

Estimation of Forest Fire Danger by Using Fire Weather Index in the CORDEX MENA Region

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Abstract

Forest fires constitute a natural element of Mediterranean ecosystems. Nevertheless, over the past decade, rising temperatures and aridification associated with climate change in the Mediterranean Basin are anticipated to intensify meteorological conditions that promote wildfires. Consequently, forecasting fire danger in this region using fire indices is essential for implementing appropriate precautions. This study used projected changes for 2070–2099, relative to the 1981–2000 reference period, to evaluate forest fire danger using the Canadian Fire Weather Index (FWI) in the Mediterranean region and Turkey, a subset of the MENA domain. The analysis incorporated RCP4.5 and RCP8.5 (IPCC) output scenarios from the MPI-ESM-MR and HadGEM2-ES global models, which were dynamically downscaled to 50 km resolution for the CORDEX-MENA domain using RegCM4. Observational data from ERA-Interim, provided by ECMWF and covering the period 1981–2000, were also utilized to evaluate model performance. The MPI-ESM-MR model outputs showed fire-danger predictions that more closely aligned with the reforecast of observational data (ERA-Interim). Therefore, the MPI-ESM-MR model may be more appropriate for estimating fire danger levels utilizing the FWI. The most significant projected increases in future fire danger are anticipated over the Iberian Peninsula, Southern Europe, and parts of Turkey, particularly under the high-emission RCP8.5 scenario. These findings underscore the growing vulnerability of Mediterranean ecosystems to future climate change and accentuate the importance of regional wildfire adaptation and mitigation strategies. Based on future projections, forest fire danger intensity is expected to rise considerably across the region during the last three decades of this century

1. INTRODUCTION

Wildfires are an integral component of Mediterranean ecosystems. In regions with a Mediterranean climate, rising temperatures due to climate change increase the number of forest fires. (Schröter et al. 2005; Westerling et al. 2006; Turco et al. 2014; Lozano et al. 2017). Many studies indicate forest fires are related not only to temperature increase but also to atmospheric instability and low humidity (Jenkins, 2002, 2004; Choi et al., 2006; Winkler et al., 2007; Peace et al., 2012; Barbera et al., 2015). Additionally, climate change is associated with rising temperatures, drought, and persistent temperature fluctuations. Therefore, prolonged summer aridity and the exacerbation of droughts in other seasons pose a risk of forest fires and burning in the Mediterranean basin, as well as in parts of the Middle East and North Africa (MENA) (Tatli and Türkeş, 2014).

Human-induced increases in temperature and vapor pressure deficit have caused greater fuel aridity since the 1970s, significantly contributing to recent fire outbreaks. This trend is likely to intensify with climate change, leading to more frequent fires (Pausas et al. 2012; Abatzoglou and Williams 2016). In the Anthropocene, escalating fire weather will continue to influence global forest fire patterns. In Mediterranean Europe, the potential for fire danger and burned areas is expected to rise due to global warming. Consequently, wildfire adaptation strategies will be essential to reduce their negative impacts (Abatzoglou et al. 2019; Morán-Ordóñez et al., 2020; Grünig et al., 2023).

In many countries of the Mediterranean Basin, especially in western and southern regions, forest fires are among the leading threats to forests. In the Mediterranean climate zone, summers are very hot and arid, and winters are warm and rainy (Türkeş and Altan 2012; Turco et al. 2017). The regions with the highest risk of forest fires due to arid climate conditions include western Turkey, southern Italy, Greece, France, Spain, and Portugal. A high number of forest fires occur in these regions during the period from July to August (Tatli and Türkeş 2014; Turco et al. 2017; Sutanto et al. 2020; Satır et al. 2016).

Drought and hot weather alone are not sufficient to start a forest fire. A forest fire requires a specific combination of oxygen, heat, and fuel (grass or fine, flammable materials commonly called combustible material on the surface) to ignite and burn (Tatli and Türkeş 2014; Johnson and Miyanishi 2001). Additionally, high moisture levels support stable, abundant vegetation growth and provide a barrier to wildfire growth until moisture content drops below the critical lower bound (Abatzoglou and Kolden 2013). Laboratory experiments also show that live-fuel moisture content affects fire behavior and spread (Pimont et al., 2019). Therefore, soil and fuel moisture content substantially influence both combustibility and wildfire duration (Blackwell et al., 1992; Valette et al., 1994; Dimitrakopoulos et al., 2010). Ultimately, moisture, fuel type, and spatial continuity are crucial in determining the fire regime (Flannigan et al. 2000, 2009).

Fire danger indices assess the potential risk of forest fires (Herrera et al., 2013). As wildfire frequency rises, it becomes crucial to understand how fire events relate to weather conditions to improve fire threat evaluations (Ruffault et al., 2017). Many countries use different indices to assess the connection between drought and forest fires. Some widely used fire danger indices include the Canadian Fire Weather Index (FWI) (Van Wagner, 1987), the Haines Index (HI) (Haines, 1989), the Keetch-Byram Drought Index (KBDI) (Keetch and Byram, 1968), the McArthur Mark 5 (Mk5) Forest Fire Danger Index, the Mark 4 (Mk4) Grassland Fire Danger Index (Noble et al., 1980), the Fosberg Fire Weather Index (Goodrick, 2002), and the Nesterov Index (Nesterov, 1949; Ganatsas et al., 2011).

The Canadian Fire Weather Index (FWI) is a widely used tool for predicting extreme fire seasons, offering reliable forecasts (Bedia et al. 2018; Ntinopoulos et al. 2022; Rovithakis et al. 2022). It is also the official index for fire danger alerts issued by the European Forest Fire Information System (EFFIS 2019). Most studies employ the MPI-ESM-LR model (Max Planck Institute Earth System Model Mixed Resolution) to compute FWI values (Costa et al. 2020; Calheiros et al. 2021; Ntinopoulos et al. 2022; Rovithakis et al. 2022).

In this study, the effect of climate change on future fire danger was evaluated for the Mediterranean region and Turkey using FWI output from climate models MPI-ESM-MR and HadGEM2-ES (Met Office Hadley Center Earth System Model), as well as the global reanalysis dataset ERA-Interim. This study offers a comprehensive evaluation of future fire hazard within the Mediterranean Basin, utilizing the Canadian Fire Weather Index (FWI) derived from MPI-ESM-MR-driven CORDEX-MENA regional climate simulations.

Despite the increasing number of studies investigating future wildfire danger in the Mediterranean Basin, important uncertainties remain regarding the performance of different regional climate model configurations over the CORDEX-MENA domain. Previous studies have primarily focused on the MPI-ESM-LR model and have generally evaluated fire danger over limited regions of Southern Europe. In contrast, comparatively fewer studies have examined the performance of MPI-ESM-MR-driven regional simulations for wildfire danger assessment across the broader Mediterranean and MENA regions.

Therefore, this study aims to evaluate future forest fire danger over the Mediterranean Basin using the Canadian Fire Weather Index (FWI) based on dynamically downscaled CORDEX-MENA climate projections. In particular, the study compares the performance of MPI-ESM-MR and HadGEM2-ES global climate models under the RCP4.5 and RCP8.5 scenarios for the period 2070–2099 relative to 1981–2000. This study also provides a regional-scale assessment of future wildfire danger hotspots and examines spatial differences in projected fire danger across major Mediterranean subdomains. The findings contribute to understanding the potential impacts of climate change on future wildfire danger in one of the world's most climate-sensitive regions.

2. METHODS

2.1 Study area

The Mediterranean basin, where forest fires are frequently observed, has temperate climates (Group C) under the Köppen-Geiger climate classification (Peel et al. 2007). According to the Köppen-Geiger classification, the Mediterranean basin is in the Cs group, which is generally mild and rainy in winter and hot and arid in summer.

The study domain includes the Mediterranean basin, spanning latitudes from 30°N to 50°N and longitudes from – 12°E to 53°E. The domain was divided into five subdomains to calculate the average FWI values for these areas (Fig. 1).

2.2 The Canadian Fire Weather Index (FWI)

The Canadian Fire Weather Index (FWI), based on the Canadian Fire Danger Rating System, was first published in 1970, drawing on results of fire research conducted by the Canadian Forestry Service (Van Wagner 1987). FWI is a numerical rating of fire intensity, derived from the Initial Spread Index (ISI) and the Buildup Index (BUI), and indicates fire danger in forested areas (Natural Resources Canada, FWI 2022 <https://cwffis.cfs.nrcan.gc.ca/background/summary/fwi>). It was improved for Canadian forests, but the FWI system indices (ISI, BUI, and FWI) are now most widely used in other countries such as Mexico, Southeast Asia, Florida, and Argentina. Additionally, several studies indicate that the Canadian Fire Weather Index is suitable for forecasting forest fire danger in the Mediterranean region (Moriondo et al. 2006; Viegas et al. 2001; Aguado et al. 2003; Carvalho et al. 2008; Bedia et al. 2018; Ntinopoulos et al. 2022). FWI is also one of the official indexes for fire danger predictions issued by the European Forest Fire Information System (EFFIS 2019 <https://effis.jrc.ec.europa.eu/about-effis/technical-background/fire-danger-forecast/>). Projected changes for the period 2070–2099 (long term) in common climatic parameters (24h accumulated precipitation (mm), noon temperature (°C), relative humidity (%), and wind speed (km/h)) relative to the control period 1981–2000 were used to forecast the fire danger level by FWI. In the study, the R package for fire danger was used to calculate FWI (Bedia et al. 2014, 2018).

The fire danger level, as measured by the FWI, is defined in 6 classes: very low, low, medium, high, very high, and extreme, and is used in Canada (Van Wagner 1987). The FWI classes are redefined using simple thresholding to assess fire danger consistently across Europe by the European Forest Fire Information System (EFFIS) (EFFIS 2019). In this study, we used the EFFIS FWI classification to assess fire danger because it is better suited to the Mediterranean region (Table 1).

Table 1
EFFIS classification thresholds used to evaluate fire danger levels based on the Canadian Fire Weather Index (FWI).

Fire Danger Classes	FWI Values
Extreme	≥ 50.0
Very high	38.0–50.0
High	21.3–38.0
Moderate	11.2–21.3
Low	5.2–11.2
Very low	< 5.2

2.3 Seasonal forecast and observational data

In the present study, MPI-ESM-MR (Max Planck Institute Earth System Model, Mixed Resolution) and HadGEM2-ES (Met Office Hadley Centre Earth System Model) were used to calculate the average fire-season Fire Weather Index (FWI) for the Mediterranean and Turkey, a part of the MENA domain. Climate projections under future scenarios were obtained using the Representative Concentration Pathways (RCPs) (Pachauri et al., 2014), based on human-induced greenhouse gas emissions. Climate data for FWI were gathered from datasets provided by Boğaziçi University's Center for Climate Change and Policy Studies (iklimBU), covering the historical period, RCP4.5 (moderate stabilization), and RCP8.5 (high emission scenario), as outlined by the IPCC. These data were downscaled to 50 km resolution for the MENA-CORDEX domain (MNA-44) using version 4.3 of the regional climate model RegCM (Giorgi et al., 2012; Ozturk et al., 2018). The downscaling employed two models chosen for their superior performance over other GCMs in northern MENA (Endris et al., 2016). Daily accumulated precipitation (mm), noon temperature ($^{\circ}\text{C}$), and noon wind speed (km/h) were derived from three-hourly RegCM outputs, while noon relative humidity (%) was calculated using the Clausius-Clapeyron Equation (Koutsoyiannis, 2012), based on temperature, air pressure, and specific humidity. Additionally, the ERA-Interim global reanalysis dataset from ECMWF, covering 1981–2000, was used to compute FWI and evaluate model performance.

The study uses a 20-year model reforecast (1981–2000), including the historical hindcast, the 20-year FWI reforecast, and future FWI projections for 2070–2099, focusing on the mean for May–October (MJJASO), the fire season. Traditionally, the Mediterranean fire season is defined as June–September (JJAS) in previous research (Moriondo et al. 2006; Schelhaas et al. 2010; Bedia et al. 2014; Casanueva et al. 2018; Copernicus Climate Change Service, 2020; Fargeon et al. 2020). In this study, we identified the fire season (May–October) by forecasting FWI for each month and determining start and end dates based on high-fire-risk areas, particularly in Turkey, using EFFIS FWI classifications. The model mask is a static grid indicating land cover fraction, from 0 (non-forest or urban areas, water, glaciers, deserts, tundra) to 1 (forest, shrub, tall grass). This mask helps exclude non-forest, shrub, and tall grass regions from FWI calculation (see Fig. 1). On maps, forest and shrubland areas are shown in color, while other regions are white.

Although the Canadian Fire Weather Index (FWI) is widely used to estimate meteorological fire danger, wildfire occurrence and spread are also influenced by several non-climatic factors, including vegetation type, fuel continuity, land management practices, and anthropogenic ignition sources. Therefore, the present study focuses primarily on the climatic component of wildfire danger. In addition, using two regional climate model simulations introduces uncertainties associated with model structure, internal climate variability, and emission scenarios. Nevertheless, the selected models have previously demonstrated relatively strong performance over the CORDEX-MENA domain, particularly in reproducing temperature and precipitation climatology.

2.4 Statistical Analysis

The spatial comparison of projected Fire Weather Index (FWI) values was conducted between the reference period (1981–2000) and the future period (2070–2099) for the 1,991 valid land grid cells in the study area, the Mediterranean and Turkey, a part of the MENA domain. The dataset includes the time-averaged climatological mean FWI values for each grid cell under each scenario. The statistical comparisons focused on differences in the spatial distributions of the period means, not on temporal variability. Shapiro-Wilk tests (Shapiro and Wilk, 1965) carried out on random samples of 500 grid cells revealed significant deviations from normality for all FWI variables ($p < 0.001$ in all cases). For this reason, non-parametric tests were employed. Exact effect sizes and p-values are reported throughout, consistent with recommended practice for the interpretation and communication of statistical significance (Wasserstein and Lazar 2016).

Projected future FWI values were compared with the historical model baseline at corresponding grid cell locations using the Wilcoxon signed-rank test (Wilcoxon, 1945). A one-sided alternative hypothesis was used, consistent with the expectation that future values will be higher than historical values due to climate change. Cohen's d effect size (Cohen, 1988) was calculated for each scenario relative to the ERA-Interim observed reference, using the pooled standard deviation. Effect sizes were categorized as small ($|d| < 0.5$), medium ($0.5 \leq |d| < 0.8$), or large ($|d| \geq 0.8$). The spatial extent of projected increases was measured as the percentage of land grid cells with a positive ΔFWI ($\Delta FWI > 0$).

In order to provide an operational context, the FWI values were categorised according to the EFFIS fire danger classification system (Table 1; San-Miguel-Ayanz et al., 2013), this system setting out six levels of danger: Very Low (< 5.2), Low ($5.2-11.2$), Moderate ($11.2-21.3$), High ($21.3-38.0$), Very High ($38.0-50.0$) and Extreme (≥ 50.0). The percentage of grid cells falling into each danger category was calculated for both the reference period and for each of the future scenarios, and the changes in the main category were examined. The entire analysis was carried out using Python 3.12 (Van Rossum and Drake, 2009) and the SciPy (Virtanen et al., 2020) and NumPy (Harris et al., 2020) libraries.

3. RESULTS

The spatial distribution of the historical FWI climatology, obtained from regional climate model simulations, was initially compared with the ERA-Interim reanalysis dataset to assess the consistency of the model outputs. The comparison predominantly concentrated on the models' ability to accurately reproduce the geographical patterns and relative intensity of fire danger across the Mediterranean Basin. In general, both models successfully identified the principal fire-prone regions as indicated by ERA-Interim, although discernible differences in the magnitude of fire danger were observed between the simulations.

The validation of the re-forecast provides an assessment of the quality of the estimates based on their past performance. It supports decision-making at a later operational stage (Goddard et al. 2010; Doblas-Reyes et al. 2013; Bedia et al. 2018). Furthermore, ERA-interim is generally used to evaluate model performance. The first FWI output was forced by the ERA-interim dataset (Fig. 2a), and then FWI historical hindcasts were calculated using the MPI-ESM-MR and HadGEM2-ES models, as shown in Figs. 2b and 2c.

The output of FWI re-forecast by observational data matched up more with the FWI historical hindcast output by the MPI-ESM-MR model than the FWI historical hindcast by the HadGEM2-ES model (Fig. 2). The evaluation was primarily based on the spatial consistency of the simulated FWI climatology with the ERA-Interim-derived patterns across the Mediterranean Basin. This preliminary assessment suggests that the MPI-ESM-MR model provides comparatively more consistent FWI estimates for the study region.

FWI forecasts for the period 2070–2099, relative to the reference period 1981–2000, were computed using the MPI-ESM-MR and HadGEM2-ES models for the IPCC's RCP4.5 (Figs. 3a and 3b) and RCP8.5 (Figs. 3c and 3d) scenarios. The projections indicate a significant increase in forest fire danger throughout the region over the last 30 years of this century under the MPI-ESM-MR model for RCP8.5 and the HadGEM2-ES models for the IPCC's RCP4.5 and 8.5 (Table 2).

Table 2

Descriptive stats, Wilcoxon test results, and EFFIS danger class shifts for each scenario ($n = 1,991$ land grid cells). ΔFWI = future minus baseline. % Area $\uparrow$ = grid cells with $\Delta FWI > 0$. P-values one-sided (future > historical). Cohen's d vs ERA-Interim.

Scenario	Mean FWI	SD	Mean ΔFWI	% Area $\uparrow$	Wilcoxon p	Cohen's d	Danger class shift
ERA-Interim (ref)	17.68	13.77	—	—	—	—	Moderate (ref)
HadGEM2 RCP4.5	27.40	11.19	+ 8.58	99.9%	< 0.001 ***	0.775	Moderate $\rightarrow$ High $\uparrow$
HadGEM2 RCP8.5	40.18	13.76	+ 21.37	97.7%	< 0.001 ***	1.635	Moderate $\rightarrow$ Very High $\uparrow\uparrow$
MPI RCP4.5	19.52	13.81	+ 0.71	45.0%	0.075 ns	0.134	Moderate $\rightarrow$ Moderate (no change)
MPI RCP8.5	25.27	14.51	+ 6.46	68.2%	< 0.001 ***	0.537	Moderate $\rightarrow$ High $\uparrow$
*** $p < 0.001$; ns = not significant ($p > 0.05$). Effect size: small $ d < 0.5$; medium $0.5 \leq d < 0.8$; large $ d \geq 0.8$ (Cohen, 1988).							

The descriptive statistics, the results of the significance tests, and the shifts in EFFIS danger class for all the scenarios are given in Table 2. For both emission scenarios, HadGEM2-ES projected statistically significant increases in fire weather danger, each of these corresponding to a change in the dominant danger class. In the case of RCP4.5, the projected mean FWI shows a transition from Moderate to High danger class ($W = 1,983,030$, $p < 0.001$; Cohen's $d = 0.775$, which is a medium effect; $\Delta FWI = + 8.58 \pm 3.62$). With respect to RCP8.5, the projected mean FWI puts the domain mean in the Very High danger class ($W = 1,969,599$, $p < 0.001$; $d = 1.635$, a large effect; $\Delta FWI = + 21.37 \pm 9.95$). This is the most severe increase projected in the dataset.

The MPI-ESM-MR model found more spatially heterogeneous changes. With RCP8.5, a statistically significant increase was detected, showing a shift from the Moderate to the High danger category ($W = 1,557,458$, $p < 0.001$; $d = 0.537$, medium effect size; $\Delta FWI = + 6.46 \pm 10.29$). On the other hand, under RCP4.5, the expected change did not reach statistical significance ($W = 1,028,451$, $p = 0.075$; $d = 0.134$, small effect size; $\Delta FWI = + 0.71 \pm 10.20$). Accordingly, in agreement with this lack of significance, the domain mean remained in the Moderate danger class.

The difference between the FWI forecast (RCP4.5) output and the historical hindcast shows how much fire danger is expected to increase in the future. As shown in Fig. 4a, the FWI-MPI-ESM-MR projection under the low-concentration RCP4.5 scenario indicates only a slight increase in fire danger according to the EFFIS FWI classification. Additionally, low increases in fire danger can be seen in northwestern Morocco, northern Algeria, Tunisia, and the Iberian Peninsula (Spain and Portugal). Furthermore, the comparison of FWI outputs from the HadGEM2-ES model for 2070–2099 under RCP4.5 and for 1981–2000 (Fig. 4b) reveals low to moderate fire danger increases in Greece, southern and western Turkey, Albania, Macedonia, southern France, Italy, Slovenia, northwestern Morocco, northern Algeria and Tunisia, and the Iberian Peninsula.

The difference between the FWI future forecast under the RCP8.5 scenario and the estimated FWI output from the MPI-ESM-MR model (shown in Fig. 4c) indicates a moderate increase in fire danger in southern and western Turkey, Greece, Albania, Macedonia, southern France, Italy, and Slovenia, based on the EFFIS FWI classification. Additionally, the rise in forest fire danger in northwestern Morocco, northern Algeria and Tunisia, and the Iberian Peninsula (Spain, Portugal) is nearly at a high level.

Additionally, the difference between the FWI future forecast under the RCP8.5 scenario, as modeled by HadGEM2-ES, and the FWI past estimates from HadGEM2-ES indicates a significant rise in fire danger in the southern and western regions of Turkey, Greece, Albania, Macedonia, Southern France, Italy, and Slovenia. Furthermore, the increase in fire danger in northwestern Morocco, northern Algeria and Tunisia, and the Iberian Peninsula (Spain, Portugal) is generally very high to extreme, with southern Spain (Andalusia) reaching extreme levels.

3.1 FWI results of the subdomains

The average past forecast FWI (MJJASO) values for the subdomains (Fig. 1) derived from the HadGEM2-ES and MPI-ESM-MR models (1981–2000), along with the mean FWI outputs for the same subdomains from the MPI-ESM-MR and HadGEM2-ES models (MJJASO, 2070–2099) under RCP4.5 and RCP8.5 scenarios, suggest that fire danger increases across all subdomains as per the EFFIS FWI classification (Table 3). Furthermore, the percentage rise in fire danger, calculated from the average historical forecast FWI and the average future FWI values under RCP4.5 and RCP8.5 from both models, indicates a notable increase in fire hazard in subdomains 4 and 5, particularly under the high-emission RCP8.5 scenario (Table 3).

Table 3

Mean fire-season FWI values (MJJASO) for the five subdomains during the historical period (1981–2000) and future period (2070–2099) under RCP4.5 and RCP8.5 scenarios, including the percentage increase in projected fire danger.

Regions	Subdomains	MPI-ESM-MR Model					HadGEM2-ES Model				
		Avg. value of FWI (1981–2000)	Avg. value of FWI with RCP4.5 (2070–2099)	Avg. value of FWI with RCP8.5 (2070–2099)	The rise of the fire danger with RCP4.5	The rise of the fire danger with RCP8.5	Avg. value of FWI (1981–2000)	Avg. value of FWI with RCP4.5 (2070–2099)	Avg. value of FWI with RCP8.5 (2070–2099)	The rise of the fire danger with RCP4.5	The rise of the fire danger with RCP8.5
1	Aegean and Western Mediterranean of Turkey	32.78	36.00	42.50	10%	30%	22.41	32.50	40.80	45%	82%
2	The Black Sea Region of Turkey	7.96	10.50	14.90	32%	87%	15.11	21.20	27.40	40%	81%
3	Greece	25.87	28.40	36.10	10%	40%	20.71	29.20	34.90	41%	69%
4	The Area of Northern Italy, Southern Switzerland, and Southern France	5.33	8.40	13.20	58%	148%	12.81	21.20	36.50	65%	185%
5	The Iberian Peninsula	13.34	18.30	24.80	37%	86%	14.42	23.60	41.70	64%	189%

Overall, the subdomain analysis indicates that the strongest relative increases in future fire danger are projected over Southern Europe and the Iberian Peninsula, particularly under the RCP8.5 scenario. These regions exhibit substantially larger percentage increases compared to eastern Mediterranean subdomains, suggesting a pronounced regional sensitivity to future warming and drying conditions.

4. DISCUSSION

The impact of climate change on wildfires in the Mediterranean basin has intensified in recent years. This issue primarily stems from rising summer temperatures and aridity in Mediterranean-climate regions, a direct consequence of global warming. Such climatic trends have already led to an increase in forest fire incidences. Furthermore, research on wildfires indicates a significant escalation in their anticipated frequency (Bedia et al., 2018; Casanueva et al., 2018; Fargeon et al., 2020; Calda et al., 2020). Wildfires not only destroy arboreal species but also threaten living organisms. Therefore, it is of paramount importance to develop and employ forest fire indices to predict regions at risk. This proactive measure facilitates the implementation of necessary precautions in vulnerable areas.

The results of FWI reforecasts from the MPI-ESM-MR and HadGEM2-ES models indicate that MPI-ESM-MR produces fire danger estimates that more closely match those from the historical hindcast of observational data (ERA-Interim) than HadGEM2-ES. In the literature, RegCM outputs driven by MPI-ESM-MR have shown better agreement with the observational dataset than those from RegCM driven by HadGEM2-ES for the MENA domain (Ozturk et al. 2018). Moreover, HadGEM2-ES uses a 360-day calendar, with each year containing 12 months of 30 days, whereas MPI-ESM-MR uses a 365-day calendar, including leap years, which provides a more realistic setting for this study, as daily data are used to calculate FWI (Demiroglu et al. 2020). Therefore, the MPI-ESM-MR model could be more suitable for making a skillful FWI forecast, according to the preliminary assessment.

The projected increase in fire danger aligns with expected warming and drying trends across the Mediterranean Basin under future climate change scenarios. Rising temperatures increase evapotranspiration and atmospheric moisture demand, lowering fuel moisture and creating conditions more favorable for fire ignition and spread. In addition, projected declines in precipitation and prolonged summer droughts are expected to further intensify fuel aridity, particularly in Southern Europe and North Africa. These mechanisms likely explain the substantial increase in FWI values projected for the Iberian Peninsula, the southern Mediterranean coasts, and parts of Turkey under the RCP8.5 scenario.

FWI forecast outputs for 2070–2099, compared with the reference period 1981–2000, indicate a substantial increase in forest fire danger across the Mediterranean Basin under both RCP4.5 and RCP8.5 scenarios. The FWI fire danger forecast from the MPI-ESM-MR model under

RCP4.5 indicates high forest fire danger in southern and western Turkey, Greece, southern Italy, France, northwestern Morocco, northern Algeria and Tunisia, and the southern Iberian Peninsula, according to the EFFIS FWI classification. Additionally, HadGEM2-ES projections under the same scenario indicate very high fire danger levels in these regions and in the Balkans.

Under the high-emission RCP8.5 scenario, the projected increase in fire danger is substantially stronger. Future FWI estimates using the MPI-ESM-MR model indicate very high forest fire danger across southern and western Turkey, Greece, southern Italy, France, northwestern Morocco, northern Algeria and Tunisia, and the southern Iberian Peninsula. Furthermore, the HadGEM2-ES model projects extreme fire danger across these regions and parts of the Balkans. The stronger fire danger projections from the HadGEM2-ES-driven simulations may be associated with differences in how the two climate models represent regional temperature and precipitation patterns. They may also reflect model-dependent differences in how regional temperature, precipitation, humidity, and wind fields are represented. Since FWI is calculated from daily meteorological variables, differences in simulated climate conditions can directly affect the magnitude of projected fire danger. Therefore, model-related uncertainty should be considered when interpreting future wildfire danger projections.

The findings of this study are generally consistent with previous studies reporting increased wildfire danger across the Mediterranean Basin under future climate change scenarios (Moriondo et al. 2006; Bedia et al. 2018; Rovithakis et al. 2022). Similar increases in fire weather severity have been reported, particularly in Southern Europe, the Iberian Peninsula, and coastal Mediterranean regions, supporting the robustness of the projected trends in this study. In addition, previous studies have highlighted that increasing drought severity and prolonged summer aridity play a critical role in intensifying wildfire activity in Mediterranean ecosystems (Pausas 2004; Pausas and Fernández-Muñoz 2012; Turco et al. 2017; Grünig et al. 2023).

Certain limitations of this research must be acknowledged. First, the analysis is based on two regional climate model simulations and therefore does not fully capture the full spectrum of uncertainty associated with future climate projections. In addition, the analysis relies on CMIP5-generation global climate models (MPI-ESM-MR and HadGEM2-ES) under the RCP4.5/RCP8.5 scenarios, with model performance evaluated against the ERA-Interim reanalysis, which ECMWF discontinued in 2019 in favor of ERA5. CMIP6/SSP-based CORDEX-MENA downscaling was not yet available for this domain at the time of analysis; incorporating CMIP6-generation projections is recommended for future work as they become available for the region. Secondly, the Canadian Fire Weather Index (FWI) assesses meteorological fire danger but does not explicitly incorporate factors such as vegetation dynamics, fuel availability, land-use changes, fire suppression capacities, or anthropogenic ignition sources. Additionally, the land-cover mask utilized in the study is static and does not account for potential future alterations in vegetation distribution under climate change scenarios. Consequently, the findings predominantly reflect the climatic component of wildfire danger. Future research could enhance this assessment by employing larger multi-model ensembles, higher-resolution simulations, and integrated fire–vegetation modeling techniques.

CONCLUSION

This study assessed future forest fire danger throughout the Mediterranean Basin by utilizing the Canadian Fire Weather Index (FWI), derived from dynamically downscaled climate projections provided by CORDEX-MENA. Changes in fire danger for the period 2070–2099, relative to 1981–2000, were evaluated using climate model simulations from MPI-ESM-MR and HadGEM2-ES under the RCP4.5 and RCP8.5 emission scenarios.

The comparison between model outputs and ERA-Interim-based FWI estimates indicates that simulations driven by MPI-ESM-MR more accurately reproduce the spatial distribution of historical fire danger than those driven by HadGEM2-ES within the study region. Both climate models project a significant increase in meteorological fire danger throughout the Mediterranean Basin during the late twenty-first century. However, the extent of the projected change is markedly greater under the high-emission RCP8.5 scenario.

The most significant rise in fire danger is expected in the Iberian Peninsula, Southern Europe, northwestern North Africa, and parts of Turkey. Based on the EFFIS FWI classification, areas presently marked as moderate or high fire danger could shift to very high or extreme levels in the future, especially under RCP8.5. These results suggest that climate change could substantially increase how often and how severely wildfire-favorable conditions occur in Mediterranean ecosystems.

Overall, the results underscore the increasing vulnerability of the Mediterranean Basin to climate-induced wildfire dangers. The findings emphasize the importance of strengthening regional wildfire adaptation strategies, developing advanced early warning systems, and formulating sustainable policies for forest and land management to mitigate the environmental and socio-economic consequences of future wildfire incidents.

Declarations

Declarations of AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Claude (Anthropic) to support statistical analysis, verify calculations, cross-check the completeness and accuracy of the reference list against original sources, and assist with manuscript drafting and revision. After using this tool, the author(s) reviewed and edited the content as necessary and take full responsibility for the content of the published article.

Conflicts of interest

The authors declare no conflicts of interest.

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Author Contribution

B.C.: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. K.C.: Methodology, Software, Resources, Data curation, Visualization. N.A.: Resources, Writing – review & editing. M.T.T.: Resources, Writing – review & editing. M.L.K.: Conceptualization, Supervision, Project administration, Writing – review & editing.

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Data Availability

The ERA-Interim reanalysis data used in this study are publicly available from the European Centre for Medium-Range Weather Forecasts (ECMWF). The RegCM4-downscaled CORDEX-MENA climate model output (MPI-ESM-MR and HadGEM2-ES) were provided by Boğaziçi University's Center for Climate Change and Policy Studies (iklimBU) and are available from the corresponding author upon reasonable request. The derived Fire Weather Index datasets generated in this study are available from the corresponding author upon reasonable request.

References

1. Abatzoglou JT, Williams AP, Barbero R (2019) Global Emergence of Anthropogenic Climate Change in Fire Weather Indices. *Geophys Res Lett* 46:326–336. 10.1029/2018gl080959
2. Abatzoglou JT, Williams AP (2016) Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* 113, 11770–11775. 10.1073/pnas.1607171113
3. Abatzoglou JT, Kolden CA (2013) Relationships between climate and macroscale area burned in the western United States. *Int J Wildland Fire* 22:1003–1020
4. Aguado I, Chuvieco E, Martin P, Salas J (2003) Assessment of forest fire danger conditions in southern Spain from NOAA images and meteorological indices. *Int J Remote Sens* 24:1653–1668
5. Barbera MJ, Niclos R, Estrela MJ, Valiente JA (2015) Climatology of the stability and humidity terms in the Haines Index to improve the estimate of forest fire risk in the Western Mediterranean Basin (Valencia region, Spain). *Int J Climatol* 35:1212–1223. 10.1002/joc.4048
6. Bedia J, Golding N, Casanueva A, Iturbide M, Buontempo C, Gutiérrez JM (2018) Seasonal predictions of Fire Weather Index: Paving the way for their operational applicability in Mediterranean Europe. *Clim Serv* 9:101–110. 10.1016/j.cliser.2017.04.001
7. Bedia J, Herrera S, Camia A, Moreno JM, Gutiérrez JM (2014) Forest fire danger projections in the Mediterranean using ENSEMBLES regional climate change scenarios. *Clim Change* 122:185–199. 10.1007/s10584-013-1005-z

8. Blackwell B, Feller MC, Trowbridge R (1992) Conversion of dense lodgepole pine stands in west-central British Columbia into young lodgepole pine plantations using prescribed fire. 1. Biomass consumption during burning treatments. *Can J For Res* 22:572–581. <https://doi.org/10.1139/x92-076>
9. Calda B, An N, Turp MT, Kurnaz ML (2020) İklim Değişikliğinin Akdeniz Havzasındaki Orman Yangınlarına Etkisi. *Int J Adv Eng Pure Sci* 32:15–32. 10.7240/jeps.571001
10. Calheiros T, Pereira MG, Nunes JP (2021) Assessing impacts of future climate change on extreme fire weather and pyro-regions in Iberian Peninsula. *Sci Total Environ* 754:142233. <https://doi.org/10.1016/j.scitotenv.2020.142233>
11. Carvalho A, Flannigan MD, Logan K, Miranda AI, Borrego C (2008) Fire activity in Portugal and its relationship to weather and the Canadian Fire Weather Index System. *Int J Wildland Fire* 17:328–338
12. Casanueva A, Bedia J, Herrera S, Fernández J, Gutiérrez JM (2018) Direct and component-wise bias correction of multi-variate climate indices: the percentile adjustment function diagnostic tool. *Clim Change* 147:411–425. 10.1007/s10584-018-2167-5
13. Cohen J (1988) *Statistical Power Analysis for the Behavioral Sciences*, 2nd edn. Lawrence Erlbaum Associates
14. Choi G, Kim J, Won MS (2006) Spatial patterns and temporal variability of the Haines Index related to the wildland fire growth potential over the Korean Peninsula. *J Korean Geographical Soc* 41:168–187
15. Copernicus Climate Change Service, Climate Data Store (2020) : Fire danger indicators for Europe from 1970 to 2098 derived from climate projection. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on 13-February-2023). 10.24381/cds.ca755de7
16. Costa H, de Rigo D, Libertà G, Durrant H, San-Miguel-Ayanz T (2020) J., European wildfire danger and vulnerability under a changing climate: towards integrating risk dimensions, EUR 30116 EN, Publications Office of the European Union, Luxembourg, ISBN: 978-92-76-16898-0. 10.2760/46951, JRC119980
17. Demiroglu OC, Saygili-Araci FS, Pacal A, Hall CM, Kurnaz ML (2020) Future Holiday Climate Index (HCI) Performance of Urban and Beach Destinations in the Mediterranean. *Atmosphere* 11:911. 10.3390/atmos11090911
18. Dimitrakopoulos AP, Mitsopoulos ID, Gatoulas K (2010) Assessing ignition probability and moisture of extinction in a Mediterranean grass fuel. *Int J Wildland Fire* 19:29–34. <https://doi.org/10.1071/WF08124>
19. Doblas-Reyes FJ, García-Serrano J, Lienert F, Biescas AP, Rodrigues LRL (2013) Seasonal climate predictability and forecasting: status and prospects. *WIREs Clim Change* 4(4):245–268. 10.1002/wcc.217
20. EFFIS (2019) Fire Danger Forecast. <https://effis.jrc.ec.europa.eu/about-effis/technical-background/fire-danger-forecast/>. [Verified 8 November 2019]
21. Endris HS, Lennard C, Hewitson B, Dosio A, Nikulin G, Panitz HJ (2016) Teleconnection responses in multi-GCM driven CORDEX RCMs over Eastern Africa. *Clim Dyn* 46:2821–2846. 10.1007/s00382-015-2734-7
22. Fargeon H, Pimont F, Martin-Stpaul N, De Caceres M, Ruffault J, Barbero R, Dupuy JL (2020) Projections of fire danger under climate change over France: where do the greatest uncertainties lie? *Clim Change* 160:479–493. 10.1007/s10584-019-02629-w
23. Flannigan MD, Krawchuk MA, de Groot WJ, Wotton BM, Gowman LM (2009) Implications of changing climate for global wildland fire. *Int J wildland fire* 18:483–507
24. Flannigan MD, Stocks BJ, Wotton BM (2000) Climate change and forest fires. *Sci Total Environ* 262:221–229
25. Ganatsas P, Antonis M, Marianthi T (2011) Development of an adapted empirical drought index to the Mediterranean conditions for use in forestry. *Agric For Meteorol* 151:241–250
26. Giorgi F, Coppola E, Solmon F, Mariotti L, Sylla M, Bi X, Elguindi N, Diro G, Nair V, Giuliani G, Turuncoglu U, Cozzini S, Güttler I, O'Brien T, Tawfik A, Shalaby A, Zakey A, Steiner A, Stordal F, Sloan L, Brankovic C (2012) RegCM4: model description and preliminary tests over multiple CORDEX domains. *Climate Res* 52:7–29. 10.3354/cr01018
27. Goddard L, Aitchellouche Y, Baethgen W, Dettinger M, Graham R, Hayman P, Kadi M, Martínez R, Meinke H (2010) Providing Seasonal-to-Interannual Climate Information for Risk Management and Decision-making. *Procedia Environ Sci* 1:81–101. 10.1016/j.proenv.2010.09.007
28. Goodrick SL (2002) Modification of the Fosberg fire weather index to include drought. *Int J Wildland Fire* 11(4):205–211
29. Grünig M, Seidl R, Senf C (2023) Increasing aridity causes larger and more severe forest fires across Europe. *Glob Change Biol* 29(6):1648–1659
30. Haines DA (1989) A lower atmosphere severity index for wildlife fires. *Natl Weather Digest* 13:23–27
31. Harris CR, Millman KJ, van der Walt SJ, Gommers R, Virtanen P, Cournapeau D, Oliphant TE (2020) Array programming with NumPy. *Nature* 585(7825):357–362. <https://doi.org/10.1038/s41586-020-2649-2>

32. Herrera S, Bedia J, Gutiérrez JM, Fernández J, Moreno JM (2013) On the projection of future fire danger conditions with various instantaneous/mean-daily data sources. *Clim Change* 118:827–840. 10.1007/s10584-012-0667-2
33. International Centre for Theoretical Physics (ICTP) (2010) RegCM4 <https://www.ictp.it/research/esp/models/regcm4.aspx>. [Verified 5 October 2019]
34. Jenkins MA (2004) Investigating the Haines Index using parcel model theory. *Int J Wildland Fire* 13:297–309
35. Jenkins MA (2002) An examination of the sensitivity of numerically simulated wildfires to low-level atmospheric stability and moisture, and the consequences for the Haines Index. *Int J Wildland Fire* 11:213–232. <https://doi.org/10.1071/WF02006>
36. Johnson EA, Miyanishi K (2001) *Forest Fires: Behavior and Ecological Effects*. Academic, San Diego, CA
37. Keetch JJ, Byram GM (1968) A drought index for forest fire control. *Res. Pap. SE-38. Asheville, NC: US Department of Agriculture, Forest Service, Southeastern Forest Experiment Station*. 35 p., 38
38. Koutsoyiannis D (2012) *Clausius–Clapeyron equation and saturation vapour pressure: simple theory reconciled with practice*. *European Journal of Physics*, 33(2), 295–305. 10.1088/0143-0807/33/2/295
39. Lozano OM, Salis M, Ager AA, Arca B, Alcasena FJ, Monteiro AT, Finney MA, Del Giudice L, Scoccimarro E, Spano D (2017) Assessing climate change impacts on wildfire exposure in Mediterranean areas. *Risk Anal* 37(10):1898–1916
40. Morán-Ordóñez A, Duane A, Gil-Tena A, De Cáceres M, Aquilué N, Guerra CA, Brotons L (2020) Future impact of climate extremes in the Mediterranean: Soil erosion projections when fire and extreme rainfall meet. *Land Degrad Dev* 31(18):3040–3054
41. Moriondo M, Good P, Durao R, Bindi M, Giannakopoulos C, Corte-Real J (2006) Potential impact of climate change on fire risk in the Mediterranean area. *Climate Res* 31:85–95. 10.3354/cr031085
42. Natural Resources Canada, Canadian wildland fire information system: Canadian forest fire weather index (FWI) system (2022) <https://cwffis.cfs.nrcan.gc.ca/background/summary/fwi> [Retrieved January 1, 2022]
43. Nesterov VG (1949) *Fire Frequency Index and Method of its Estimation*. Goslesbumaga, Moscow. (in Russian)
44. Noble IR, Gill AM, Bary GAV (1980) McArthur's fire-danger meters expressed as equations. *Aust J Ecol* 5(2):201–203
45. Ntinopoulos N, Spiliotopoulos M, Vasiliades L, Mylopoulos N (2022) Contribution to the Study of Forest Fires in Semi-Arid Regions with the Use of Canadian Fire Weather Index Application in Greece. *Climate* 10(10):143
46. Ozturk T, Turp MT, Türkeş M, Kurnaz ML (2018) Future projections of temperature and precipitation climatology for CORDEX-MENA domain using RegCM4.4. *Atmos Res* 206:87–107. 10.1016/j.atmosres.2018.02.009
47. Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, Church JA, Clarke L, Dahe Q, Dasgupta P, Dubash NK, Edenhofer O, Elgizouli I, Field CB, Forster P, Friedlingstein P, Fuglestad J, Gomez-Echeverri L, Hallegatte S, Hegerl G, Howden M, Jiang K, Jimenez Cisneros B, Kattsov V, Lee H, Mach KJ, Marotzke J, Mastrandrea MD, Meyer L, Minx J, Mulugetta Y, O'Brien K, Oppenheimer M, Pereira JJ, Pichs-Madruga R, Plattner GK, Pörtner HO, Power SB, Preston B, Ravindranath NH, Reisinger A, Riahi K, Rusticucci M, Scholes R, Seyboth K, Sokona Y, Stavins R, Stocker TF, Tschakert P, van Vuuren D, van Ypserle JP (2014) *IPCC: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, Switzerland)
48. Pausas JG, Fernández-Muñoz S (2012) Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. *Clim Change* 110:215–226. 10.1007/s10584-011-0060-6
49. Pausas JG (2004) Changes in fire and climate in the eastern Iberian Peninsula (Mediterranean basin). *Clim Change* 63:337–350
50. Peace M, McCaw L, Mills G (2012) Meteorological dynamics in a fire environment; a case study of the Layman prescribed burn in Western Australia. *Aust Meteorol Oceanogr J* 62:127–141
51. Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. *Hydrol Earth Syst Sci* 11(5):1633–1644
52. Pimont F, Ruffault J, Martin-StPaul NK, Dupuy JL (2019) Why is the effect of live fuel moisture content on fire rate of spread underestimated in field experiments in shrublands? *Int J Wildland Fire* 28:127–137
53. Rovithakis A, Grillakis MG, Seiradakis KD, Giannakopoulos C, Karali A, Field R, Voulgarakis A (2022) Future climate change impact on wildfire danger over the Mediterranean: the case of Greece. *Environ Res Lett* 17(4):045022
54. Ruffault J, Moron V, Trigo RM, Curt T (2017) Daily synoptic conditions associated with large fire occurrence in Mediterranean France: evidence for a wind-driven fire regime. *Int J Climatol* 37:524–533. 10.1002/joc.4680
55. San-Miguel-Ayanz J, Moreno JM, Camia A (2013) The European Forest Fire Information System in the context of environmental policies of the European Union. *For Policy Econ* 29:19–25

56. Satır O, Berberoğlu S, Cilek A (2016) Modelling long-term forest fire risk using Fire Weather Index under climate change in Turkey. *Ecol Environ* 14:537–551
57. Schelhaas M-J, Hengeveld G, Moriondo M, Reinds GJ, Kundzewicz ZW, Ter Maat H, Bindi M (2010) Assessing risk and adaptation options to fires and windstorms in European forestry. *Mitig Adapt Strat Glob Change* 15:681–701. 10.1007/s11027-010-9243-0
58. Schröter D, Cramer W, Leemans R, Prentice IC, Araújo MB, Arnell NW, Bondeau A, Bugmann H, Carter TR, Gracia CA, de la Vega-Leinert AC, Erhard M, Ewert F, Glendining M, House JI, Kankaanpää S, Klein RJT, Lavorel S, Lindner M, Metzger MJ, Meyer J, Mitchell TD, Reginster I, Rounsevell M, Sabaté S, Sitch S, Smith B, Smith J, Smith P, Sykes MT, Thonicke K, Thuiller W, Tuck G, Zaehle S, Zierl B (2005) Ecosystem service supply and vulnerability to global change in Europe. *Science* 310:1333–1337
59. Shapiro SS, Wilk MB (1965) An analysis of variance test for normality (complete samples). *Biometrika* 52(3–4):591–611. <https://doi.org/10.2307/2333709>
60. Sutanto SJ, Vitolo C, Di Napoli C, D'Andrea M, Van Lanen HAJ (2020) Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale. *Environ Int* 134:105276. 10.1016/j.envint.2019.105276
61. Tatlı H, Türkeş M (2014) Climatological evaluation of Haines forest fire weather index over the Mediterranean basin. *Meteorol Appl* 21:545–552
62. Turco M, Marcos-Matamoros R, Castro X, Canyameras E, Llasat MC (2019) Seasonal prediction of climate-driven fire risk for decision-making and operational applications in a Mediterranean region. *Sci Total Environ* 676:577–583. 10.1016/j.scitotenv.2019.04.296
63. Turco M, Von Hardenberg J, Aghakouchak A, Llasat MC, Provenzale A, Trigo RM (2017) On the key role of droughts in the dynamics of summer fires in Mediterranean Europe. *Sci Rep* 7. 10.1038/s41598-017-00116-9
64. Turco M, Llasat MC, von Hardenberg J, Provenzale A (2014) Climate change impacts on wildfires in a Mediterranean environment. *Clim Change* 125:369–380
65. Türkeş M, Altan G (2012) Analysis of the year 2008 fires in the forest lands of the Muğla Regional Forest Service by using drought indices. *J Hum Sci* 9:912–931
66. Valette JC, Gomendy V, Marechal J, Houssard C, Gillon D (1994) Heat-Transfer in the Soil During Very Low-Intensity Experimental Fires - the Role of Duff and Soil-Moisture Content. *Int J Wildland Fire* 4:225–237
67. Van Rossum G, Drake FL (2009) Python 3 Reference Manual. CreateSpace
68. Van Wagner CE (1987) The development and structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service, *Forest Technical Report* 35. (Ottawa, ON)
69. Viegas DX, Piñol J, Viegas MT, Ogaya R (2001) Estimating live fine fuels moisture content using meteorologically-based indices. *Int J Wildland Fire* 10:223–240. 10.1071/WF01022
70. Virtanen P, Gommers R, Oliphant TE, Haberland M, Reddy T, Cournapeau D, van Mulbregt P (2020) SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nat Methods* 17(3):261–272. <https://doi.org/10.1038/s41592-019-0686-2>
71. Wasserstein RL, Lazar NA (2016) The ASA statement on p-values: context, process, and purpose. *Am Stat* 70(2):129–133. <https://doi.org/10.1080/00031305.2016.1154108>
72. Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science* 313:940–943. 10.1126/science.1128834
73. Wilcoxon F (1945) Individual comparisons by ranking methods. *Biometrics Bull* 1(6):80–83. <https://doi.org/10.2307/3001968>
74. Winkler JA, Potter BE, Wilhelm DF, Shadbolt RP, Piromsopa K, Bian X (2007) Climatological and statistical characteristics of the Haines Index for North America. *Int J Wildland Fire* 16:139. 10.1071/wf060

Figures

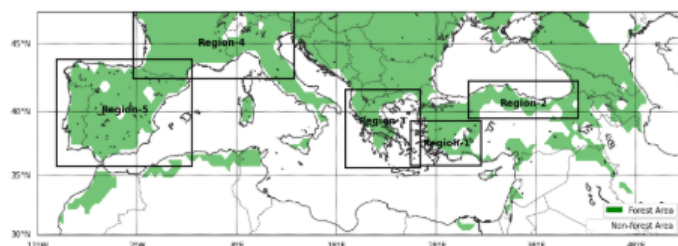


Figure 1

Subdomains used in the study. Forest areas are shown in green.

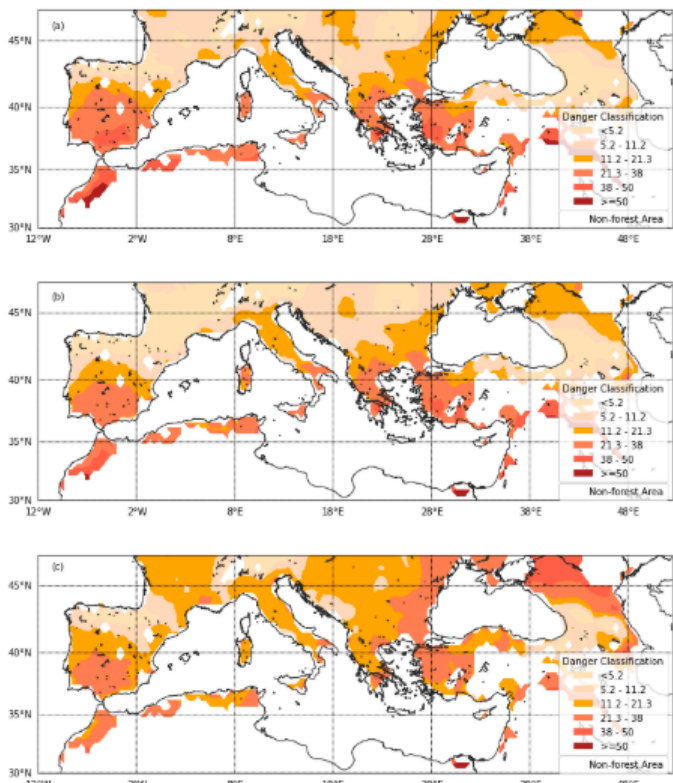


Figure 2

(a) The mean fire season (MJJASO) FWI using the ERA-Interim observational dataset for the period 1981–2000. (b) The mean fire season FWI using hindcast regional downscaling of the MPI-ESM-MR global model for the period 1981–2000. (c) The mean fire season FWI using hindcast regional downscaling of the HadGEM2-ES global model for the period 1981–2000.

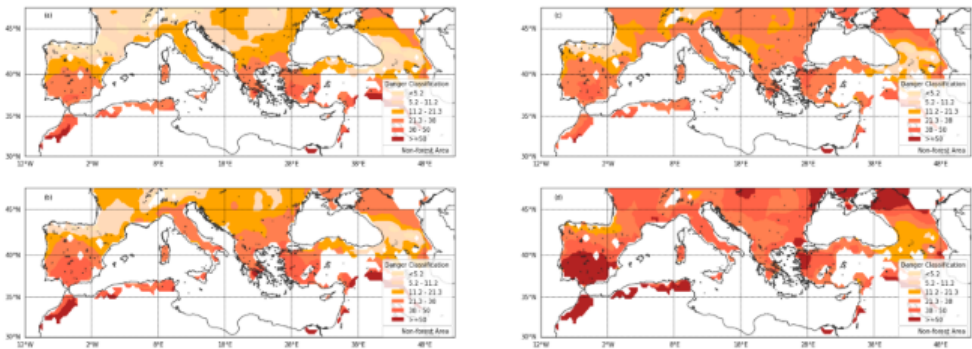


Figure 3

The mean fire season future FWI forecast (MJJASO, 2070–2099) using MPI-ESM-MR model with RCP4.5 (a) and RCP8.5 (b) emission scenarios. The mean fire season future FWI forecast (MJJASO, 2070–2099) using HadGEM2-ES model with RCP4.5 (c) and RCP8.5(d) emission scenarios.

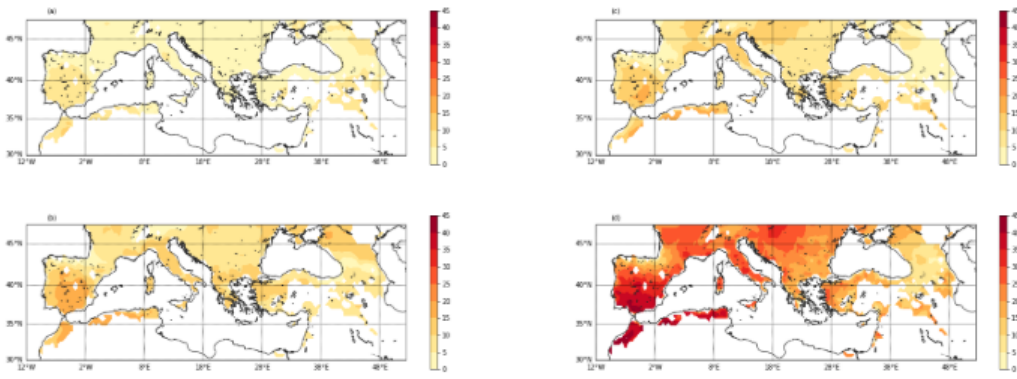


Figure 4

The difference of the output of the mean fire season FWI by MPI-ESM-MR model (2070–2099) with RCP4.5 (a) and RCP 8.5 (b) emission scenarios from the mean past fire season FWI output using MPI-ESM-MR model (1981–2000). The difference of the output of the mean fire season FWI by HadGEM2-ES model (2070–2099) with RCP4.5 (c) and RCP 8.5 (d) emission scenarios from the mean past fire season FWI output using HadGEM2-ES model (1981–2000).