaches concentration increases of 32 $\mu g.m^{-3}$. Climate change alone may increase the PM10 average levels in

30 µg.m-3 (Carvalho et al., 2010b). At some extent this should be related to the different dispersion characteristics that may prevail in future climate namely related to boundary layer height, relative humidity and wind speed (Carvalho, 2008). Using a global chemical transport model Spracklen 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.



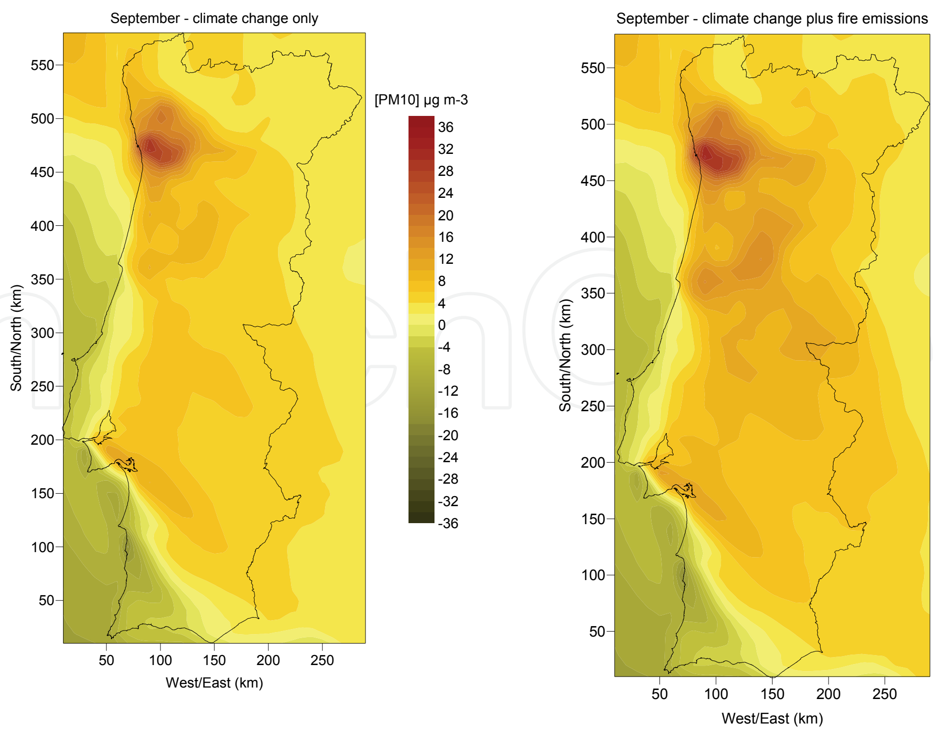


Fig. 11. Monthly average PM10 concentrations over Portugal considering climate change only (S1 – C1) and climate change and future fire emissions (S2 – C1) for July, August and September.

6. Final remarks

The main aim of this study was to evaluate the impacts of the IPCC SRES A2 climatic scenario on forest fire activity and on air quality over Portugal.

The analysis indicates an increase in the average and extremes values of the FWI component in all Portuguese districts. The fire weather severity attains higher values in a future climatic scenario. The districts of the north and centre of Portugal show the highest raises in the FWI component. Almost all the Portuguese districts will face at least 100 % increase on the fire weather risk during spring.

The percentile estimations of the FWI system components were evaluated for both climates and for each Portuguese district. The obtained cumulative frequency functions clearly show the fire weather severity shifts to attain higher values in a future climatic scenario. The districts of the north and centre of Portugal show the highest increases in the FWI cumulative frequency distribution. This fact may be closely related to the occurrence of a higher number of extreme events under the SRES A2 scenario. The occurrence of these extreme weather conditions will dramatically influence forest fire activity over Portugal.

The estimated impact on future fire weather risk will dramatically increase the future area burned and number of fires. The implication of the projected area burned on future forest fire emissions and its impacts on air quality was assessed. The MM5/CHIMERE simulations pointed out that there may be significant increases of O_3 and PM10 levels in the atmosphere under climate change conditions but decreases over specific regions may also be registered.

This analysis revealed that an increase on future forest fire emissions does not directly mean that ozone levels in the atmosphere will increase. The interplay between pollutants concentrations (like NO_x and VOC), surface emissions, and meteorology leads to strong nonlinearities for the atmospheric ozone chemistry. The interaction between ozone precursor's emissions and ozone formation and depletion may be deeply impacted under future climatic scenarios. The knowledge of these relationships constitutes an important tool to correctly evaluate the role of forest fires on air quality under a changing climate.

The projected impacts of forest fire emissions on O_3 and PM10 levels in the atmosphere raise the concern regarding the application of prescribed burning as a management tool. It is recognized that forest fires release high amounts of pollutants to the atmosphere that, in the short term, may lead to acute air pollution episodes with important human health injuries. An adequate prescribed burning planning should also consider the potential impacts of forest fire emissions on the air quality of a region. The obligation for the fulfilment of the European and national air quality standards is an important issue to be taken into account during these initiatives.

The achieved results point to dramatic consequences of climate change on future forest fire activity and on air quality over Portugal. Future developments should consider other variables that could better represent the relationship between climate change, forestry dynamics, land-use change and future human activities. The use of dynamic vegetation models and/or landscape models could better represent the interaction between weather, vegetation changes, forest fires and human activities. The application of today's developed statistical models implies that the relationships between forest fires and weather would remain the same under future climatic scenario and this may not correspond to the truth. A dynamic analysis of these interactions could lead to a better representation of the weather, fire and climate relationships.

The human influence on forest fire activity is another variable that should be addressed. Due to lack of information it was not possible to effectively assess the influence of human activities and human behaviour on forest fire numbers. This variable may change dramatically in future and thus influencing the forest fire statistics and their related impacts.

The application of more than one climatic scenario gives the opportunity to better characterize the range of possible changes that can be detected in future. An ensemble of the several possible scenarios for future climate may give important information regarding uncertainty analysis and promote a better characterization of the future forest fire activity and air quality over Portugal. The use of an ensemble approach will be particularly important to provide uncertainty information and bracket the response. This would represent an important added value to the already projected changes. The analysis of the impacts of climate change and designed pollutant emissions reduction policies would constitute an important step forward to effectively assess the impact of the implemented measures on the air quality of the next 20 to 30 years.

This work represents an important attempt to relate climate change, forest fires and air quality over Portugal. The achieved results and main outcomes constitute an adequate scientific tool to support the implementation of measures and plans in the forest fire management and in the air quality fields.

7. References

Amiro, B.D.; Todd, J.B., Wotton; B.M., Logan, K.A.; Flannigan, M.D.; Stocks, B.J.; Mason, J.A.; Martell, D.L. & Hirsch, K.G. (2001a). Direct carbon emissions from Canadian forest fires, 1959 to 1999. *Canadian Journal of Forestry Research* 31, 512-525.

Amiro, B.D.; Stocks, B.J.; Alexander, M.E.; Flannigan, M.D. & Wotton, B.M. (2001b). Fire, climate change, carbon and fuel management in the Canadian boreal forest. *International Journal of Wildland Fire* **10**, 405–413.

APIF – Agência para a Prevenção de Incêndios Florestais (Agency for the Forests Fires Prevention) (2005). Proposta Técnica de Plano Nacional de Defesa da Floresta contra Incêndios – Plano de Acção. Vol. II, (Lisboa, Portugal).

Aquilina, N.; Dudek, A.V.; Carvalho, A.; Borrego, C. & Nordeng, T.E. (2005). MM5 high resolution simulations over Lisbon. Geophysical Research Abstracts. Vol. 7, 08685, SRef-ID: 1607-7962/gra/EGU05-A-08685. European Geosciences Union 2005.

Bessagnet, B.; Hodzic, A.; Vautard, R.; Beekmann, M.; Cheinet, S.; Honore; C.; Liousse, C. & Rouil, L. (2004). Aerosol modeling with CHIMERE— Preliminary evaluation at the continental scale. *Atmospheric Environment* 38, 2803– 2817.

Boo, K.; Kwon, W.; Oh, J. & Baek, H. (2004). Response of global warming on regional climate change over Korea: An experiment with the MM5 model. *Geophysical Research Letters* 31, L21206, doi: 10.1029/2004GL021171

Borrego, C.; Miranda, A.I.; Carvalho, A.C. & Fernandez, C. (2000). Climate change impact on the air quality: the Portuguese case. *Global Nest – the International Journal* 2(2), 199-208.

Borrego, C.; Valente, J.; Carvalho, A.; Sá, E.; Lopes, M. & Miranda, A.I. (2010). Contribution of residential wood combustion to the PM10 levels in the atmosphere. *Atmospheric Environment* 44, 642-651, DOI:10.1016/j.atmosenv.2009.11.020

Brown, T.J.; Hall, B.L. & Westerling, A.L. (2004). The impacts of twenty-first century climate change on wildland fire danger in the western United States: an application perspective. *Climatic Change* **62**, 365-388.

Carvalho, A. (2008). Forest fires and air quality under a climate change scenario. PhD Thesis. Department of Environment and Planning. University of Aveiro. Aveiro.

Carvalho, A.; Flannigan, M.; Logan, K.; Gowman, L.; Miranda, A.I. & Borrego C. (2010a). The impact of spatial resolution on area burned and fire occurrence projections in Portugal under climate change. *Climatic Change* **98**, 177–197 DOI: 10.1007/s10584-009-9667-2

Carvalho, A.; Flannigan, M.; Logan, K.; Miranda, A.I. & Borrego, C., 2008: Fire activity in Portugal and its relationship to weather and the Canadian Fire Weather Index System. *International Journal of Wildland Fire* **17**, 328-338.

Carvalho, A., Monteiro, A., Solman, S., Miranda, A.I., Borrego, C., 2010b. Climate-driven changes in air quality over Europe by the end of the 21st century, with special reference to Portugal. Environment Science & Policy, DOI: 10.1016/ j.envsci.2010.05.001.

Carvalho, A.C.; Carvalho, A.; Gelpi, I.; Barreiro, M.; Borrego, C.; Miranda, A.I. & Perez-Munuzuri, V. (2006). Influence of topography and land use on pollutants dispersion in the Atlantic coast of Iberian Peninsula. *Atmospheric Environment* 40 (21), 3969-3982.

Christensen, J.H. & Christensen, O.B. (2007). A summary of the PRUDENCE model projections of changes in European climate by the end of this century. *Climatic Change*, doi: 10.1007/s10584-006-9210-7.

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.

Crutzen, P.; Heidt, L.; Krasnec, J.; Pollock, W. & Seiler, W. (1979). Biomass burning as a source of atmospheric gases CO, H2, N2O, NO, CH3Cl and COS. *Nature* 282(5736), 253-256.

Dentener, F.; Stevenson, D.; Ellingsen, K.; van Noije, T.; Schultz, M.; Amann, M.; Atherton, C.; Bell, N.; Bergmann, D.; Bey, I.; Bouwman, L.; Butler, T.; Cofala, J.; Collins, B.; Drevet, J.; Doherty, R.; Eickhout, B.; Eskes, H.; Fiore, A.; Gauss, M.; Hauglustaine, D.; Horowitz, L.; Isaksen, I.; Josse, B.; Lawrence, M.; Krol, M.; Lamarque, J. F.; Montanaro, V.; Möller, J. F.; Peuch, V. H.; Pitari, G.; Pyle, J.; Rast, S.; Rodriguez, J.; Sanderson, M.; Savage, N.; Shindell, D.; Strahan, S.; Szopa, S.; Sudo, K.; Wild, O. & Zeng, G. (2006). The Global Atmospheric Environment for the Next Generation. *Environment Science and Technology* **40**, 3586-3594.

DGRF – Direcção Geral dos Recursos Florestais (Forestry Resources General Directorate), 2006: Inventário Florestal Nacional de 1995-1998 (3ª Revisão). Divisão de Planeamento e Estatística, Direcção Geral dos Recursos Florestais. (Lisboa, Portugal)

EC - European Commission (2003). Forest Fires in Europe: 2002 fire campaign. Directorate-General Joint Research Centre, Directorate-General Environment, S.P.I.03.83 EN. (Ispra, Italy)

EC - European Commission (2005). Forest Fires in Europe 2004. Directorate-General Joint Research Centre, Directorate-General Environment, S.P.I.05.147 EN. (Ispra, Italy)

Fernández, J.; Montávez, J.P; Sáenz, J.; González-Rouco, J.F. & Zorita, E. (2007). Sensitivity of the MM5 mesoscale model to physical parameterizations for regional climate studies: Annual cycle. *Journal of Geophysical Research* 112, D04101, doi:10.1029/2005JD006649.

Ferreira, J.; Salmim, L.; Monteiro, A.; Miranda, A. I. & Borrego, C. (2004). Avaliação de episódios de ozono em Portugal através da modelação fotoquímica. In: Actas da 8ª Conferência Nacional de Ambiente, 27-29 Outubro, Lisboa, Portugal, 383-384. (Proceedings in CD Rom).

Flannigan, M.D.; Logan, K.A.; Amiro, B.D.; Skinner, W.R. & Stocks, B.J. (2005). Future area burned in Canada. *Climatic Change* **72**, 1-16.

Flannigan, M.D.; Krawchuk, M.A.; de Groot, W.J.; Wotton, B.M. & Gowman, L.M. (2009). Implications of changing climate for global wildland fire. *International Journal of Wildland Fire* 18, 483–507.

GENEMIS – Generation of European Emission Data for Episodes Project (1994). EUROTRAC Annual Report, 1993, Part 5. EUROTRAC International Scientific Secretariat, Garmisch-Partenkirchen.

Ginoux, P.; Chin, M.; Tegen, I.; Prospero, J.M.; Holben, B.; Dubovik, O. & Lin, S.J. (2001). Sources and distributions of dust aerosols simulated with the GOCART model. *Journal of Geophysical Research* 106, 20255 - 20273.

Grell, G.A.; Dudhia, J. & Stauffer, D.R. (1994). A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5), Tech. Rep. NCAR/TN-398+STR, Natl. Cent. for Atmos. Res., Boulder, Colorado.

Hansen, M.C.; DeFries, R.S.; Townsend, J.R. & Sohlberg, R. (2000). Global land cover classification at 1 km spatial resolution using a classification tree approach. *International Journal of Remote Sensing* 21(6,7), 1331-1364.

Hauglustaine, D.A.; Hourdin, F.; Jourdain, L.; Filiberti, M.-A.; Walters, S.; Lamarque, J.-F. & Holland, E.A. (2004). Interactive chemistry in the Laboratoire de Météorologie Dynamique general circulation model: description and background tropospheric chemistry evaluation. *Journal of Geophysical Research* 109, D04314, doi:10.1029/2003JD003957.

Hodzic, A.; Vautard, R.; Bessagnet, B.; Lattuati, M. & Moreto, F. (2005). Long-term urban aerosol simulation versus routine particulate matter. *Atmospheric Environment* 39, 5851-5864.

Hogrefe, C.; Leung, L.R.; Mickley, L.J.; Hunt, S.W. & Winner, D.A. (2005). Considering climate change in U.S. air quality management. *Environmental Manager*, 19-23.

Hoinka, K.; Carvalho, A. & Miranda, A.I. (2009). Regional-scale weather patterns and wildland fires in Central Portugal. *International Journal of Wildland Fire* 18, 36–49 DOI: 10.1071/WF07045

INE – Instituto Nacional de Estatística (2003). XIV Recenseamento Geral da População, resultados definitivos. INE, Estimativas Provisórias de População Residente para 31.12.2002, aferidas dos resultados definitivos dos Censos 2001, ajustados com as taxas de cobertura. Instituto Geográfico Português (IGP), Carta Adminisrativa Oficial de Portugal. (Lisboa, Portugal)

IPCC – Intergovernmental Panel on Climate Change (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller (Eds.), Cambridge University Press, Cambridge, 996 pp.

Jones, R.G.; Murphy, J.M.; Hassel, D.C. & Woodage, M.J. (2005). A high resolution atmospheric GCM for the generation of regional climate scenarios. Hadley Center Technical Note 63, Met Office, Exeter, UK.

Jones, R.G.; Murphy, J.M.; Hassel, D.C. & Woodage, M.J. (2005). A high resolution atmospheric GCM for the generation of regional climate scenarios. Hadley Center Technical Note 63, Met Office, Exeter, UK.

Lattuati, M. (1997). Contribution à l'étude du bilan de l'ozone troposphérique à l'interface de l'Europe et de l'Atlantique Nord: modélisation lagrangienne et mesures en altitude. Thèse de sciences, Université Paris 6, France.

Miller, M. (2007). The San Diego Declaration on Climate Change and Fire Management. 4th International Wildland Fire Conference, 13-17 May, Seville, Spain. (Proceedings in CD Rom)

Miranda, A.I.; Borrego, C.; Santos, P.; Sousa, M. & Valente, J. (2004). Database of Forest Fire Emission Factors. Departamento de Ambiente e Ordenamento, Universidade de Aveiro: 2004, AMB-QA-08/2004. Deliverable D251 of SPREAD Project [EVG1-CT-2001-00043].

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.

Monteiro, A.; Miranda, A.I.; Borrego, C.; Vautard, R., Ferreira, J. & Perez, A.T. (2007). Long-term assessment of particulate matter using CHIMERE model. *Atmospheric Environment*, doi:10.1016/j.atmosenv.2007.06.008

Monteiro, A.; Vautard, R.; Borrego, C. & Miranda, A.I. (2005). Long-term simulations of photo oxidant pollution over Portugal using the CHIMERE model. *Atmospheric Environment* **39**, 3089-3101.

Moriondo, M.; Good, P.; Durão, R.; Bindi, M.; Giannakopoulos, C. & Corte-Real, J. (2006). Potential impact of climate change on fire risk in the Mediterranean area. *Climate Research* **31**, 85-95. doi: 10.3354/cr031085

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.

Passant, N.R. (2002). Speciation of U.K. emissions of non-methane VOC, AEAT/ENV/0545.

Pausas, J.G. & Vallejo, V.R. (1999). The role of fire in European Mediterranean Ecosystems. In: Chuvieco E. (ed.) Remote sensing of large wildfires in the European Mediterranean basin, Springer-Verlag, 3-16.

Pyne, S. (2007). Megaburning: The Meaning of Megafires and the Means of the Management. 4th International Wildland Fire Conference, 13-17 May, Seville, Spain (http://www.wildfire07.es/doc/cd/INTRODUCTORIAS_ST/Pyne_ST1.pdf)

Riebau, A. & Fox, D. (2001). The new smoke management. *International Journal of Wildland Fire* 10, 415–427.

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 Institude Inc. (2004). SAS OnlineDoc®, Version 9.1.3, SAS Institude Inc., Cary, NC.

Schmidt, H.; Derognat, C.; Vautard, R. & Beekmann, M. (2001). A comparison of simulated and observed ozone mixing ratios for the summer of 1998 in Western Europe. *Atmospheric Environment* 35(36), 6277– 6297.

Schumaker, L.L. (1981). Spline functions, basic theory. Wiley–Interscience, 553 pp.

Sitch, S.; Cox, P.; Collins, W. & Huntingford, C. (2007). Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. Nature 448(7155), 791-794.

Solman, S.; Nuñez, M. & Cabré, M.F. (2007). Regional climate change experiments over southern South America. I: present climate. *Climate Dynamics*, doi: 10.1007/s00382-007-0304-3

Spracklen, D.V.; Mickley, L.J.; Logan, J.A.; Hudman, R.C.; Yevich, R.; Flannigan, M.D. & Westerling, A.L. (2009). Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *Journal of Geophysical Research* **114**, D20301, doi:10.1029/2008JD010966.

Stohl, A.; Williams, E.; Wotawa, G. & Kromp-Kolb, H. (1996). A European inventory for soil nitric oxide emissions and the effect of these emissions on the photochemical formation of ozone. *Atmospheric Environment* 30, 374-3755.

Szopa, S.; Hauglustaine, D.A.; Vautard, R. & Menut, L. (2006). Future global tropospheric ozone changes and impact on European air quality. *Geophysical Research Letters* 33, L14805, doi:10.1029/2006GL025860.

Valente, J.; Miranda, A.I.; Lopes, A.G.; Borrego, C.; Viegas, D.X. & Lopes, M. (2007). A local-scale modelling system to simulate smoke dispersion. *International Journal of Wildland Fire* 16, 196-203.

Van Dijck, S.; Laouina, A.; Carvalho, A.; Loos, S.; Schipper, A.; Kwast, H.; Nafaa R.; Antari, M.; Rocha, A.; Borrego, C. & Ritsema, C. (2005). Desertification in Northern Morocco due to effects of climate change on groundwater recharge. Desertification in the Mediterranean Region. A Security Issue. Eds. Kepner, W., Rubio, J., Mouat, D., Pedrazzini, F., Springer New York, 614 p., ISBN:1-4020-3758-9.

Van Wagner, C.E. (1987). Development and Structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service, Forestry Technical Report 35, Ottowa, Canada

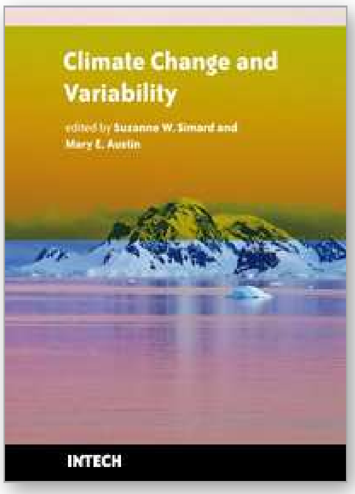
Vautard, R.; Bessagnet, B.; Chin, M. & Menut, L. (2005). On the contribution of natural Aeolian sources to particulate matter concentrations in Europe: testing hypotheses with a modelling approach. *Atmospheric Environment* 39 (18), 3291-3303

Vestreng, V. (2003). Review and revision of emission data reported to CLRTAP, EMEP Status Report, July 2003.

Viegas, D.X.; Reis, R.M.; Cruz, M.G. & Viegas, M.T. (2004). Calibração do Sistema Canadiano de Perigo de Incêndio para Aplicação em Portugal (Calibration of the Canadian Fire Weather Index System for application over Portugal). Silva Lusitana 12(1), 77-93.

Viegas, D.X.; Sol. B.; Bovio, G.; Nosenzo, A. & Ferreira, A.D. (1999). Comparative study of various methods of fire danger. *International Journal of Wildland Fire* **9**(4), 235-246.

Viegas, D.X.; Abrantes, T.; Palheiro, P.; Santo, F.E.; Viegas, M.T.; Silva, J. & Pessanha, L. (2006). Fire weather during the 2003, 2004 and 2005 fire seasons in Portugal. In V International Conference on Forest Fire Research. Ed D.X. Viegas, Figueira-da-Foz, 2006. Proceedings in CD.



Climate Change and Variability

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Climate change is emerging as one of the most important issues of our time, with the potential to cause profound cascading effects on ecosystems and society. However, these effects are poorly understood and our projections for climate change trends and effects have thus far proven to be inaccurate. In this collection of 24 chapters, we present a cross-section of some of the most challenging issues related to oceans, lakes, forests, and agricultural systems under a changing climate. The authors present evidence for changes and variability in climatic and atmospheric conditions, investigate some the impacts that climate change is having on the Earth's ecological and social systems, and provide novel ideas, advances and applications for mitigation and adaptation of our socio-ecological systems to climate change. Difficult questions are asked. What have been some of the impacts of climate change on our natural and managed ecosystems? How do we manage for resilient socio-ecological systems? How do we predict the future? What are relevant climatic change and management scenarios? How can we shape management regimes to increase our adaptive capacity to climate change? These themes are visited across broad spatial and temporal scales, touch on important and relevant ecological patterns and processes, and represent broad geographic regions, from the tropics, to temperate and boreal regions, to the Arctic.