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The impact of spatial resolution on area burned and fire occurrence projections in Portugal under climate change

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Abstract In this study, we investigated the impact of future climate change on fire activity in 12 districts across Portugal. Using historical relationships and the HIRHAM (High Resolution Hamburg Model) 12 and 25 km climate simulations, we assessed the fire weather and subsequent fire activity under a $2 \times CO_2$ scenario. We found that the fire activity prediction was not affected by the spatial resolution of the climate model used (12 vs. 25 km). Future area burned is predicted to increase 478% for Portugal as a whole, which equates to an increase from 1.4% to 7.8% of the available burnable area burning annually. Fire occurrence will also see a dramatic increase (279%) for all of Portugal. There is significant spatial variation within these results; the north and central districts of the country generally will see larger increases in fire activity.

1 Introduction

Europe has recently seen a large number of forest fires causing enormous losses in terms of human life and environmental damages. Most of the fires take place in the Mediterranean region, which suffers over 95% of the forest fire damage (EC 2003). Portugal is one of the European countries most affected by forest fires, mainly during the summer season, which is characterized by hot and dry weather (EC 2005). Fire activity is influenced by a number of factors including fuels, management, and climate/weather (Hély et al. 2001). In Portugal and in other areas around the world, relationships between fire activity and weather have been established, and

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in some areas of the world, weather has been found to be the most important factor influencing forest fires (Flannigan and Harrington 1988; Flannigan and Wotton 2001; Harrington et al. 1983; Hély et al. 2001; Pausas 2004; Stocks and Street 1983; Viegas et al. 1992; Viegas and Viegas 1994). In Portugal, weather and fuel moisture (particularly the fine surface fuel moisture) has been found to be most closely related to area burned, whereas fire ignitions are primarily human-caused (Carvalho et al. 2008; Viegas et al. 2001).

Wildland fires in Portugal have been on the rise since the early 1980s, which has been thought to be mostly due to changes in farming and land-use (Moreira et al. 2001; Pereira et al. 2005). However, temperature has been increasing and precipitation decreasing in Portugal in recent years (Santos et al. 2002). These trends are predicted to continue (Christensen and Christensen 2007; IPCC 2007; Santos et al. 2002), which would likely result in drastic increases in fire activity as has been predicted worldwide (Brown et al. 2004; Carvalho et al. 2001; Flannigan et al. 1998, 2000, 2006; Flannigan and van Wagner 1991; Fried et al. 2004; Hennessy et al. 2005; Moreno 2005; Stocks et al. 1998; Wotton et al. 1998).

The future forecast for forest fires is crucial information to have for many reasons. Wildland fire has a direct impact on human safety, livelihood, and property; these impacts would be amplified in a future with increased fire activity. Additionally, suppression operations may become unaffordable in the future, and in extreme situations it may even become largely ineffective relative to the cost (McAlpine and Hirsch 1998). From an ecological perspective fire is a beneficial and essential process; however, too much fire could irreversibly damage and change the ecosystem. Emissions from forest fires are also an important factor to consider (see Amiro et al. 2001a, b; Andreae and Merlet 2001; Crutzen and Andreae 1990; Miranda et al. 1994, 2005) as these emissions can affect ecosystem and human health (Heil and Goldammer 2001; Riebau and Fox 2001; Sitch et al. 2007). These emissions also contribute to global warming, and may therefore result in a positive feedback where global warming results in more fires, which results in more global warming and so on.

In this study, we estimate the potential area burned and fire occurrence in a $2 \times CO_2$ future climatic scenario for Portugal. To our knowledge, no previous studies have addressed this issue in Portugal. In addition, we address the issue of model spatial resolution discussed in Christensen and Christensen (2007) by comparing the results produced by two different spatial resolutions.

2 Data and methodology

2.1 Portugal forest fire background information

In Portugal, the annual average area burned in the last 6 years (2000 to 2005) was 107% higher than the 1990s, which was already 40% higher than the 1980s (Fig. 1a). The 2003 and 2005 fire seasons were largely responsible for the increase of area burned in recent years (Fig. 1b). In 2003 approximately 8.5% of the forested area was burned.

All 18 districts in mainland Portugal (Fig. 2) have shown an increase in recent fire activity; the highest increases in area burned are found in the districts of Castelo Branco, Setúbal, Portalegre, Évora, Beja, and Faro (Fig. 1a). The southern districts

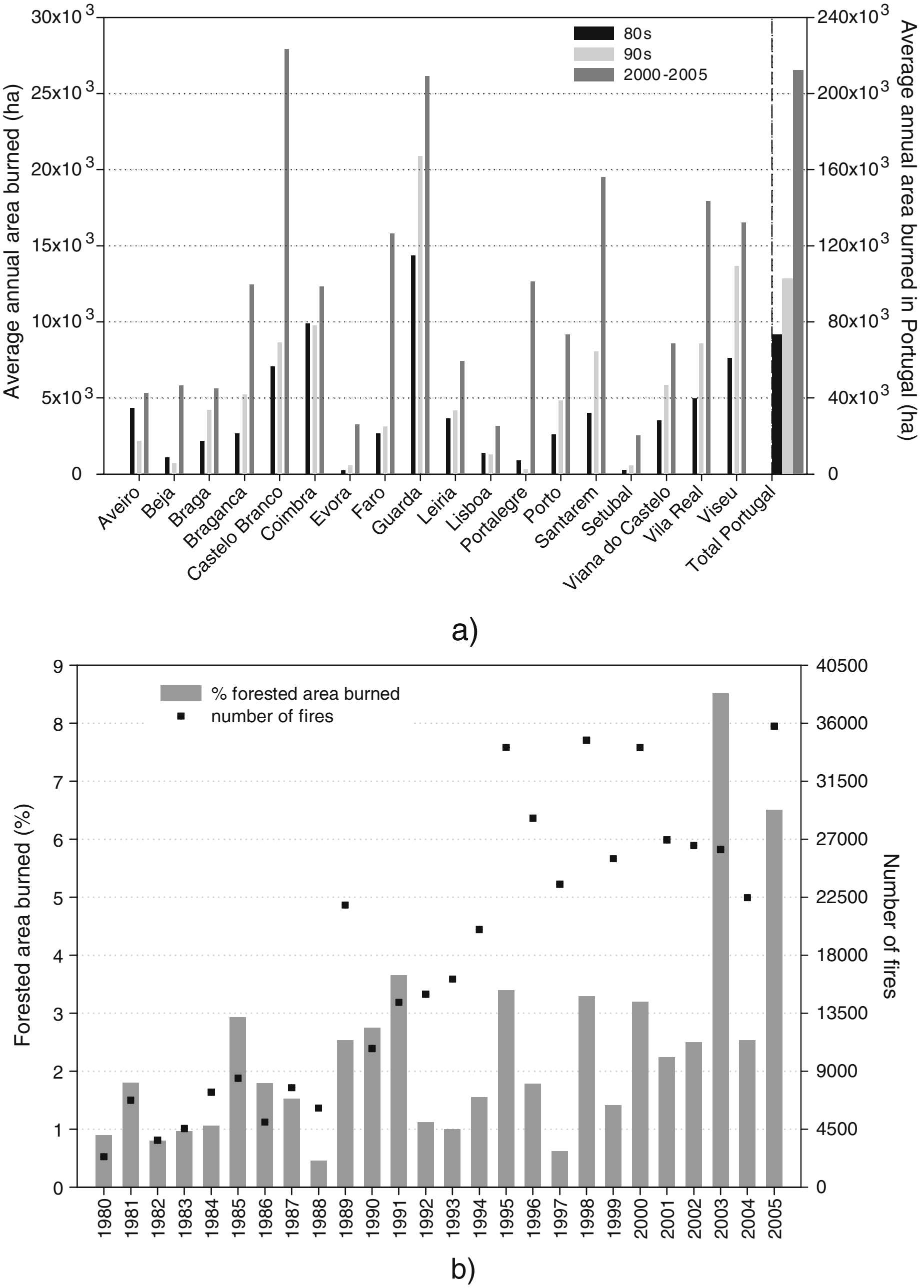


Fig. 1 **a** Annual average area burned for the 1980s, 1990s, and 2000–2005 period, by Portuguese district and for the entire country. *Dashed line* separates the districts vertical axis (*left side*) from the total Portugal vertical axis (*right side*). **b** Area burned (% of forested area) and number of fires for Portugal in 1980–2005

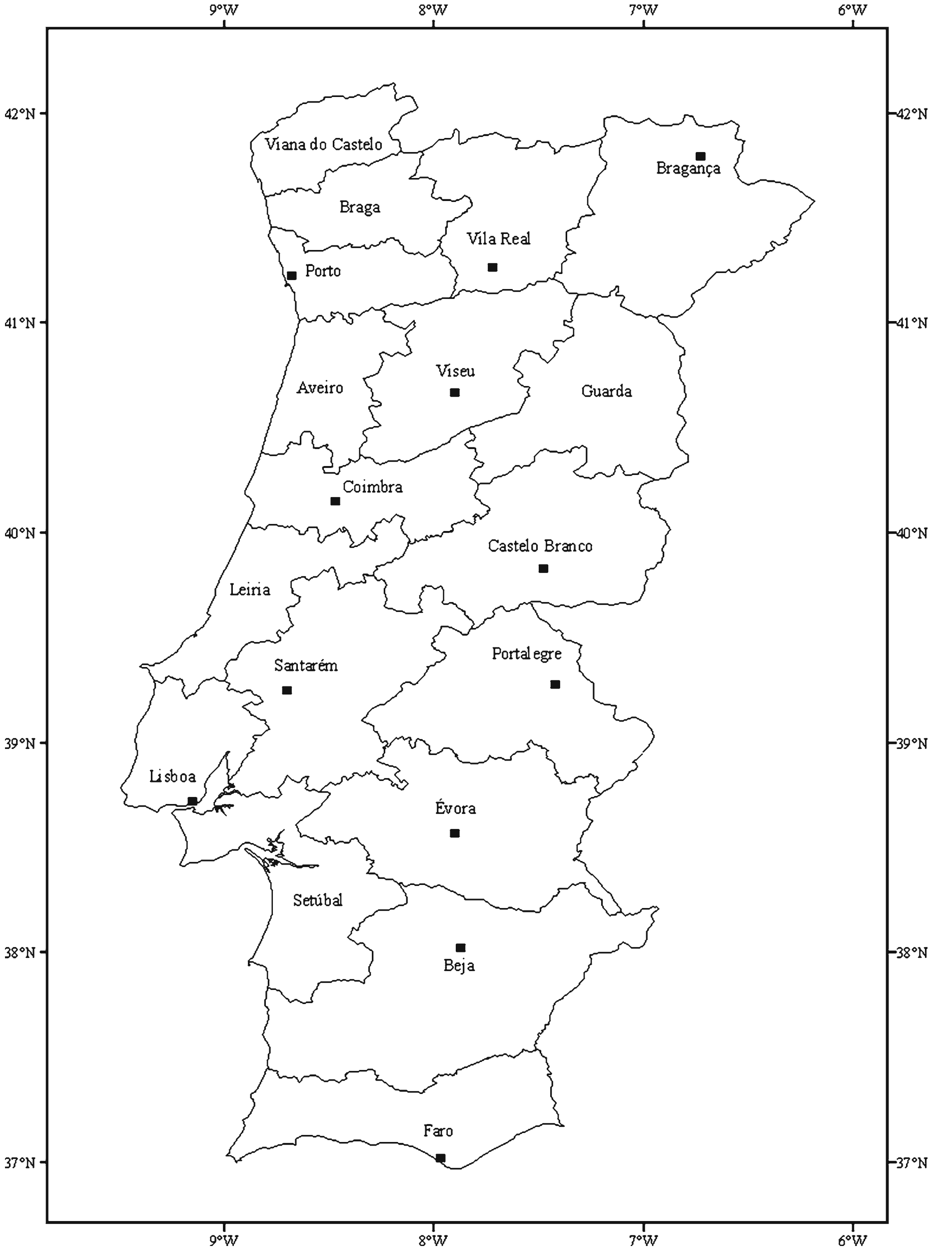


Fig. 2 Map showing Portuguese districts and the meteorological stations location (*black squares*)

of Portalegre, Évora, and Beja have shown the highest percentage increase in area burned even though human land-use patterns (which have resulted in landscape fragmentation) do not favour fire spread. The largest forest fire from 1980–2005 occurred in the Portalegre district in 2003 where it consumed almost 41 100 ha of forest and brushlands (Fig. 3). However, it is interesting to note that there have been

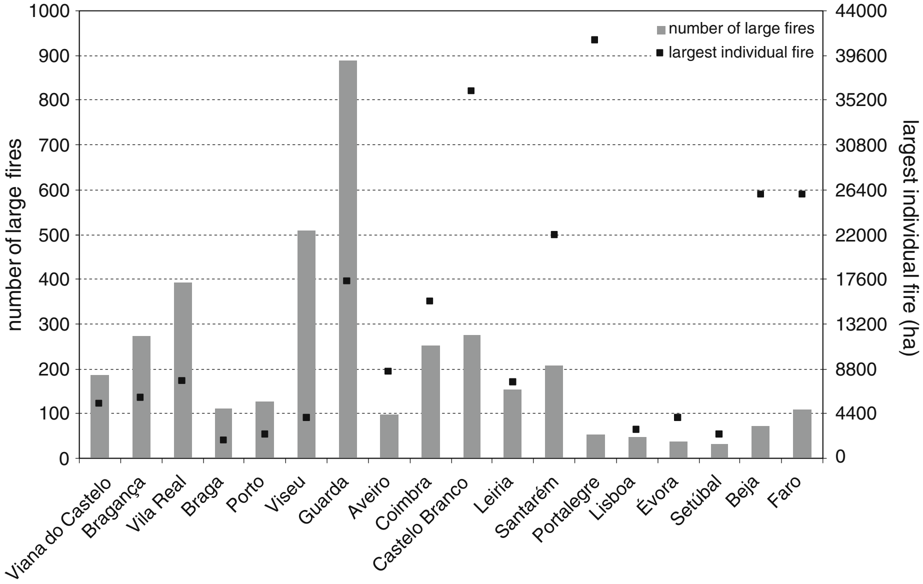


Fig. 3 Number of large fires (area burned above 100 ha) and largest individual fire for 1980–2005 period, by district

a relatively small number of large fires (defined as fires greater than 100 ha) in the Portalegre district. Conversely, the district of Guarda has the highest number of large fires (almost 900) but the largest fire on record was only 17,500 ha. Due to this large variation between the districts, our analysis was done at the district level instead of just for the country as a whole.

Increases in fire activity are likely due to changes in human behaviour including arson fires, land abandonment, and harvesting. Arson fires and land abandonment are both on the rise in Portugal, which has led to expansion of fire-prone brushland and fuel accumulation (Moreira et al. 2001; Carvalho et al. 2008). Harvesting of fire-resistant species such as cork oak (*Quercus suber*) and holm oak (*Quercus rotundifolia*) has resulted in their decline, and more flammable species such as eucalyptus are growing in their place.

2.2 Fire weather relationships

According to Flannigan et al. (2005) there are a number of methods to estimate future fire. The use of historical relationships between observed fires and associated weather and fire weather indices seemed an appropriate methodology to apply in Portugal; mainly because successful relationships between weather and forest fires had already been established in some regions of the country (Viegas et al. 1992; Viegas and Viegas 1994).

The Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) was computed for the period 1980–2004 to investigate the fire weather. Viegas et al. (1999) indicate that the FWI System is the most suitable fire risk assessment tool for Mediterranean countries, namely Portugal. The FWI System 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 are related to the fuel moisture of fine fuels (Fine Fuel Moisture Code, FFMC), loosely compacted organic material (Duff Moisture Code, DMC) and a deep layer of compact organic material (Drought Code, DC). The DMC and DC 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 speed to estimate the potential spread rate of a fire (Initial Spread Index, ISI). The BUI and ISI are then 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 power function of the FWI intended to increase the weight of higher values of FWI in order to compensate for the non-linear increase in difficulty of fire suppression (Williams 1959; Van Wagner 1970).

Twelve meteorological stations (Fig. 2) were analyzed, covering the majority of the country; stations in the six additional districts were not used due to a lack of data. Furthermore, the FWI system uses noon-hour measurements of weather as inputs, but we only had noon-hour measurements at two stations. When we compared these noon measurements to the daily mean, we found a highly significant Pearson correlation coefficient of 0.93 ($p < 0.0001$). Based on these results we determined the means would be sufficient to use as inputs to the FWI System. Therefore, we used mean daily temperature, relative humidity (RH), and wind speed along with 24-h total precipitation data at each station to compute the FWI System components.

The Statistical Analysis System (SAS) version 9.1.3 (SAS 2004) was used for the FWI System components estimation and for all the statistical analysis carried out. All the analyses were performed at a 0.05 significance level. Means and extremes of the meteorological variables and the FWI System components were calculated at every station for each month and fire season (May 1st to October 31st). Extremes of the variables (maximum and the 90th percentile) were also estimated because much of the area burned occurs during extreme fire weather conditions.

2.3 Climatic scenarios

In this study, the data from the PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects) project were used to predict future climate in Portugal. Within PRUDENCE several Atmospheric General Circulation Models (AGCMs) and multiple Regional Climate Models (RCMs) are combined in order to predict and to get an estimate of the uncertainty for reference (1961–1990) and future (2071–2100) climate scenarios (PRUDENCE 2005). The observed sea surface temperatures (SSTs) and emissions of trace gases and sulphate aerosols were used to drive the models. For future climate, the sea surface conditions as predicted from state of the art Atmosphere Ocean General Circulation Models (AOGCMs) and the changes in the radiative forcing derived from the SRES (Special Report on Emissions Scenarios) A2 scenario were used (Christensen and Christensen 2007). The A2 scenario is considered a high emission scenario, and for the time period under consideration in this study, it is equivalent to a $2 \times CO_2$ climatic scenario (IPCC 2007). To ensure model accuracy, Jacob et al. (2007) compared the present-day modeled climate as determined by PRUDENCE to interpolated observations from the Climatological Research Unit

(CRU) (New et al. 2002). It was found that the ensemble RCM prediction was more accurate than any single RCM; also there was evidence that one of the RCMs, HIRHAM (High Resolution Hamburg Model), showed slightly different predictions depending on the spatial resolution employed (50, 25, and 12 km). In this study, we compared the higher-resolution simulations of HIRHAM, 25 and 12 km, in order to assess the influence of spatial resolution on climate and consequently future area burned and fire occurrence in Portugal. We chose to use the 25 and 12 km resolutions, leaving out the 50 km resolution due to the fact that Portugal is a very small country (less than 93,000 km^2) with spatially variable climatological patterns due to the proximity to the Atlantic Ocean and complex topography.

To validate the model in our specific study area, a statistical analysis was performed to compare the simulated (from HIRHAM) and observed (from the 12 meteorological stations) weather and fire weather data. We used a nonparametric test, the Wilcoxon Score Test (van Elteren 1960) for 1980–1990 only since the data was incomplete for the entire 1961–1990 observed data set. For convenience the Wilcoxon Score Test was applied to all variables even when normally distributed. For the 25 km simulation, each station was compared to four grid cells that surrounded its location. For the 12 km simulation, nine surrounding cells were averaged. The Wilcoxon Score Test found that overall, the HIRHAM simulations over Portugal accurately simulated the meteorological and FWI variables for the 1980–1990 period. Some corrections were performed (the remainder of this section details these corrections) to account for differences between the observed and modelled variables.

No corrections were performed for either temperature or wind speed. For temperature all stations were within the accepted range (±3°C) for fire weather impact assessment studies as suggested by Flannigan et al. (2002). Differences in wind speed were also inside the suggested acceptable range (±3 km h^{-1}) for this type of study (Flannigan et al. 2002), except two northern stations (Vila Real and Viseu) and one central (Santarém) were overestimated.

The simulated RH at 12 km resolution showed significant differences from the observed data. The largest differences in RH were in the southern districts (Évora, Beja, and Faro). Flannigan et al. (2002) suggests that the relative humidity should be ±5% for climate change impact studies on forest fire activity. The HIRHAM control simulation does not satisfy this criterion, and considering that the fire weather is highly influenced by humidity (Wotton et al. 1998), we decided to evaluate how well the model predicts the dew point temperature (Tdew). Comparing the simulated Tdew with the observed values it was detected that the HIRHAM model had a cold bias. The highest differences are in the south of the country, especially in autumn. We decided to correct the Tdew simulated values in order to get a more reliable RH estimate. We did not perform a spatial adjustment, but only a temporal (monthly) discrimination. In October and November we corrected the Tdew by +2.5°C, and +1°C for the rest of the year. At 25 km resolution the RH also had lower values than the observed data although it was not so marked as the 12 km simulation. The Tdew was corrected by +0.5°C in all months except in October and November where +2°C correction was applied. After these corrections differences between simulated and observed RH were within ±5% except in the southern Beja and Faro districts where there was still an underestimation (Fig. 4) of about 10%.

Monthly mean of daily precipitation amounts at 12 km resolution were similar to the observed precipitation except at station (Bragança); no correction was applied.

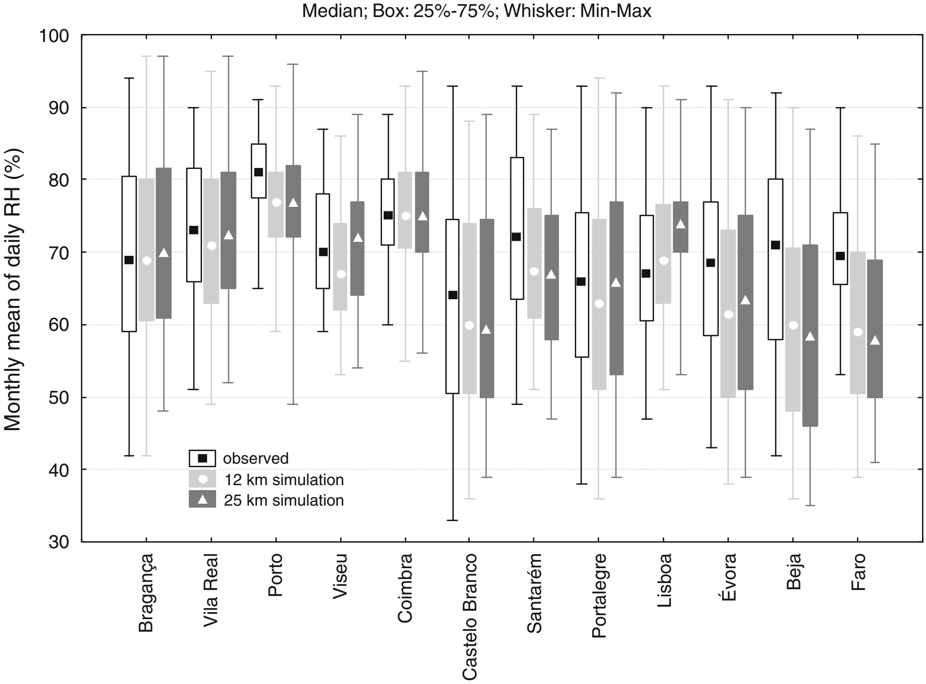
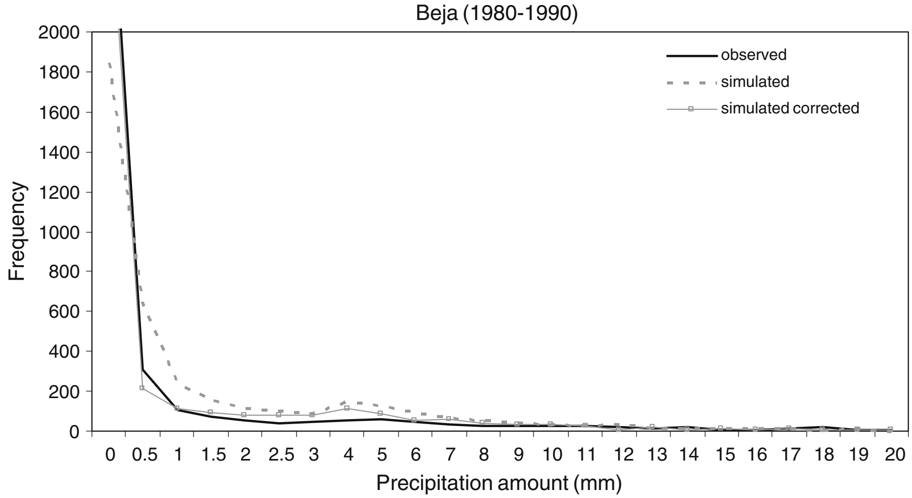


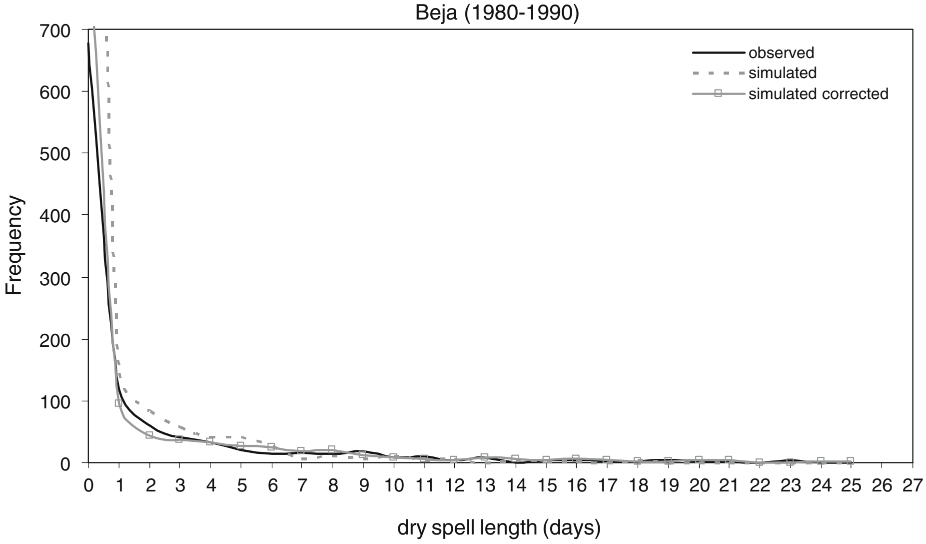
Fig. 4 Maximum, 75th percentile, median, 25th percentile, and minimum values of monthly mean of daily relative humidity (RH) (%) by station for observed data (*blank boxes* and *black squares*), HIRHAM 12 km simulation (*light grey boxes* and *white circles*) and HIRHAM 25 km simulation (*dark grey boxes* and *white triangles*) for the 1980–1990 period

At 25 km resolution, the model results were similar except in the southern districts of the country (Évora, Beja, Lisboa, and Santarém). Since forest fire activity is highly dependent on precipitation regimes (Viegas et al. 1992; Viegas and Viegas 1994), we compared modelled and observed precipitation amounts, precipitation frequency, and the duration of rain-free periods in these southern districts. Several correction values were tested in order to set the precipitation frequencies as close as possible to the observations. A correction of −1.5 mm was found to be most appropriate and was applied to the 25 km resolution model, similar to what has been effective in other studies (e.g. Bergeron and Flannigan 1995; Beer and Williams 1995; Mearns et al. 1995; Wotton et al. 1998; Flannigan et al. 2005). As an example, Fig. 5 exhibits the daily rainfall amount frequencies and the dry spell length at Beja. The applied correction led to a better representation of the precipitation regime. Figure 6 shows a reasonable agreement between the observed values and the reference simulation at 12 km (no correction performed) and at 25 km resolution (after daily precipitation correction) except in Bragança. Differences between 12 and 25 km resolution may be due to the fact that the 25 km scenario incorporates data over a larger area and thus has less variability than the 12 km scenario.

The FWI System components were generally in good agreement with the observed values at the majority of the analyzed stations and for both spatial resolutions and no



a)



b)

Fig. 5 Daily rainfall amount frequencies (**a**) and dry spell length frequencies (**b**) at Beja. The *solid line* represents the observed daily precipitation data for the period 1980–1990. The *dashed line* represents the uncorrected frequencies from the HIRHAM 25 km simulation. The *line with squares* represents the frequencies from the HIRHAM 25 km simulation after the correction (−1.5 mm) was applied

corrections were performed. Figure 7 shows the simulated and observed FFMC; the differences are largest for Bragança, likely due to the overestimation of precipitation.

In summary, the southern part of the country exhibits the least accurate results for 1980–1990 when comparing the simulated to the modelled data, namely RH at

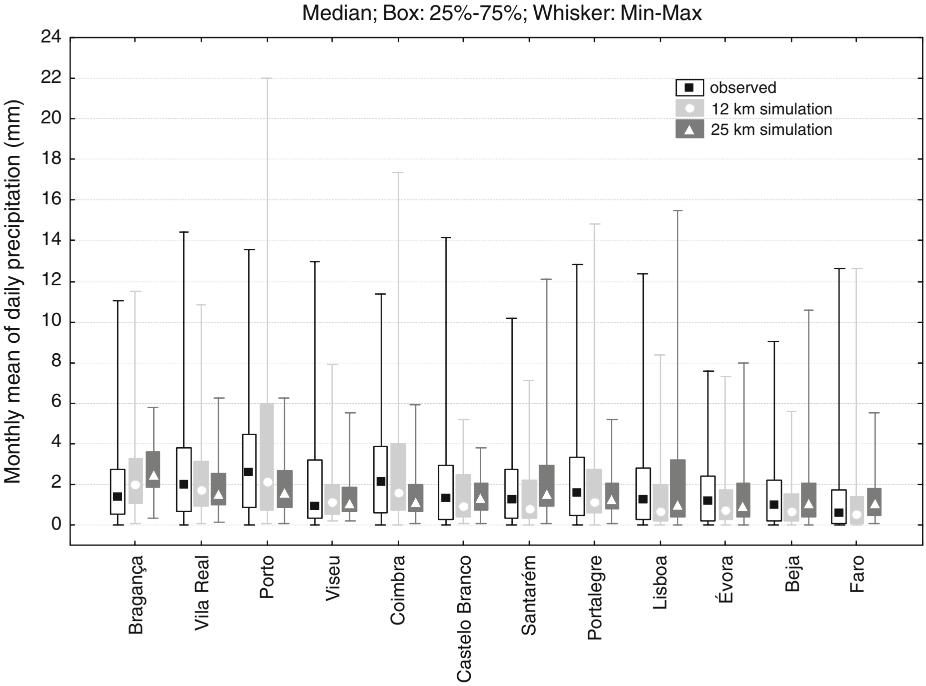


Fig. 6 Maximum, 75th percentile, median, 25th percentile, and minimum values of monthly mean of daily precipitation (mm) for observed data (*blank boxes* and *black squares*), HIRHAM 12 km simulation (*light grey boxes* and *white circles*) and HIRHAM 25 km simulation (*dark grey boxes* and *white triangles*) by station for 1980–1990

both resolutions, and also for precipitation at 25 km resolution. Corrections were performed on RH for both 12 and 25 km resolutions, and on precipitation in southern districts for 25 km. These corrections were then applied to the future modelled scenario to obtain more accurate estimates of future conditions.

2.4 Area burned and fire occurrence

In a related study, Carvalho et al. (2008) performed regressions between the area burned and fire occurrence with the meteorological and FWI variables. They used the same reference period (1980–2004) and the same data sources as in the present paper. Their results showed that monthly values of the meteorological and FWI variables explained more of the variance at each location as compared to seasonal or daily values. Additionally, Carvalho et al. (2008) found that their regression approach explained 61% to 80% of the variance in area burned and 48 to 77% of the variance in the fire occurrence, depending on location ($p < 0.0001$). The DC, BUI, DMC, FWI, DSR, and FFMC components along with the means and extremes of temperature and RH were the selected significant variables across all the districts. In the present study, we applied the regression equations from Carvalho et al. (2008) to the future climate scenario as modelled by the HIRHAM simulations. However, the regression equations were found to be inappropriate for the future climate. The

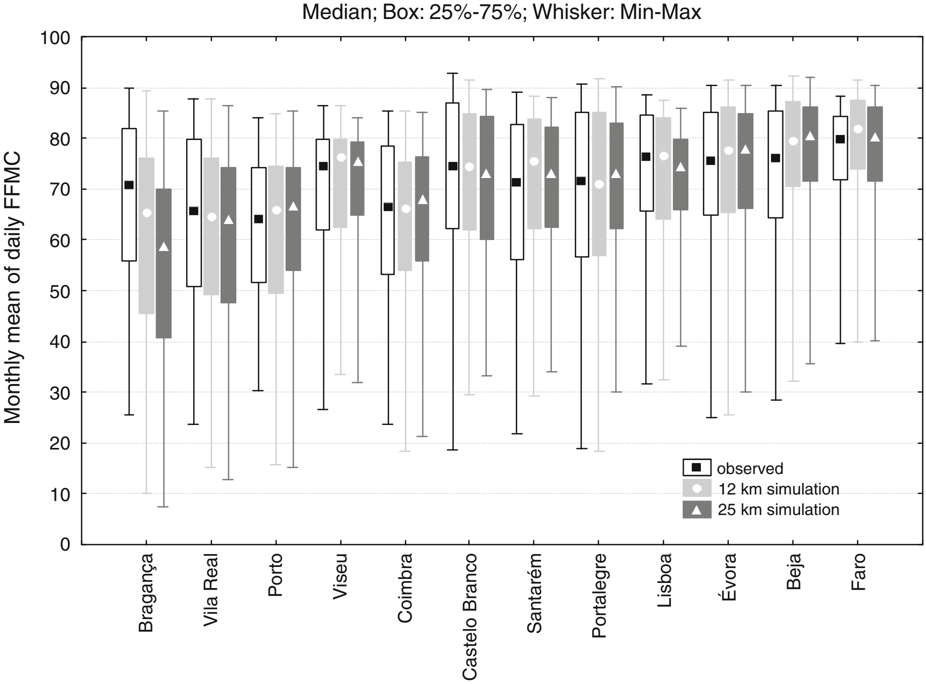


Fig. 7 Maximum, 75th percentile, median, 25th percentile, and minimum values of monthly mean of daily FFMC for observed data (*blank boxes* and *black squares*), HIRHAM 12 km simulation (*light grey boxes* and *white circles*) and HIRHAM 25 km simulation (*dark grey boxes* and *white triangles*) by station for 1980–1990

reason for this is that the DC and DMC components of the FWI system are not bounded with a maximum value and thus the predicted future hotter climate resulted in extreme DC and DMC values. This caused the area burned projections to be unrealistically high (i.e. higher than the total area present in each district). Therefore, DC and DMC were left out of the regression analysis in this study. We used the monthly mean of both the daily FFMC and the daily maximum temperature (TX) as predictors of the monthly area burned and fire occurrence. The FFMC was selected because, unlike the unbounded DC and DMC, it has a maximum value that it cannot exceed. TX was used since Carvalho et al. (2008) found that it explained a large portion of the variation in area burned (71%) and the fire occurrence (59%).

The distributions of the area burned and the fire occurrence for the reference period (1980–2004) were both found to be non-normal, so the data were transformed (prior to the regression analysis) using the natural logarithm. SAS software was used to perform the regression analysis during the reference period for each of the districts individually, though the districts of Portalegre, Évora and Beja were analyzed as a group following the methods of Carvalho et al. (2008). An F test was applied to the regression models to determine how well the regression fit the data. We then used the regression models to estimate the area burned and fire occurrence for the future climate as simulated by the HIRHAM model.

In order to investigate the impact of spatial resolution on future fire activity the Wilcoxon Score Test was used to determine if there is a statistically significant difference in the area burned and the fire occurrence ratios between the 12 and 25 km spatial resolutions.

3 Results and discussion

3.1 Fire weather in a 2 × CO_2 scenario

The HIRHAM projections over Portugal suggested that the mean temperature will rise in all seasons, and that in summer the increase may reach 6°C in the central districts of Portugal ($p < 0.0001$). This is in line with the results of Christensen and Christensen (2007), where all models within the PRUDENCE project showed that the largest warming will occur in the Mediterranean region, and most of the models suggested that southern France and the Iberian Peninsula will experience the most dramatic warming (more than 6°C).

At 12 km resolution, we found the daily precipitation will decrease across Portugal in all seasons. Spring will be the most affected, with reductions reaching almost 2.2 mm in the northwest region of the country ($p = 0.0009$). The north and centre of Portugal will register the highest reductions in rainfall amounts. At 25 km resolution, spring, summer, and autumn will exhibit daily precipitation reductions in all districts. In the winter, precipitation is predicted to decrease in most areas, but increase (1.0 to 2.3 mm) in some districts in the north and centre of the country. The northwest of Portugal will experience the greatest precipitation reduction (1.5 mm). This kind of variation in spatial and seasonal patterns in precipitation will have a dramatic influence in the fire weather patterns in a future climate. According to previous studies (Viegas et al. 1992; Viegas and Viegas 1994), the precipitation regime in Portugal influences the forest fire activity in two different ways: the rainfall in the beginning of the fire season, particularly in June, has a marked importance in the reduction of the area burned; on the other hand, the precipitation during the winter season is very important for the development of the fine surface fuels that are mainly responsible for the fire propagation during the summer months.

The FFMC showed an increase, especially in the spring and summer months, as can be seen in Fig. 8. Throughout the year, with the exception of the winter months, both the 12 and 25 km scenarios predicted an increase in FWI in all districts (Fig. 9). Additionally, as shown in Figs. 8 and 9, future fire seasons were predicted to start earlier and end later. The month of May had the highest relative increase in FWI and the months of October and November also exhibited considerable increases. The increase in FFMC was also most pronounced in the spring.

There was also a clear trend of increasing FWI from North to South, likely due to the fact that the southern districts have more of a Mediterranean climate. This trend is already apparent for the reference period, but appears to become more pronounced in the future (Fig. 9). Future FWI will also become more intense due to the fact that the higher values of the 25th percentile are predicted to increase dramatically. Additionally, the minimum values will also increase, resulting in fewer low-intensity fires. The increase in the fire weather variables values will have a major impact in the area burned and the fire occurrence in a 2 × CO_2 climatic scenario over Portugal.

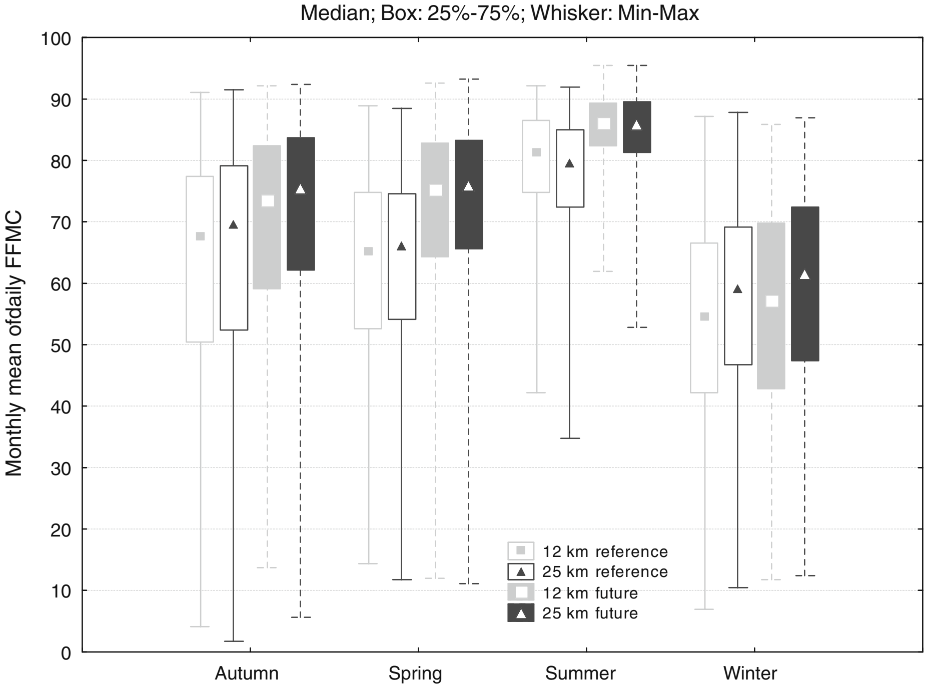


Fig. 8 Monthly average of daily FFMC for HIRHAM 12 km simulation (*squares*) and HIRHAM 25 km simulation (*triangles*) by season, for 1961–1990 reference (*blank boxes*) and 2071–2100 future scenario (*dark boxes*)

Most of the projected variables were not significantly different between the 12 and 25 km simulations ($\alpha = 0.05$). In each district, the projected mean and the maximum temperature increases and the relative humidity decreases in both datasets are not statistically significantly different. Eleven of the 18 districts exhibited statistically significant differences for predicted precipitation changes between the 12 and 25 km simulations. The future increase in FWI was shown to be significantly larger for the 25 km simulation than for the 12 km simulation in several of the districts in the south and central areas of the country (Leiria, Santarém, Lisboa, Évora, Setúbal, Beja and Faro) in the summer months only. All other variables were not statistically significantly different between 12 and 25 km resolutions.

There have been very few studies that look at fire weather in Portugal, and almost none that take the next step of predicting future fire weather. Moriondo et al. (2006) found that for the Mediterranean region there will be a dramatic increase in extreme fire weather events by 2100. Additionally, they predicted an increased length of fire season, as was found in the present study.

3.2 Area burned and fire occurrence in a 2 × CO_2 scenario

Table 1 presents the regression models obtained by multiple regression and the variance explained (%) by TX and FFMC for the natural logarithm of monthly area

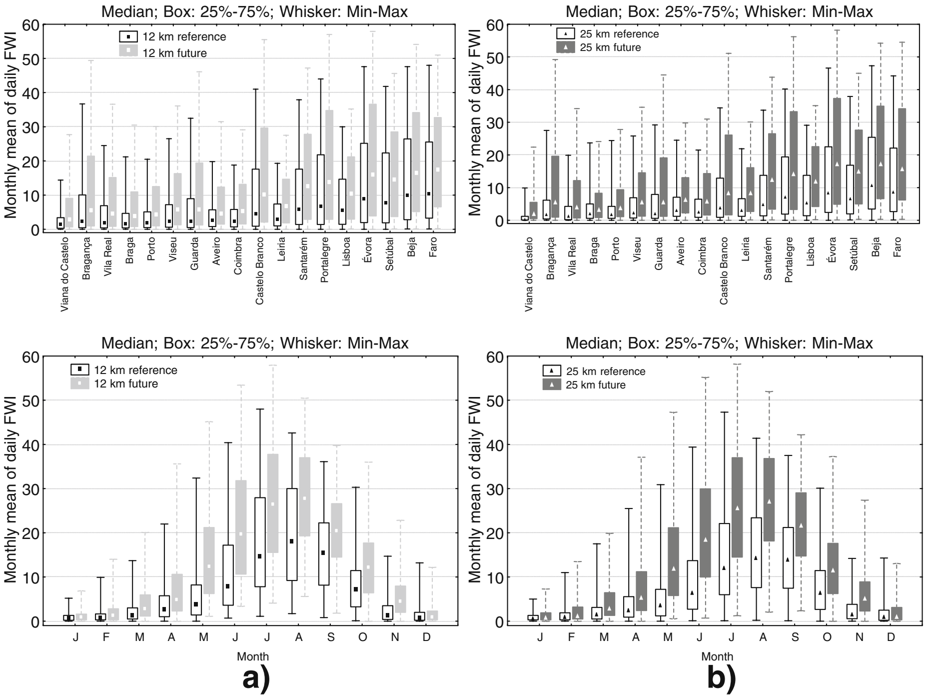


Fig. 9 Monthly mean of daily FWI by district and by month, for 2071–2100 future scenario (*grey boxes*) and 1961–1990 reference period (*blank boxes*) for (**a**) HIRHAM 12 km simulation and (**b**) HIRHAM 25 km resolution

burned for each district. The regression models explain 58% to 71% of the variation depending on district (all p values <0.0001).

According to Table 2, the variance explained (%) in the monthly fire occurrence by TX and FFMC ranges from 46% to 69%, depending on region (p values all

Table 1 Regression model selected by multiple regression for the natural logarithm of the monthly area burned, using maximum temperature (TX) in degrees Celsius and the Fine Fuel Moisture Code (FFMC)

District	Regression model Ln(ab)	Variance explained (%)	Parameter	*P* value
Bragança	$-3.245 + 0.289TX + 0.0119FFMC$	59	300	<0.0001
Vila Real	$-4.248 + 0.208TX + 0.0593FFMC$	61	300	<0.0001
Porto	$-7.961 + 0.389TX + 0.0555FFMC$	58	300	<0.0001
Viseu	$-5.281 + 0.246TX + 0.0685FFMC$	60	138	<0.0001
Coimbra	$-6.899 + 0.338TX + 0.0408FFMC$	64	300	<0.0001
Castelo Branco	$-5.125 + 0.317TX + 0.0237FFMC$	71	236	<0.0001
Santarém	$-6.452 + 0.355TX + 0.0140FFMC$	67	180	<0.0001
Lisboa	$-6.245 + 0.353TX + 0.0174FFMC$	64	300	<0.0001
Portalegre, Évora and Beja	$-4.351 + 0.269TX + 0.0149FFMC$	58	300	<0.0001
Faro	$-8.732 + 0.413TX + 0.0257FFMC$	63	300	<0.0001

Table 2 Regression model selected by multiple regression for natural logarithm of monthly number of fires (nf), using maximum temperature (TX) in degrees Celsius and the Fine Fuel Moisture Code (FFMC)

District	Regression model Ln(nf)	Variance explained (%)	Parameter	*P* value
Bragança	$-1.696 + 0.194TX + 0.00331FFMC$	51	300	<0.0001
Vila Real	$-2.735 + 0.157TX + 0.0399FFMC$	54	300	<0.0001
Porto	$-6.843 + 0.348TX + 0.0542FFMC$	49	300	<0.0001
Viseu	$-2.220 + 0.137TX + 0.0505FFMC$	51	138	<0.0001
Coimbra	$-4.548 + 0.196TX + 0.0452FFMC$	63	300	<0.0001
Castelo Branco	$-3.023 + 0.179TX + 0.0258FFMC$	66	236	<0.0001
Santarém	$-3.736 + 0.216TX + 0.00740FFMC$	69	180	<0.0001
Lisboa	$-4.287 + 0.296TX + 0.00895FFMC$	47	300	<0.0001
Portalegre, Évora and Beja	$-2.393 + 0.137TX + 0.0180FFMC$	46	300	<0.0001
Faro	$-4.737 + 0.232TX + 0.0199FFMC$	53	300	<0.0001

<0.0001). The group of three of the southern districts (Portalegre, Évora and Beja) had the lowest explained variance for both area burned and fire occurrence. Similarly, two of the central districts (Santarém and Castelo Branco) had the highest explained variances.

Table 3 shows the ratio of 2 × CO_2/1 × CO_2 area burned and fire occurrence, by district, using the HIRHAM 12 and 25 km simulations as predicted by the regression models. The 12 km resolution produced a slightly lower average ratio (by 0.16) than the 25 km for area burned, likely due to the fact that the 25 km simulation had a slightly higher increase in FFMC. For the fire occurrence, the average of the ratios differed by only 0.01. The Wilcoxon Score Test was applied for the two spatial resolutions and it was found that there is no difference in the predicted fire activity between the 12 and 25 km spatial resolutions ($\alpha = 0.05$, $p = 0.6501$).

Table 4 presents the observed annual area burned for the 1980–1990 period along with the predicted area burned for each district and all analyzed districts for the 2 × CO_2 scenario. Since no statistically significant difference in the 2 × CO_2/1 × CO_2

Table 3 Ratio of 2 × CO_2/1 × CO_2 area burned and number of fires, by district, using the HIRHAM model outputs at 12 and 25 km resolution

District	Area burned ratio		Number of fires ratio	
	12 km	25 km	12 km	25 km
Bragança	7.51	7.35	3.44	3.37
Vila Real	4.94	5.27	3.18	3.33
Porto	6.97	7.14	5.79	5.86
Viseu	6.40	5.74	3.00	2.78
Coimbra	6.25	6.53	3.24	3.29
Castelo Branco	6.69	7.09	3.04	3.14
Santarém	5.11	5.81	2.66	2.87
Lisboa	3.71	3.04	2.98	2.50
Portalegre, Évora and Beja	3.88	4.19	2.06	2.15
Faro	4.10	5.08	2.26	2.55
All districts	5.56	5.72	3.17	3.18

Table 4 Annual area burned (ha) by district, observed in 1980–1990 period and predicted for the $2 \times CO_2$ climate, considering the average $2 \times CO_2/1 \times CO_2$ ratio between HIRHAM 12 km and HIRHAM 25 km simulations

District	Observed annual area burned (1980–1990)		$2 \times CO_2$ area burned		$(2 \times CO_2 - \text{obs})/\text{obs}(\%)$
	(ha)	(%)	(ha)	(%)	
Bragança	2,804.5	5.3	20,837.4	6.8	643
Vila Real	5,717.1	10.8	29,185.8	9.5	411
Porto	2,970.5	5.6	20,956.9	6.8	606
Viseu	9,064.7	17.1	55,022.7	18.0	507
Coimbra	11,089.4	20.9	70861.3	23.2	539
Castelo Branco	6,897.5	13.0	47,523.8	15.5	589
Santarém	4,160.6	7.9	22,716.9	7.4	446
Lisboa	5,717.1	10.8	19,295.2	6.3	238
Portalegre, Évora and Beja	2,017.6	3.8	8,141.0	2.7	304
Faro	2,500.9	4.7	11479.2	3.8	359
All districts	52,939.9	100.0	306,020.1	100.0	478

Percent of total annual area burned by district for observed and $2 \times CO_2$ scenario and percent of increase in area burned in future scenario

ratios was detected between 12 and 25 km, the projections here were based on the average ratios of the two resolutions.

The projections for $2 \times CO_2$ scenario showed a substantial increase in area burned in all of the analyzed districts (Table 4). The country as a whole shows a 478% increase in area burned. This future area burned equates to approximately 7.8% of the burnable area (EEA 2008; "burnable area" includes forests, shrublands, and other areas with the potential to burn) burning annually, as compared to the present 1.4%. The Northern districts of Bragança and Porto showed the most dramatic percentage increases, 643% and 606%, respectively. The southern district of Lisboa showed the lowest percentage increase (238%). This north/south dichotomy was apparent, with higher increases in the North and Central part and lesser in the South. The north/central part of the country has historically had the largest amounts of area burned, and it appears that this trend will continue. For example, in the 1980–1990 period, Coimbra already had the highest contribution (20.9%) to the overall area burned (52,939.9 ha) of all the districts. In the $2 \times CO_2$ scenario Coimbra was also predicted to have the highest contribution to the total area burned, and this contribution will increase (to 23.2%).

According to Table 5, in a $2 \times CO_2$ scenario all districts showed an increase in fire occurrence, and the country as a whole shows a 279% increase. Similar to the results for the area burned, there will be a greater increase in the northern part of the country than in the southern part. The highest increase in fire occurrence will be in the northern district of Porto (483%), and the smallest increase will be in the southern group of districts of Portalegre, Évora and Beja (111%).

Though not all districts in Portugal were analyzed in this study, the fire activity projections for a $2 \times CO_2$ scenario suggest that the country will see many more fires and much larger area burned. The districts not analyzed (due to lack of data) share similar climate and land-use patterns with other districts in the country, and would likely produce comparable results to what was found here.

Table 5 Annual number of fires by district, observed in 1980–1990 period and predicted for the 2 × CO_2 climate, considering the average 2 × CO_2/1 × CO_2 ratio between HIRHAM 12 km and HIRHAM 25 km simulations

District	Observed annual number of fires (1980–1990)		2 × CO_2 number of fires		(2 × CO_2 – obs)/obs (%)
	(#)	(%)	(#)	(%)	
Bragança	154	3.2	524	2.9	241
Vila Real	455	9.6	1,481	8.2	226
Porto	1,334	28.1	7,771	43.2	483
Viseu	951	20.0	2,748	15.3	189
Coimbra	626	13.2	2,044	11.4	227
Castelo Branco	483	10.2	1,492	8.3	209
Santarém	205	4.3	567	3.1	177
Lisboa	307	6.5	841	4.7	174
Portalegre, Évora and Beja	131	2.8	276	1.5	111
Faro	108	2.3	260	1.4	140
All districts	4,754	100.0	18,004	100.0	279

Percent of annual number of fires by district for observed and 2 × CO_2 scenario and percent of increase in number of fires in future scenario

The increases in fire activity found here were much higher than projections for other parts of the world such as Canada due to the much more severe projected increases in fire weather over Portugal. For example, Flannigan et al. (2005) found that by the end of twenty-first century area burned in Canada could increase from 74% to 118% in a 3 × CO_2 scenario. For Alaska and western Canada, a 90% to 100% increase is expected in a 2 × CO_2 scenario (Balshi et al. 2008; Krawchuk et al. 2009). Before the end of the century, a 50% increase is predicted for both lightning fire initiations in Alberta (Krawchuk et al. 2009) and human-caused fire ignitions in Ontario (Wotton et al. 2003).

There are some limitations in this study. The corrections performed on the regressions improved the accuracy of the results significantly, but the regressions are not completely accurate. For example, one problem that persisted includes inaccuracies in some districts (typically the southern districts) due to the large spatial variation between districts. Additionally, there is an unknown amount of uncertainty in the collected meteorological and fire data. For example, the area burned records prior to 1992 are known to be less precise than later years. Another limitation includes the fact that accounting for micrometeorological factors is not possible with using only a few meteorological stations across the country, which is particularly problematic in a country like Portugal since it has highly variable topography and weather patterns. Finally, as always with a RCM model, there is uncertainty in the predictions of the future climate that could potentially result in our fire activity predictions to be inaccurate.

Issues to approach in future studies include determining if there is a difference between the HIRHAM 50 km resolution and the higher resolution (12 and 25 km) versions. Though the 12 and 25 km simulations produced similar results, there may be differences between the 50 and 12 km simulations. Additionally, analysis of the 50 km resolution would allow for comparison to other RCMs that have 50 km resolutions (Jacob et al. 2007).

Future studies should also include predictions of future human activity. Climate is a major factor in fire activity, but human activity (e.g. land-use changes and fire management strategies) is a crucial element to consider in these types of studies (Moreira et al. 2001). Also, predicting the potential interactions and feedbacks between climate change, forest fire, fire emissions, fuel characteristics and amounts, and human activity are essential in predicting future patterns. To be able to make these types of predictions is the long term goal of this work.

This study revealed that the historical relationships established between the area burned and fire occurrence and the weather and FWI components were not appropriate in a $2 \times CO_2$ scenario. This may constitute an important outcome regarding the limitations of today's developed statistical models and its application under future climatic scenarios. Additionally, it shows that the current FWI system will likely not be useful in Portugal in the future. The FWI system was developed for forest fires in Canada in the present climate, and though it works well for forest fires in Portugal currently (Viegas et al. 1999, 2004), it may not be able to handle the future extreme weather conditions in Portugal.

In summary, the present work investigated the relationship between the weather, the FWI System components, and both the area burned and fire occurrence across Portugal. Projections for the future were made using these relationships, and it was found that different spatial resolutions of the RCMs used did not affect the results. Temperature was predicted to increase and precipitation to decrease, resulting in an increased FWI in all areas studied along with more severe and longer fire seasons. Future fire activity will increase dramatically across the entire country, with area burned and fire occurrence both rising substantially. These predicted increases in fire activity would have environmental, social, and economic impacts and would dramatically impact the organizational structures that deal with wildland fire and also society in general.

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