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Fire weather risk assessment under climate change using a dynamical downscaling approach

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ABSTRACT

Results from general circulation models suggest that the increase of forest fire activity at the global scale will be one of the impacts of climate change. As attention shifts to regional climate further spatial resolution is needed to handle the forcings and circulations that occur at smaller scales. One of the available techniques to assess the impact of climate change on fire activity at the regional scale is the dynamical downscaling between global climate models and regional models.

In the present work, the impact of climate change on fire danger at the regional scale was examined by means of dynamical downscaling between a general circulation model (MUGCM) and a regional meteorological model (MM5). A Southern European country, Portugal, was selected as case-study since general circulation models predict significant surface air temperature increases over Southern and Mediterranean Europe.

Present and future climates, centred in 1990 and 2050, respectively, were obtained using daily data previously simulated by MUGCM. Climate change signals on temperature and precipitation derived from the MUGCM ensemble simulations were analysed using spatial averages over the Iberian Peninsula and cluster analysis applied over Portugal. For the Iberian Peninsula, a positive trend for temperature for all seasons, with higher variability for the winter months, was obtained. Over Portugal, for the future climate, the average winter temperature is expected to be higher. Precipitation increases are simulated for the end of autumn/beginning of winter, and negative changes are expected for the end of winter/beginning of spring and beginning of summer. The cluster analysis revealed important temporal changes on the meteorological variables which may be relevant for fire management planning, namely a longer fire season over Portugal is expected.

The spatial refinement of the projected climate change impacts on the fire weather risk over Portugal was performed through numerical downscaling between MUGCM and MM5. The MM5 outputs, at 10 km resolution, were used to estimate the Canadian Fire Weather Index (FWI) System components. Results show higher FWI values in the beginning of summer for the 2050 scenario. An increase of the maximum values of the Drought Code (DC) in the inner part of Portugal was also detected. An increase in the total area burned is anticipated, with the consequent increase of pollutants emissions.

1. Introduction

Climate and weather are of extreme importance for the ignition and propagation of forest fires. The climate (regarded as the slowly varying aspects of the atmosphere – hydrosphere – land surface system) determines the total quantity of vegetation available for combustion, and duration and degree of severity of the forest fire season. On the other hand, weather conditions (the state of the atmosphere at a given time and place) regulate the moisture content of the dead biomass, and consequently its flammability potential.

Forest fires ignition and spread are sensitive to a number of different interactions within an ecosystem, such as weather, fuel load/type and topography. Hence, weather and climate play a crucial role in determining the fire regime of an area; in return, the fire regime is very sensitive to changes in climate (Pyne et al., 1996; Viegas et al., 1999; Skinner et al., 2000; Kunkel, 2001; Pereira et al., 2005). In Canada, significant relationships were

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established between historical area burned and weather (Harrington et al., 1983; Flannigan and Harrington, 1988). Other studies also pointed out that weather and climate are the most important natural factor influencing forest fires (Stocks and Street, 1983; Flannigan and Wotton, 2001; Hely et al., 2001). Considering these interactions, a question is raised: how will forest fire activity be in the future climate?

Since the 80s, when global climate modelling was in its early stages, a few studies were conducted in order to establish the links between future climate change and forest fire occurrences (Beer et al., 1988; Street, 1989). Based on global climate models results, the Intergovernmental Panel on Climate Change (IPCC) report (Fischlin et al., 2007) suggests that, with global warming, forest fires frequency will increase all over the world. In particular over Europe, General Circulation Models (GCMs) predict increases in surface air temperatures, especially in the southern part and the Mediterranean. This has the potential to create a drier forest at both the surface and in the organic layers of the forest soil through increased potential evaporation, especially during the summer months (Boer et al., 2000).

A recent study integrating vegetation response to climate change and surface hydrological processes (Alo and Wang, 2008), used offline simulations with a land-surface model to explore the future response to elevated carbon dioxide (CO_2) concentrations. The authors demonstrated that CO_2-induced changes in potential vegetation structure substantially influences the surface hydrological processes, concluding that the soil moisture simulated by different GCMs varies when considering changes on vegetation structure and that the hydrological cycle may, indeed, intensify.

Assessments of the potential impacts of climate change on fire weather risk in the forests of Canada and United States (Flannigan and Van Wagner, 1991; Stocks et al., 1998; Wotton et al., 1998, Flannigan et al., 1998, 2000) have used GCMs outputs to project fire severity using, for example, components of the Canadian Fire Weather Index (FWI) System (defined in section 2.2). Results have shown increasingly severe fire weather across most of the western boreal forest of Canada and United States. In addition to rises in seasonal means of fire severity indices, these studies also predict enhancements in the frequency of occurrence of extreme fire severity in specific areas (Wotton et al., 2003) and increase in the fire season length (Wotton and Flannigan, 1993).

Research with respect to climate simulation and prediction has attracted considerable efforts throughout the last 30 years with global aspects clearly dominating. However, it is the regional and the local climate that is of central importance to societies and to the biosphere (Grell et al., 2000). The horizontal atmospheric resolution of present day GCMs is still relatively coarse, and regional climate is often affected by forcings and circulations that occur at smaller scales (Giorgi and Mearns, 1991). As a result, GCMs cannot explicitly capture the fine scale structure that characterizes climate variables in many regions of the world and which is needed for many impact assessment studies. Examples of fine scale phenomena are mesoscale processes that contribute for intense precipitation events, like those promoted by vertical upward motions and coupling between regional circulation and convection; local and extreme winds, as well as extreme temperature values, due to topographic effects and/or short term variability.

In order to better simulate the fine scale atmospheric processes it is necessary to use mesoscale models, also named regional or limited area models. This type of models, with time scales less than 1 h and spatial resolution of a few kilometres, have the possibility to resolve land surface features such as strong gradients on topographic and land-use features that may be important for land-atmospheric fluxes calculations (Bader et al., 2008). Topography, land-use and land-water mask, are examples of important static fields that influence regional to local weather. Mesoscale models need lateral boundary conditions obtained either from observations or from global climate models. The method by which a mesoscale model is forced in its lateral boundaries, and eventually initialized, by a global climate model is called dynamical downscaling (Wilby et al., 2002; Christensen et al., 2007a; Thatcher and Hurley, 2010).

Benefits from this approach over European regions are explored in Bojariu and Giorgi (2005). The authors show the importance of having a better description of topographic features in the presence of a realistic account of the atmospheric processes when detecting the Northern Atlantic Oscillation (NAO) in climate simulations. This study compares the obtained correlations between observed pressure and the GCM model results, with a horizontal resolution of 1.25° latitude by 1.875° longitude, and also the regional climate simulation (forced with the GCM outputs) results obtained with a horizontal resolution of 50 km over several regions of Europe, namely over the Iberian Peninsula. When using dynamical downscaling the authors were able to simulate the large scale NAO variability taking into account the fine scale processes. Moreover, they were able to determine the importance of topography on the interaction between the large scale NAO and precipitation.

During summer, Europe experiences a large number of forest fires which may cause enormous losses in terms of environmental damage and even human lives. Most of the fires take place in the Mediterranean region, with more than 95% of its area burned (EC, 2003). Consequently, governments currently allocate a part of their national budget to prevent, fight and remediate forest fires.

The Mediterranean is located in the subtropics and, as such, has been experiencing a warming and drying trend in the last decades (Trenberth et al., 2007). Also, climate projections from the latest IPCC report (Christensen et al., 2007b), resulting from a regional multi-model application, show that these trends, which are stronger and of opposite sign of those in the mid-latitudes in the European region, should continue and even intensify in the future. Christensen et al. (2007b) present results from climate projections of an ensemble of 21 models; regarding temperature and precipitation responses over Europe, Table 1 shows the median of annual average and warm season (June, July and August) temperature anomalies and precipitation responses (in percentage) for Northern Europe (NE) and Southern Europe and Mediterranean (SEM).

Warmer and drier conditions will increase the forest fire risk in the region (Moriondo et al., 2006). Portugal is one of the European countries most affected by forest fires, mainly during summer, which is characterised by hot and dry weather (EC, 2005). In Portugal, the peak season of wildfires takes place between June and September, with 93% of the annual area burned (Hoinka et al., 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 (Carvalho et al., 2008).

In Pausas (2004) the link between forest fire occurrences and climate variables is analysed for the Valencia region in Spain, concluding that summer rainfall is an important factor for determining the amount of area burned. The author also concludes that fire ignitions may be determined by human factors, while some of the variability in the annual area burned is explained by climatic parameters. In Portugal, Viegas et al. (1992) and Viegas and Viegas (1994) established a clear dependency between the annual area burned and the total rainfall from May to September. The authors also stressed that the rainfall in the beginning of the fire season, namely in June, has a marked influence in the reduction of the area burned. More recently, Carvalho et al. (2008) performed regressions between the area burned and fire occurrence with the meteorological and the Canadian FWI variables for the period between 1980 and 2004 for twelve districts across Portugal. Their regression

Table 1
Regional averages of temperature and precipitation projections from a set of 21 global models in the multi-model application for the A1B scenario for Northern Europe (NE) and Southern Europe and Mediterranean (SEM) (adapted from Christensen et al., 2007b).

Region	Temperature response (°C)							Precipitation response (%)						Extreme seasons (%)		
	Season	Min	25	50	75	Max	T yrs	Min	25	50	75	Max	Tyrs	Warm	Wet	Dry
EUROPE																
NEU 4SN, 10W to 75N, 40E	DJF	2.6	3.6	4.3	5.5	8.2	40	9	13	15	22	25	50	82	43	0
	MAM	2.1	2.4	3.1	4.3	5.3	35	0	8	12	15	21	60	79	28	2
	JJA	1.4	1.9	2.7	3.3	5.0	25	−21	−5	2	7	16		88	11	
	SON	1.9	2.6	2.9	4.2	5.4	30	−5	4	8	11	13	80	87	20	2
	Annual	2.3	2.7	3.2	4.5	5.3	25	0	6	9	11	16	45	96	48	2
SEM 30N, 10W to 48N, 40E	DJF	1.7	2.5	2.6	3.3	4.6	25	−16	−10	−6	−1	6	>100	93	3	12
	MAM	2.0	3.0	3.2	3.5	4.5	20	−24	−17	−16	−8	−2	60	98	1	31
	JJA	2.7	3.7	4.1	5.0	6.5	15	−53	−35	−24	−14	−3	55	100	1	42
	SON	2.3	2.8	3.3	4.0	5.2	15	−29	−15	−12	−9	−2	90	100	1	21
	Annual	2.2	3.0	3.5	4.0	5.1	15	−27	−16	−12	−9	−4	45	100	0	46

approach explained 61–80% of the variance in area burned and 48–77% of the variance in the fire occurrence, depending on location ($p < 0.0001$).

The main objective of the present study is to investigate the future impacts of climate change scenarios on fire weather risk at the regional scale. A dynamical downscaling approach was applied from the GCM outputs to the regional scale model to better capture the effects of local and regional forcing in an area of complex topography, such as Portugal. In addition, the comparison between estimated and measured fire weather risk indexes was also performed. The paper is organized as follows: section 2 describes the data and methodology used; the results and discussion are examined in section 3; and section 4 provides the main conclusions.

2. Methodology

2.1. Global and regional climate simulations

Present and future climates (centred around 1990 and 2050 respectively) over Portugal were modelled by dynamical downscaling using the data simulated by the Melbourne University General Circulation Model (MUGCM) (Simmonds and Lynch, 1992) which were specified as initial and lateral boundary conditions to the Fifth-Generation Mesoscale Model (MM5) (Dudhia, 1993). The current fuel map data were used for the present and future climates and hence the potential interactions between climate/weather/vegetation/fires were not considered in the simulations.

The MUGCM derives from the hemispheric model described in Bourke et al. (1977) and in McAvaney et al. (1978). Several modifications have been introduced in the physics of the model, some of which along with the code structure are described in Simmonds (1985), while other modifications are described in Arguete and Simmonds (1996). The version of MUGCM used in this study is a spectral atmospheric model rhomboidal truncated at wave 31, which corresponds to a horizontal resolution of approximately 3.75°(longitude) by 2.25°(latitude).

The performance of the MUGCM in simulating the present climate is similar to that of other climate models (Simmonds et al., 1988; Boer et al., 1991; Simmonds and Lynch, 1992) and has been successfully tested in a number of sensitivity and climate experiments (Walsh et al., 2000; Noone and Simmonds, 2002; Henderson-Sellers et al., 2004). The MUGCM has also been shown to simulate well the climate over the Iberian Peninsula (Melo-Gonçalves et al., 2005; Alves and Rocha, 2004).

In this study, two global equilibrium simulations have been performed. One represents the present climate and the other represents a future climate. Each simulation is an ensemble with 30 members of one year duration each. For each ensemble, all members have the same boundary conditions but start from different initial conditions. In the present climate ensemble, the model uses climatological CO_2-equivalent greenhouse gas (GHG) concentrations and climatological SSTs obtained for a 20-year period centred in 1990 (i.e. 1981–2000). For the future climate ensemble, the model uses estimated climatological CO_2-equivalent GHG concentrations and climatological SSTs for a 20-year period centred in 2050 (i.e. 2041–2060). Both SSTs climatologies and other boundary conditions have the seasonal cycle represented. This allows evaluating the statistical significance of the difference between the two simulated climates. Both SSTs datasets were obtained for the respective period from simulations previously performed by the ocean-atmosphere coupled model of the Hadley Centre (HadCM2) (Mitchell and Johns, 1997). For the present climate simulation the CO_2-equivalent GHG concentration was specified as 348 ppmv (Moffatt, 1992; URL 1). For the future climate the CO_2 concentration was estimated according to the CO_2 forcing change between the future and the present climate, as simulated by the HadCM2. This forcing change of 3 W m^{-2} resulted in an estimate of the CO_2 concentration of 634 ppmv. The CO_2 forcing in the MUGCM and HadCM2 models is similar. The performance of the MUGCM depends on the performance of HadCM2 since SSTs have been generated by the latter. Also, inter-annual variability within each climate, as a result of inter-annual variability of SSTs (and all forcing and boundary conditions), is not present.

The MUGCM simulates well the mean patterns of various variables, at the surface and in altitude, particularly in the region of study (Simmonds et al., 1988). Also, Simmonds and Dix (1989) have shown that the model is able to retain the day-to-day variability of the mean sea level pressure, when compared to observations. An extense intercomparison of many models, including the MUGCM, has also shown that the performance of this model in simulating most characteristics of the atmosphere circulation is similar to the other models (Boer et al., 1991). Therefore, the MUGCM simulates with realism the patterns and frequency of synoptic systems in the region. This gives us confidence in using the MUGCM to represent the synoptic scale in the region and to use its results as boundary condition in the MM5.

The MM5 is a powerful meteorological model that contains comprehensive descriptions of the atmospheric motion: fields of pressure, moisture and temperature; fluxes of heat, moisture and momentum; turbulence, cloud formation, precipitation and atmospheric radiative characteristics. The MM5 is a nested-grid primitive-equation model, which uses a terrain-following sigma (nondimensional pressure) vertical coordinate. The most interesting features in MM5 are the different physical parameterizations that can be selected by the user and its capability to run on different computational platforms.

The MM5 model has already been applied in climate change assessment studies over the study region being capable of

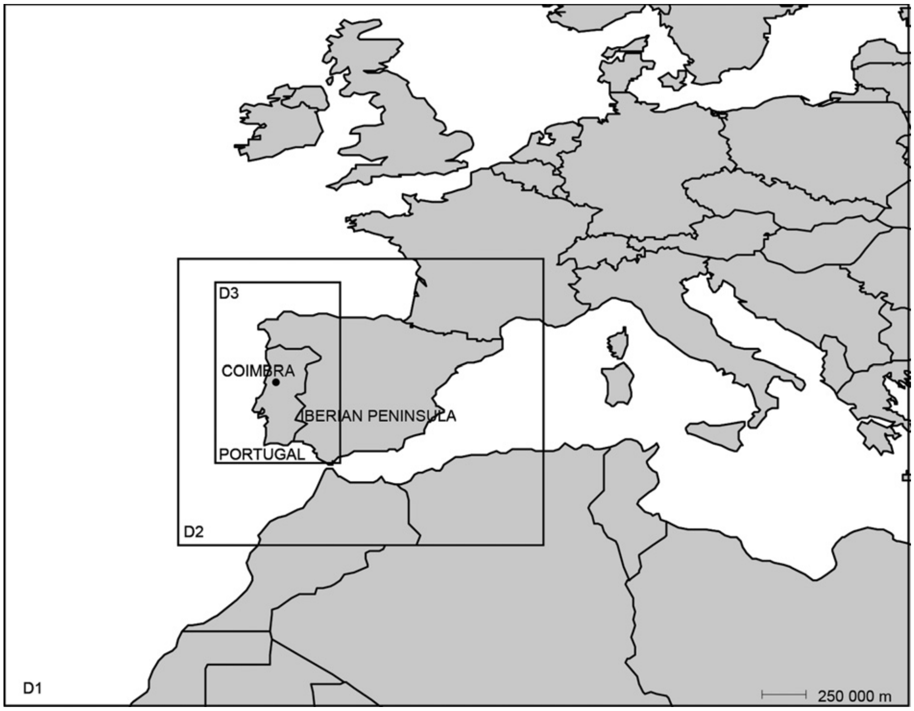

Fig. 1. MM5 modelling domains and identification of the Iberian Peninsula, Portugal and Coimbra.

simulating a realistic average temperature and the obtained results are representative of the temperature spatial patterns over Europe (Carvalho et al., 2010).

Initial and boundary conditions for the MM5 model are obtained from the MUGCM simulations. Since the FWI estimation is based on the noon atmospheric conditions, noon daily MUGCM results were used to drive the MM5. Therefore the MM5 diurnal cycle is adjusted to noon boundary conditions. The boundary variables are: temperature, relative humidity, geopotential height, zonal and meridional wind components, specified at 10 mandatory pressure levels from the surface to 100 hPa in the atmosphere; mean sea level pressure and skin temperature at surface.

Due to restrictions on computer resources, related to the impossibility to simulate the 30 equilibrium simulations for each climate scenario at the regional scale, it was necessary to impose criteria in order to select simulation periods for both climate scenarios. In order to have physical and dynamical consistent fields of the atmosphere, it was necessary to choose a simulation among the 30 global equilibrium simulations. For each time slice it was identified the MUGCM simulation for which the Drought Code (DC) value (further details on the fire risk estimations are given in section 2.2), and hence the temperature and precipitation meteorological variables on which its calculation is based, was closer to the DC average calculated for the 30 global climate simulations. By doing so, the global meteorological fields that force the boundaries of the MM5 model are derived in a physical and consistent way and presumably closer to the average climate conditions, both for the 1990 and 2050 climates.

Subsequently, the MM5 model was applied to downscale the selected equilibrium simulations for the 1990 and 2050 climates to progressively smaller spatial domains with increasing spatial and temporal resolution (Fig. 1). The extension and resolution of the MM5 spatial domains are given in Table 2.

Table 2
Spatial domains of MM5.

Domain	Geographical extent	Grid cells	Resolution (km)	Area (km^2)
D1	Europe and North Africa	45 × 48	90	4050 × 4320
D2	Iberian Peninsula	52 × 52	30	1560 × 1560
D3	Portugal and Galicia	85 × 55	10	850 × 550

All modelling domains have the same vertical structure with 23 unequally spaced σ levels. The Reisner graupel (Reisner et al., 1998) microphysics moisture scheme, a MRF (Hong and Pan, 1996) boundary layer and Kain-Fritsch (Kain and Fritsch, 1993) cumulus scheme govern all grids. The old version of the NCAR Community Climate Model version2 (CCM2) radiation scheme implemented in MM5 (Hack et al., 1993) was selected due to its flexibility regarding CO_2 concentration values adjustments, which allowed the update of the CO_2 volume mixing ratio for 634 ppmv in the future climate simulation.

2.2. The Canadian Fire Weather Index (FWI) System

Observations of temperature, relative humidity, and wind speed at 12H00 local standard time (LST) and 24-h precipitation are the inputs required to calculate the components of the Canadian FWI System (Van Wagner, 1987).The FWI system is a weather-based structure which allows calculating fire weather risk based on six components that are grouped into two main categories namely, fuel moisture codes and fire behaviour indices (Fig. 2).

There are three fuel moisture codes that are expected to follow the daily changes on the moisture content of three types of vegetation fuel:

(i) the fine fuel moisture content (FFMC), representing the moisture content of surface litter and other fine fuels;
(ii) the duff moisture code (DM) which represents the moisture content of the loosely compacted organic material, and
(iii) the drought code (DC) that reflects the moisture variations of a deep layer of compact organic material.

These moisture codes also intend to represent the fuel type that may be found in different depths of a forest responding with different water capacity and drying speed according to their depth

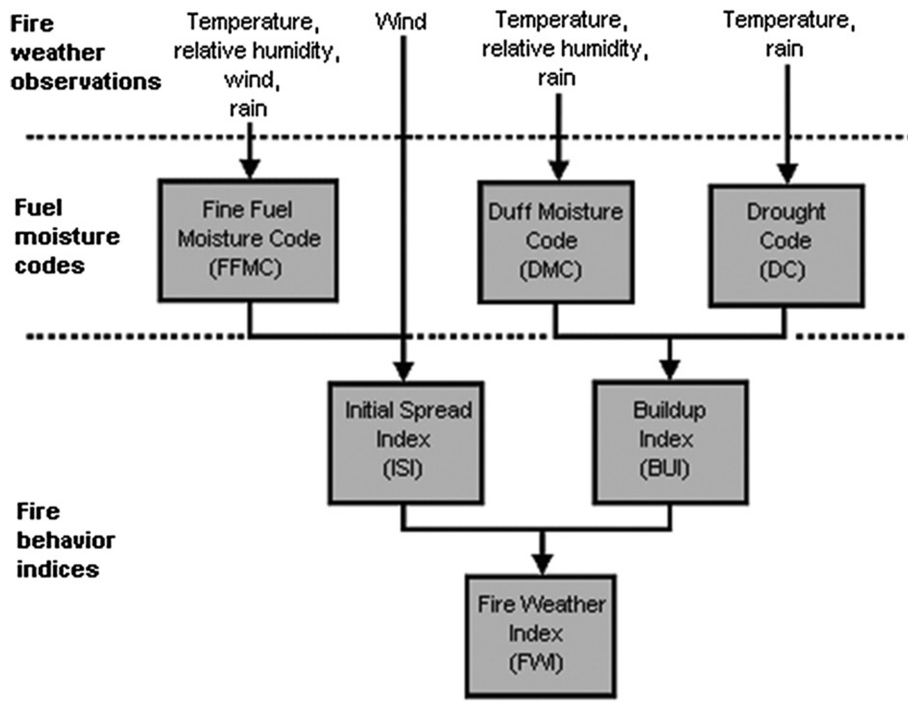

Fig. 2. Canadian fire weather index system components (adapted from Van Wagner, 1987).

and load. Hence, the drying time-lags for these three fuel layers are 2/3 of a day (more superficial layer, down to 1.2 cm), 15 days (nominal depth 7 cm) and 52 days (deepest layer representing 18 cm depth) respectively for the FFMC, DMC and DC under normal conditions (temperature 21.1 °C, relative humidity 45%). These three indices are directly related to the moisture content of the different layers of the forest floor; the FFMC influences the starting and spreading of forest fires, whereas the DMC and DC are related to the medium and long-term dryness and consequently impacts the potential fuel consumption. In this sense, the DC longer response to the meteorological variables may be used as a good indicator in climate change assessment studies.

The DMC and DC indexes are combined to create a generalized index of the availability of fuel for consumption (build up index, BUI) and the FFMC is combined with wind to estimate the potential spread rate of a fire (initial spread index, ISI). The BUI and ISI are finally combined to create the FWI which is an estimate of the potential intensity of a spreading fire. Representing different aspects of the fire behaviour, these three indices are important for fire management practices (Williams, 1959; Van Wagner, 1970).

In a study conducted by Cruz (2000) based on national historic data, the fire danger classes were defined for each component of the FWI system for Portugal (Table 3).

Studies conducted in Portugal show that the DC gives a good indication of wildfire behaviour and propagation (Cruz, 2000), and also of the relative hazardousness of a fire season due to its long-term response to daily weather variations (Viegas et al., 2004). These studies identify DC as a broadly applicable meteorologically-based indicator which can allow the evaluation of climate change impact on fire weather risk.

The FWI system components were calculated, each day at 12H00 LST, for the 10 km resolution grid using the meteorological results from the MM5 model. In order to estimate the FWI system components values, the code presented in Van Wagner and Pickett (1985) was updated from FORTRAN 77 to FORTRAN 90 and adapted to the grid of the second nest domain of the MM5 model covering Portugal (Fig. 1).

Aiming to evaluate the impact of climate change on the fire weather risk over Portugal and to compare simulation-based results with observation-based values a specific area was chosen for a detailed analysis. Coimbra location was selected since a previous study (Viegas et al., 2004) found a correlation of 0.69 between the DC calculated at Coimbra and the area burned all over the country for the period between 1975 and 1990, showing that the DC at Coimbra gives a good indication of the area burned in Portugal.

The FWI system components were calculated using the MM5 outputs at the grid cell including Coimbra location, for both climate scenarios. Each obtained series was studied concerning its frequency values distribution. The present scenario results were compared with the observed fire weather risk, calculated with the meteorological observations available for the 1988–2002 period at Coimbra.

Table 3
Fire danger classes for the FWI system components for Portugal (Cruz, 2000).

Danger class	FWI system components					
	FFMC	DMC	DC	ISI	BUI	FWI
Low	0–81	0–19	0–78	0–1,9	0–23	0–3
Moderate	82–87	20–84	78–505	2–4,9	24–115	4–17
High	88–89	85–143	506–743	5–7,9	116–180	18–27
Very high	90–92	143–187	744–882	8–11,9	181–224	28–38
Extreme	> 93	> 188	> 883	> 12	> 225	> 39

3. Results and discussion

3.1. Climate simulation analysis

Hereafter, seasons are defined for the Northern Hemisphere as such: summer (June, July and August), autumn (September, October and November), winter (December, January and February) and spring (March, April and May).

MUGCM's projected changes for the study region between the 1990 and 2050 climate are in agreement with those obtained by other models under similar global emissions scenarios (global climate model results for monthly mean temperature and precipitation may be consulted, for the CSIRO/A1a scenario (Christensen et al., 2007b), for 2050, at URL2). These include summer temperature increases of 2–3 °C and winter increases of 1.5 °C over Europe; significant increase on winter precipitation (1 mm.day^{-1}) between 50°N and 55°N in Europe; slight reduction on winter precipitation in Southern Europe, in particular over the Iberian Peninsula.

Spatial averages of temperature and precipitation were computed from the MUGCM outputs for the Iberian Peninsula. Seasonal means and standard deviations were calculated and a two-tailed student *t*-test was used to estimate the statistical significance of the differences between the 1990 and 2050 climates (ensemble means and variability). In the following analysis, a 1% significance level was used to evaluate the statistical significance, unless otherwise indicated. The warming, in this region, is statistically significant for all seasons with temperature increases around 1.6 °C in spring and autumn, 2.0 °C in winter and 2.5 °C in summer. The variability of winter temperature is higher in the future, this difference being statistically significant at a 5% significance level. The decrease of precipitation (−0.2 mm.day^{-1}) is statistically significant for the spring and summer months, also the standard deviation of spring precipitation decreases in future climate.

A cluster analysis (Wilks, 1995; Krzanowski, 1998) was also performed for the monthly mean temperature and monthly total precipitation. This analysis uses the method of hierarchical clustering with standardized Euclidean distance as the metric. In accordance with Viegas et al. (1992), the criteria that the forest fire risk is higher when the temperature is high and the precipitation is low was adopted. For both simulations, a four group's solution was found to be the most suitable. For the present climate, the obtained four groups (G1, G2, G3 and G4) are formed as (Fig. 3):

- G1: January, February, March and December, characterized by colder temperatures and higher precipitation amounts;
- G2: April, May, October and November, with low temperatures and moderate precipitation;
- G3: June, August and September, with high temperatures and moderate precipitation;
- G4: July, the driest month and with highest temperature.

Therefore, in view of the adopted criteria mentioned above, the fire risk increases in the following order: G1 < G2 < G3 < G4. For the future climate (Fig. 4), the four groups are now as follows:

- G1: January, October, November and December;
- G2: February, March, April and May;
- G3: August and September;
- G4: June and July.

Differences between the present and the future climates in the cluster analysis point to an increase of fire risk in February/March and June, and to a decrease in November. Using the method of partitioning clustering with a four groups solution (not shown), usually referred to as *k-means* (e.g. Gnanadesikan, 1997), the elements in each group are the same as those obtained with the hierarchical clustering for both simulations.

This cluster analysis of MUGCM results helps to identify the most important time periods to be simulated by the MM5 model. Therefore, based on the cluster analysis and considering that the majority of the area burned in Portugal occurs from June to September, the period between February and October (eight months) was selected as the period for the downscaling application with MM5 model. The analysis was not restricted to the summer period because under future climate conditions the extension of the fire season may be deeply impacted.

To drive the mesoscale model MM5 with the MUGCM results it was necessary to develop an interface to extract the 3D and 2D meteorological fields from the global climate model results to an intermediate format that is ingested by the mesoscale model.

Fig. 5 shows temperature and precipitation, for each month and under each climate scenario, simulated by the MUGCM and the

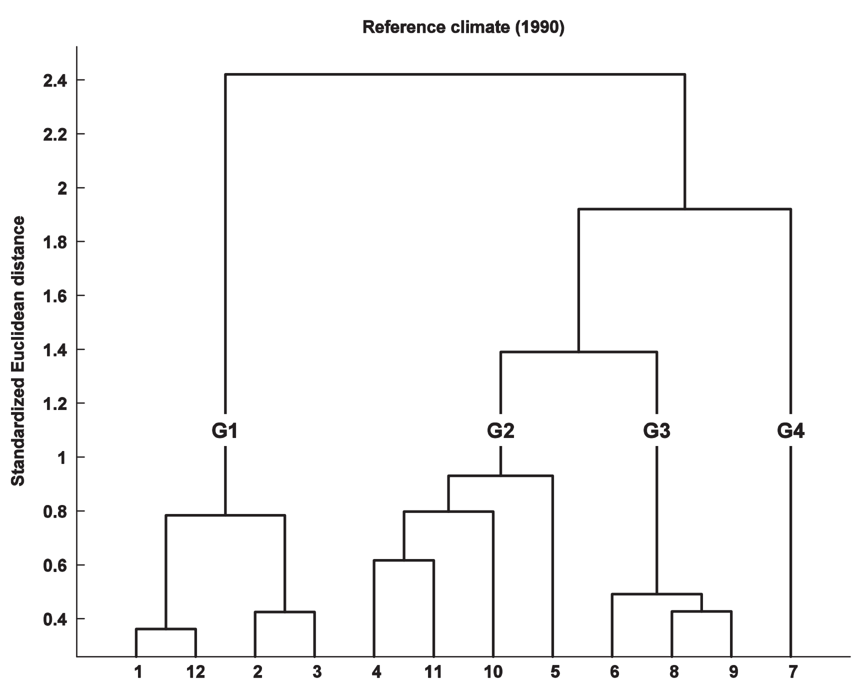

Fig. 3. Tree diagram from the cluster analysis on the 2-D monthly vectors with mean temperature and total precipitation as coordinates - results for the present climate simulation.

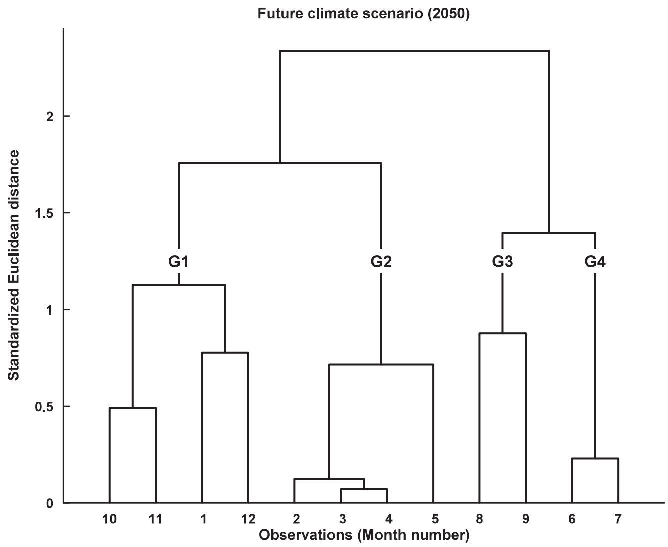

Fig. 4. Tree diagram from the cluster analysis on the 2-D monthly vectors with mean temperature and total precipitation as coordinates - results for the future climate scenario simulation (2050).

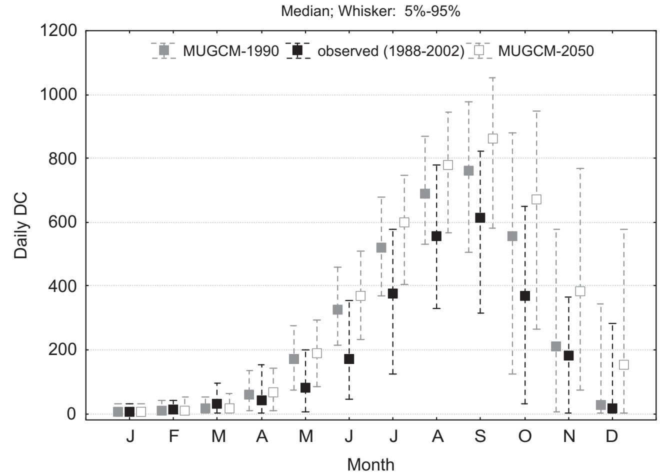

Fig. 6. MUGCM simulation results for present climate (1990) and future climate (2050) climate concerning daily DC, for each month, at Coimbra. Observed daily DC (1988–2002) is also depicted. The simulated data represent the MUGCM 30 simulations. The graphic presents the median, the 5th percentile and the 95th percentile.

MM5 at Coimbra. It is worth mentioning that Portugal is represented by three cells in the MUGCM grid cell definition, while for the MM5 the number of cells is much higher (1800). Since historical weather datasets (1988–2002) based on observations are available at Coimbra weather station, these variables were calculated for this location considering the two northernmost cells of the MUGCM domain covering Portugal. The observed time series at Coimbra is also shown for the period between 1988 and 2002 for a better representation of the present climate variability.

As can be observed, both models represent the seasonal variability of the observed data. Concerning daily mean temperature (Fig. 5a), the MUGCM follows the observed median values. However, for February/March and for the autumn months

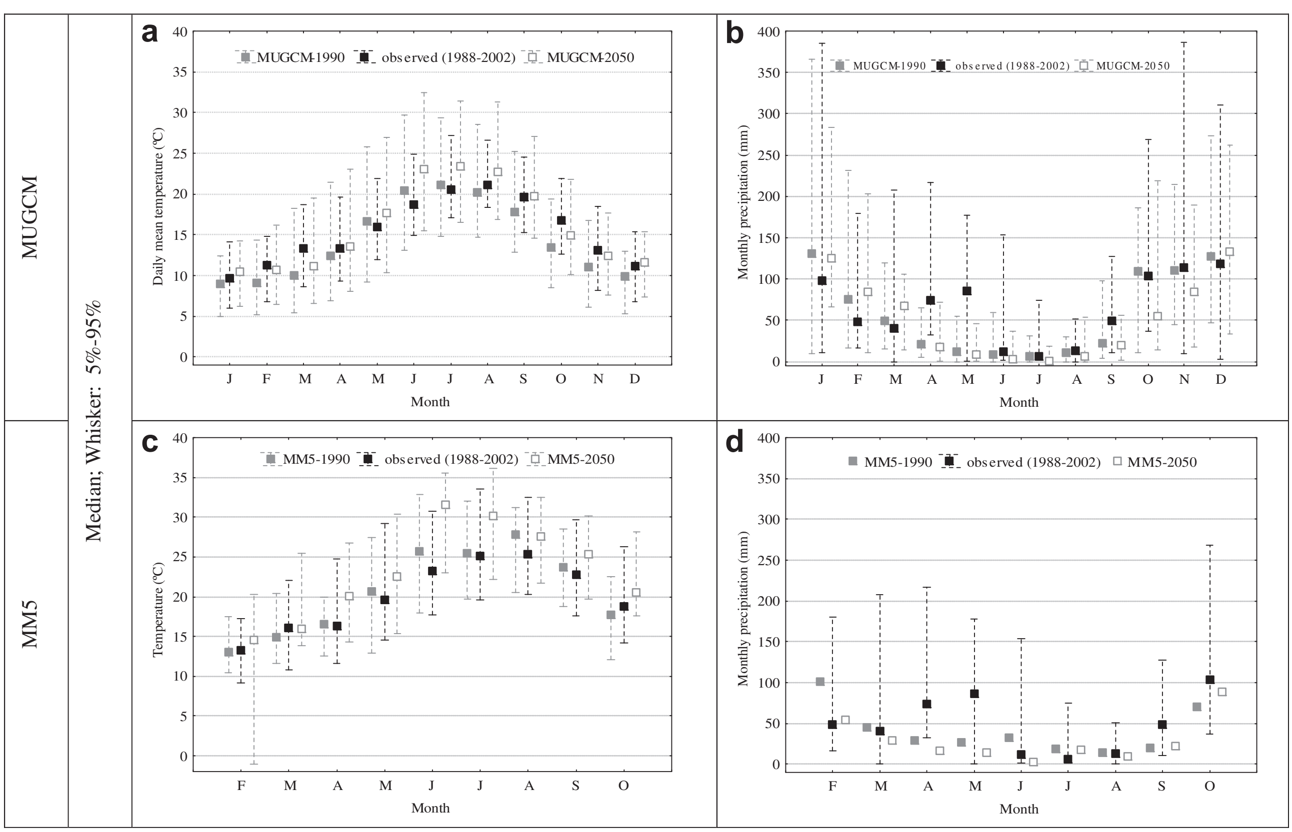

Fig. 5. MUGCM simulation (a, b) and MM5 simulation (c, d) at Coimbra concerning temperature (a, c) and monthly precipitation (b, d) for each month. The MUGCM results concern the 30 simulations. The MM5 outputs refer to the simulation period between February to October. MUGCM and MM5 projections for 2050 are also depicted. The graphic presents the median, the 5th percentile and the 95th percentile.

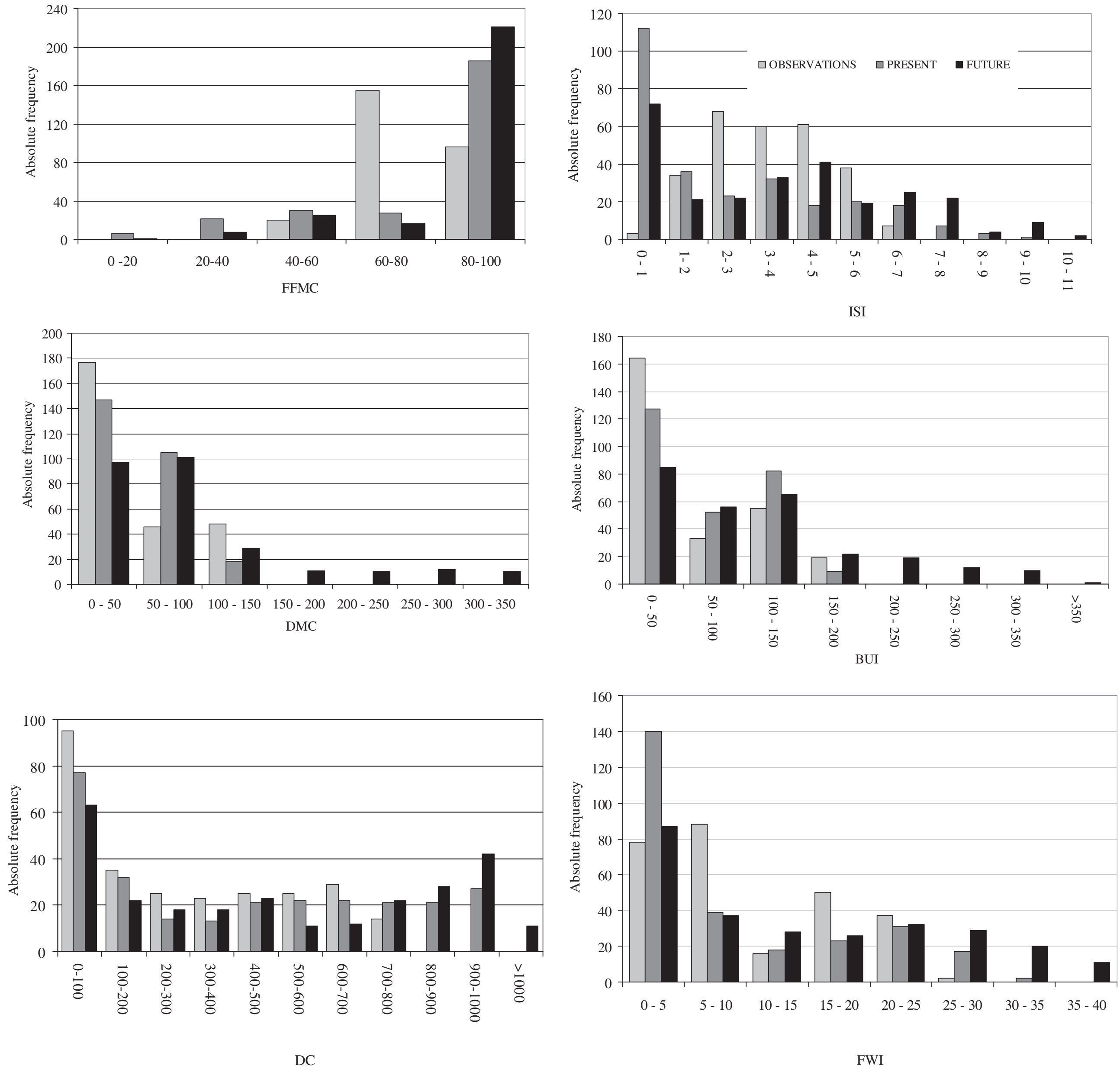

Fig. 7. Histograms of the FWI components for simulated present and future climate scenarios as well as for observations.

a 2–3 °C underestimation can be detected. For total monthly precipitation (Fig. 5b), simulated values follow the seasonal median values, except for April and May where the MUGCM underestimates it. In May the precipitation variability is also lower than the observed. MM5 outputs have been compared against noon temperature monitored at Coimbra as FWI components estimation needs noon meteorological values. The MM5 correctly simulates the median values of noon temperature (Fig. 5c), except in June and August, where a 2 °C overestimation can be detected. Monthly precipitation simulated values follow the observed ones (Fig. 5d), except for April and May, the months where the MUGCM forcing is also deviated from the observations. In general, MM5 results compare better with measurements than MUGCM ones. It should be noticed that in Fig. 5 we are comparing the outputs of a global climate model, a regional meteorological model and the observed data at Coimbra site. The considerably different spatial scales can justify the differences found for temperature and precipitation. The MUGCM and MM5 results are within the standard deviation of the observed data providing confidence on the use the simulation results as input to the fire risk analysis.

As for the differences between present climate (1990) and future climate (2050) simulations, MUGCM projects temperature increases for all the seasons, especially in the summer and the beginning of autumn (Fig. 5a). In 2050, precipitation will decrease in spring and in summer; but an increase in February and March is also projected.

MM5 predicts a maximum increase of noon temperature of, approximately, 6 °C in June. All months will register an increase in temperature that ranges from 2 to 6 °C depending on the month. Noon temperature lower and upper extreme values (5th and 95th percentiles) will be higher in future climate. Precipitation will decrease in all simulated months, except in October.

The projected changes for temperature and precipitation will deeply impact the fire weather risk at Coimbra and, due to its previously mentioned representativeness, in Portugal.

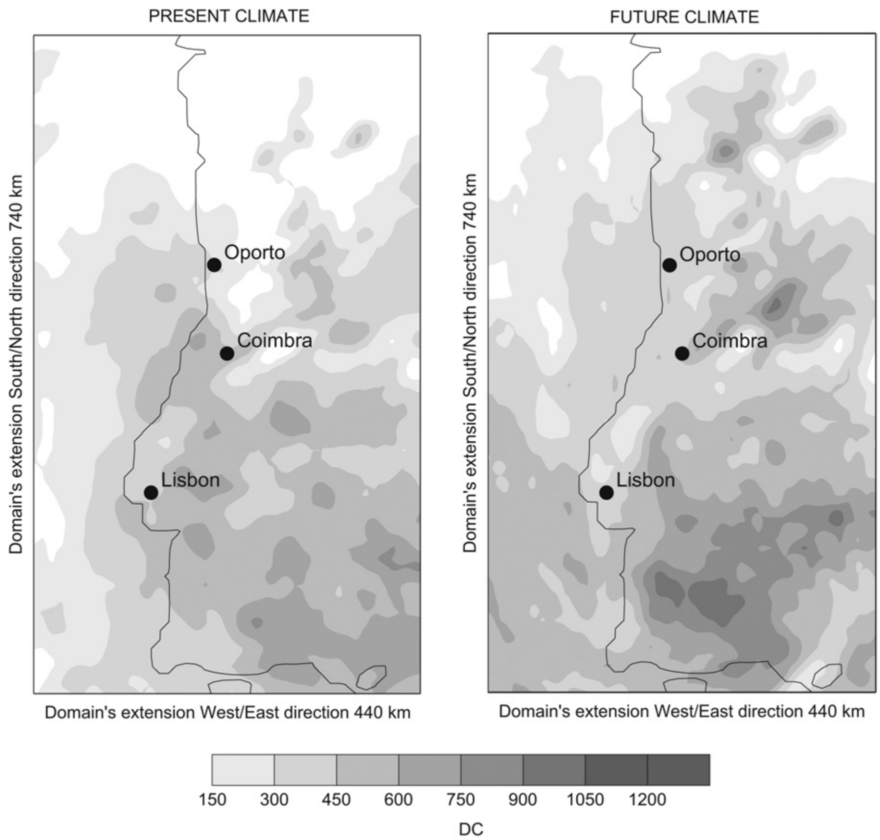

Fig. 8. Maximum DC calculated over Portugal for both climate scenarios between February and October.

3.2. Fire risk analysis

Considering the fact that DC is a good indicator of the relative hazardousness of a fire season and aiming to study the impact of global climate change on the fire risk over Portugal, the DC was calculated considering the data from the MUGCM grid cells over the study region.

An evaluation of the DC values is made for Coimbra for the present and future climate scenarios (Fig. 6); results are plotted considering all the 30 equilibrium simulations for each climate scenario. The comparison between the DC values estimated by the MUGCM for the present climate scenario and the DC based on observations shows that the model clearly follows the observed data, although there is a trend to overestimate the observed DC values, mainly at the summer months. This is closely related to the underestimation of precipitation that was detected in Fig. 5b. Fig. 6 also shows a well defined peak in September for the present climate, agreeing with the observed data.

Concerning DC, in the future climate (Fig. 6) there is an increase in its variability and consequently its peak is not as clear as in the present climate simulations. Furthermore, higher values of DC are possible for a longer time period along autumn in the future climate scenario.

In addition to the analysis of the DC index values obtained from MUGCM results, and aiming to obtain wider information regarding potential fire behaviour, all the FWI system components were estimated and evaluated based on MM5 results.

Fig. 7 presents the histograms of the six components of the FWI system for both simulated and measured values at Coimbra location, for months February to October corresponding to the MM5 application. The left-hand panels refer to the fuel moisture conditions and the fire behaviour conditions are presented in the right hand panels. In general, future climate simulated values show a higher frequency at the higher risk classes for all the FWI system indexes and consequently a lower frequency for the lower risk classes.

Regarding FFMC results, for the future climate the frequency distribution presents higher values than the historical datasets for Coimbra. The number of classes increase, as well as the frequencies associated, indicating a higher index severity for FFMC and consequently a lower moisture content of the forest fine fuel that plays a very important role on fire starting. The fastest reacting moisture codes to the daily weather changes, FFMC and DMC, show unimodal absolute frequencies distributions, for both climate scenarios and also for the observations. Also, for DMC, higher risk classes show up for the future climate, with lower values in the lower risk classes.

Concerning DC, more than one mode is present, which is explained by its slow reacting character to the variations on deep fuel moisture content. This means that DC estimated in summer still reflects spring time atmospheric conditions.

The frequencies of the fire behaviour indexes ISI and BUI are distributed among a larger number of classes in the future climate scenario. Major differences between future climate scenario and observation values for ISI are related to an increase of frequency in the lowest class and a diminishing of frequencies values in the intermediate classes. In a future climate scenario the BUI frequency distribution presents three more classes of values when compared with the observed values. The BUI index is estimated as a harmonic mean between DMC and DC values. As such, the BUI frequency distribution reflects the DC seasonal effect at the middle frequency classes and the DMC contribution to the lower ones.

Finally, the FWI presents a bi-modal distribution, with higher absolute frequencies in the lowest class due mostly to the weight that ISI and BUI impose on it. Future climate shows a higher frequency within the FWI 20–25 class, which for Portugal is associated with moderate to high fire risk. The FWI values based on observations also present this class as one of the most frequent. Nevertheless, in this case, the first two classes of the FWI present the highest occurrences reflecting the seasonal character of the index. For the future climate, low frequencies are present in lower classes and the number of classes increases.

As previously mentioned, the DC value is strongly related with the total wildfire area burned and under future climate larger area burned may be expected. Hence, to get an overview of the extreme values of this code for both climate scenarios, a map of its maximum values is presented in Fig. 8. In order to map the results a simple kriging method was applied to the discrete DC values in order to obtain a continuous field of DC maximum values. The obtained results give an indication of a positive deviation of the DC maximum values in the inner region as well as over the southern part of Portugal.

4. Conclusions

The Canadian Forest Fire Weather Index System, currently applied by the Portuguese authorities during the fire season, was selected for the evaluation of the impact of climate change on fire weather risk over Portugal.

The statistical analysis of serial data generated by the general circulation model for Portugal points towards an increase in the fire weather risk due to higher temperatures and lower precipitation. The cluster analysis applied to monthly mean temperature and monthly total precipitation, have identified July as the most critical period for wildfires occurrences in the present climate. For the future climate, this critical period is extended including also June. This analysis has also detected a fire risk increase in February/March, and a decrease in November, for the future climate.

A time period for the dynamical downscaling with MM5 was selected based on the preliminary analysis of MUGCM results, namely of the DC values. Aiming to benefit from the estimation of the FWI and the other indexes with a higher spatial and temporal resolution MM5 was applied between February and October forced by boundary and initial conditions from the MUGCM simulations, for both climates. The MUGCM/MM5 results indicate that the slow drying rate moisture code DC presents higher values over southern and inner parts of Portugal. Higher severity classes are expected for the future climate scenario for all the indexes included in the FWI system.

Although not including the dynamics between climate/weather/vegetation/fire, the results from this study indicate higher fire weather risk in Portugal and a longer fire season. It should be noticed that global and the regional model tend to underestimate the precipitation in mid to late spring and this fact can be related to an increase fire risk due to an increase in the fire risk indexes mainly dependent on soil moisture and consequently on precipitation. So, it can be stated that the early starting of the fire season can be influenced by these conditions.

The achieved results point to dramatic consequences of climate change on future forest fire activity over Portugal. The predicted increases in fire weather risk will have environmental, social, and economic impacts and may dramatically impact the organizational structures that deal with wildfire and also society in general. Policy makers, together with fire management authorities have to develop two-folded strategies that include both mitigation and adaptation. The early starting of the fire season, in relation to the historical fire season limits, indicated by fire risk increase in early summer, together with higher severity will impose greater demand on forest fire fighting management and means, including the expansion of the current fire suppression capacity. Regarding adaptation, and since in Portugal 97% of forest fires are human-induced, policy makers should be aware that without major changes in the patterns of human activities, the number of fires due to human causes is likely to increase. Therefore a better land using planning is needed if not to counteract, at least not to strengthen the effects of a dryer and warmer climate.

This work represented one of the first attempts to assess how future climate may impact fire risk over Portugal. Future research should also 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 should be considered, and the human influence on forest fire activity should be addressed, since it is a variable that could change in the future and thus influence forest fire activity and related impacts.

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