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Fire risk in the Greater Alpine Region from CMIP5 climate models

Barbarino Simona[1,2], Cane Daniele[1], von Hardenberg Jost [2], Pelosini Renata[1], Provenzale Antonello[3]

[1] Arpa Piemonte (Regional Agency for Environmental Protection), Torino, Italy

[2] CNR ISAC Institute of Atmospheric Sciences and Climate, Torino, Italy

[3] CNR IGG Institute of Geosciences and Earth Resources, Pisa, Italy

s.barbarino@arpa.piemonte.it

r.pelosini@arpa.piemonte.it

j.vonhardenberg@isac.cnr.it

antonello.provenzale@cnr.it

Corresponding author:

Simona Barbarino

Arpa Piemonte - Department of Climate and Meteorological Services

Via Pio VII,9

10135 Torino

Tel. +3901119680608

ABSTRACT

Wildfires strongly impact Central and Southern Europe. While the Mediterranean basin represents the region most prone to severe fire events, recently Alpine regions experienced an increasing number of summer forest fires. Additionally, current climate projections indicate that the Alps are especially exposed to temperature rise, leading to more suitable conditions for the forest fires ignition. The assessment of fire risk worldwide is provided by fire weather indices, closely related to daily meteorological conditions: they give information on both current fire risk and potential fire behaviour. In this study, we investigate the application of Atmosphere–Ocean Global Climate Model simulations, performed in the fifth phase of the Coupled Model Intercomparison Project (CMIP5), in order to evaluate fire risk over the alpine regions in the coming decades. Climate projections are used to estimate the Fire Weather Index and the Fine Fuel Moisture Code, based on the Canadian Forest Fire Danger Rating System. We perform a preliminary analysis aimed at the skill assessment of these models in describing wildfires: the weather variables required by fire indices and the fires indices themselves are examined comparing the CMIP5 historical simulations with the corresponding ERA-INTERIM reanalysis. The good skill revealed by CMIP5 simulations provide a quantitative basis for estimating future fire risk. At this aim, we adopt the radiative forcing scenario Representative Concentration Pathways RCP45, to evaluate changes in fire risk across the Alps over the 21st century. A general increase of mean and extreme fire events weather conditions is expected, particularly south of the Alps.

Keywords: climate change, Fire Weather Index, Alps, CMIP5, rcp45, forest fires

1. INTRODUCTION

Wildfires have an important impact on lives, natural heritage and ecosystem services and require a strong employment of human and economic resources for prevention and suppression. These phenomena significantly affect the regions across Central and Southern Europe (Barbosa et al. 2008). The regions around the Mediterranean Sea are commonly recognized to be the most prone to forest fires: besides changes in farm-land use, droughts and increasing temperature apparently contributed to a rise of fire occurrence (Vélez 2002; Moriondo et al. 2006). On the other hand, careful analysis of homogeneized data from specific regions such as Catalunya indicated that the number of fires and the burned area are decreasing, mainly thanks to the implementation of prevention measures which counteract the climate trends (Turco et al. 2013a). In the absence of proper prevention measures, however, also in such areas fire occurrence could increase in future decades (Turco et al. 2013b).

The Alpine chain is usually not considered to be strongly affected by wildfires. However, in recent years it started to be damaged by an increasing number of forest fires, particularly during summer: these events are characterized by increasing severity and intensity (Reinhard et al. 2005). In addition, recent studies have shown a change in fire seasonality (see for example Valese et al. 2011) and current climate projections predict a particularly strong rise in temperature over this region (Ruosteenoja et al. 2007; Fifth Assessment Report-AR5, IPCC, 2013). This increase may augment fuel dryness, particularly in those regions where rainfall is expected to decrease (Howden et al. 1999; Moriondo et al. 2006), favouring suitable conditions for the ignition of forest fires. Targeted prevention measures, through forest management and collective preparedness, are the only sustainable actions to preserve forest resources, together with operational activities aimed at fire danger forecasts, which actually represent the key point in order to set up early alert warning systems. Especially interesting, in this sense, is the evaluation of the feasibility of seasonal fire risk forecast (Turco et al. 2015). Forest fire prevention is considered the most cost-effective and efficient tool to protect forested ecosystems (FAO Fire management: voluntary guidelines, 2006). This outlook highlights the importance to implement reliable techniques to assess fire risk, with the aim to properly evaluate future projections addressing this natural hazard.

The tools that are usually employed to estimate fire risk include a variety of weather indices, used by the major operational fire prevention systems worldwide. Such indices are calculated from local daily weather conditions, in order to provide alert levels related to forest fire risk and potential fire behaviour.

In this study, we investigate the application of a selection of coupled Atmosphere-Ocean Global Climate Models available in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Van Vuuren et al. 2011; Taylor et al. 2012), with the aim to provide future fire risk projections over the Greater Alpine Region (Auer et al. 2007), across the 21st century. Here we adopt the Canadian Fire Weather Index and the Fine Fuel Moisture Code, both based on the Canadian Forest Fire Danger Rating System (Van Wagner 1987), which represents one of the most applied Fire Danger Rating Systems in the world.

The analysis reported here consists of two parts: a preliminary part is dedicated to the assessment of the skill of a selected set of CMIP5 global climate models to describe wildfires, or rather the related suitable conditions for forest fire ignition. This is pursued through a comparison between the simulated climate variables required for calculating fire weather indices and the corresponding ERA-INTERIM reanalysis variables (Dee et al. 2011). A similar evaluation is carried out for the fire weather indices themselves. The second part of the study uses the CMIP5 model simulations resulting from the application of the Representative Concentration Pathway RCP4.5 radiative forcing scenario (Moss et al. 2010) to estimate changes in forest fire potential over the Alps in the 21st century.

The rest of this paper is organized as follows: Section 2 provides a brief description of the selected CMIP5 models and data employed in this study, together with the methods applied to the analysis. Section 3 considers climate variables, relevant for fire indices, in CMIP5 present-day simulations and compares them with the ERA-INTERIM reanalysis dataset in the control period 1979-2003. Section 4 compares fire danger indices based on these variables in the control period. In section 4 projections for the fire weather indices are quantified, together with the expected changes from present conditions. Summary and conclusions are presented in section 5.

2. CLIMATE DATA

We analyse a representative selection of Global Climate Models available in the fifth phase of the Coupled Model Intercomparison Project (CMIP5), which involves new generation state-of-the-art models, developed by several climate modeling groups worldwide (Van Vuuren et al. 2011; Taylor et al. 2012). In spite of the relatively coarse resolution and the shortcomings of these models, they represent the most recent generation of global climate models and provide future projections obtained by applying the Representative Concentration Pathways RCPs (Moss et al. 2010), the new radiative forcing scenarios adopted by the Intergovernmental Panel on Climate Change for its fifth Assessment Report (AR5) (IPCC 2013). We choose a subset of the available CMIP5 models which provide the fields needed for calculating the weather indices investigated in this study, focusing on comparable high resolution grids. The selected models are BCC-CSM1-1M, CNRM-CM5, EC-EARTH, IPSL-CM5A-MR: the models are listed in Table 1 and described in more detail in the appendix. To assess variations of fire potential in the future decades, we select the intermediate radiative forcing scenario RCP4.5. For all analyses in this work, we consider the CMIP5 model fields at their original spatial resolution. The comparisons are performed over the period 2026-2045. The benchmark dataset for our preliminary analysis is represented by the ERA-Interim Reanalysis, the latest global atmospheric reanalysis produced by the European Centre for

Medium-Range Weather Forecasts (Dee et al. 2011) and we consider the period 1979 to 2003 for validation.

The evaluation of fire risk and potential fire behaviour are carried out through the employment of the Canadian Forest Fire Danger Rating System. Conceived and initially used in Canada, it is currently employed in many countries worldwide and adopted by the European Joint research Centre to produce daily fire danger index maps (http://effis-viewer.jrc.ec.europa.eu/). It consists of six components, three fuel moisture codes and three fire behaviour indices. The three fuel moisture codes refer to daily variations of the moisture content of classes of fuel with different drying rates, other two components represent rate of spread of propagation and burning fuel availability. The Fire Weather Index (hereafter, FWI) is the combination of these components and expresses the expected intensity of the flame front.

In order to have a wide overview, we focus our study on the evaluation of both the Fire Weather Index and the Fine Fuel Moisture Code (hereafter, FFMC), the FWI component referring to the moisture content of the surface layer of litter and fine dead fuels. The FFMC index is an indicator of the relative ease of ignition and flammability of fine fuels and it has the fastest response time due to weather conditions changes (Van Wagner 1987).

The climate variables required for the Fire Weather Index calculation are the daily instantaneous values of air temperature, air relative humidity and wind speed intensity at local noon and the total daily amount of precipitation cumulated over the previous 24 hours, from 12:00 UTC to 12:00 UTC. The CMIP5 data selected to represent the input meteorological fields include instantaneous values of 2m temperature and 10m wind speed at 12:00 UTC, retrieved from the 3-hour standard output. Relative humidity, not included in the 3-hour standard output, is calculated from the 3-hour instantaneous values of surface pressure, 2m specific humidity and 2m temperature at 12:00 UTC, for all the models but EC-Earth: in this case relative humidity is calculated by employing the 2m temperature together with the 2m dew point temperature, at 12:00 UTC. The precipitation field is obtained from the 3-hour precipitation data, cumulated over 24 hours from 12:00 to 12:00. The retrieved ERA-Interim variables are the instantaneous values of 2m temperature and 10m wind speed at 12:00 UTC; air relative humidity is obtained from instantaneous values of 2m temperature and 2m dew point temperature at 12:00 UTC. ERA-Interim reanalyses provide cumulated precipitation data at 3-hour resolution; we used daily cumulated precipitation, from 12:00 UTC to 12:00

GCM	Institution	Resolution	Grid cell	Ref
BCC-CSM1-1M	Beijing Climate Center, China Meteorological Administration, China	(1 °x 1 °) T106	160x320 L26	Wu et al.,2008; 2010
CNRM- CM5	Centre National de Recherches Meteorologiques, Meteo-France, France	(1.40625 °x 1.40625 °) T127	256X128 L31	Voldoire et al., 2013
EC-EARTH	Royal Netherlands Meteorological Institute, The Netherlands	(1.125 °x 1.125 °) T159	320X160 L62	Hazeleger et al. 2010; 2012
IPSL- CM5A-MR	Institut Pierre-Simon Laplace, France	(2.5 ° x 1.25 °)	144X143 L39	Dufresne et al., 2013

UTC. ERA-Interim fields are retrieved on a grid at 1.125 °x 1.125 °resolution.

Table1 List of CMIP5 model outputs considered in this study

The domain considered in our study is the Greater Alpine Region (GAR, 4-19 °E, 43-49 °N) (Auer et al. 2007). Within this area, forest fires show a variety of features, due to the different meteorological and topographical characteristics. The geography of this area, at the crossroads of the Mediterranean, the Atlantic and the Eurasian regions, affects the landscape, the shape and composition of forests, determining heterogeneous environments and populations. The local climate is influenced by two major factors: distance from the sea and altitude. Wind effects and scarce precipitation during spring or summer influence fuel moisture much more in the southern flank of the Alps than in the North, leading to a very different number of fire events in regions located respectively North and South of Alps (Valese et al. 2011). Another important factor, which affects fire size, is the season when fires occur. As a general overview, in the Alpine region fire frequency shows the highest peak during the winter season (from November to April), whereas during summer (from May to October) a second peak is evident, even though distinctly less pronounced. The higher percentage of burned area occurs in winter, owing to surface and fine-fuel-driven fires, classified as small or mean (< 100ha). Individual burned areas larger than 1000 ha are mainly found in summer, because of long lasting drought periods and higher temperatures, allowing ground and crown fires. Most anthropogenic fires occur between March and April, and mainly lighting-induced events characterize Austria during summer (Valese et al. 2011). Summer weather conditions are the main source of the severe forest fire events in the southernmost part of the domain enclosed in the Greater Alpine Regions, which are affected by the typical Mediterranean forest fire regime. Owing to the proper fire seasons which characterize the Alpine region, in this study we consider two periods, the vegetative season (from May to October) and the non-vegetative season (from November to April).

A preliminary study revealed that all selected CMIP5 models are characterized by significant biases in the climate variables, compared to the observed ERA-INTERIM datasets. As a consequence, we decided to apply a simple preliminary bias correction technique to the whole set of input climate fields, separately for non-vegetative and the vegetative seasons. Both for CMIP5 models and reanalysis input fields, we take into consideration the field mean value over the whole reference period considered (i.e. 1979-2003) and over the whole spatial domain. The temperature field is corrected by removing the bias (calculated as the difference between the model and the reanalysis average) from the original values. For precipitation, relative humidity and wind speed fields, the data are multiplied by the bias (in this case calculated as the ratio between the model and reanalysis average). The calculation of fire danger indices is then performed employing the bias-corrected weather fields. After this correction, deficiencies concerning the range of values and the error compared to the observations show a reduction for all models. The same bias correction is applied for the simulations run by the RCP4.5 forcing scenario: in this case the biases are computed over the 1981-2000 reference period, and the correction is applied also to the future scenarios. All the results shown in the next sections refer to the bias-corrected fields.

3. MODEL CLIMATOLOGY IN THE CONTROL PERIOD

As a first step we assess the ability of CMIP5 historical simulations to reproduce the weather conditions suitable for forest fire ignition. For the whole set of climate variables, for each grid point we analyse the median values extracted from the daily time series. Figure 1 (a,b,c,d) shows the maps of median values for the non vegetative season, for all climate fields. The maps reveal a slight overestimation of surface temperatures across the regions to the South of the Alps (figure 1a), whereas the Alps are affected by a cold bias. However, the simulations reproduce well the pattern of temperature gradients along both latitude and altitude. Considerable differences between models emerge in the wind speed maps (figure 1b), with different spatial patterns within the domain, together with a slight overestimation over the sea. The median values of precipitation and relative humidity fields reveal that almost all models overestimate these parameters, particularly in the Alps (Figure 1c, Figure 1d). Similar results are found for the maps for the vegetative season, with an overall better agreement in the spatial patterns.

Precipitation often acts like an "on-off tool" to reset the potential danger of forest fire ignition. The water vapour content of air affects the moisture availability of the different litter layers: for this reason, we focus also on precipitation/non precipitation days as key drivers for forest fire potential. We analyse the seasonal mean number of dry days (precipitation values < 1mm), in Figure 1(e,f). In keeping with the maps of the median values of temperature and precipitation, this parameter is slightly underestimated during the winter months over most of the domain. An overestimation in the Mediterranean area is observed for some models, but this is not relevant here as sea areas do not directly impact forest fires. In summer months, the CMIP5 models exhibit a general good agreement with the reanalysis.

We summarize the range of simulated daily values in Figure 2, reporting boxplots of the daily ranges over the entire domain: for most variables the CMIP5 historical runs fall in the range of ERA-Interim datasets, even if some differences are evident, in particular for the BCC-CSM1-1M model, together with a lower agreement in wind speed.

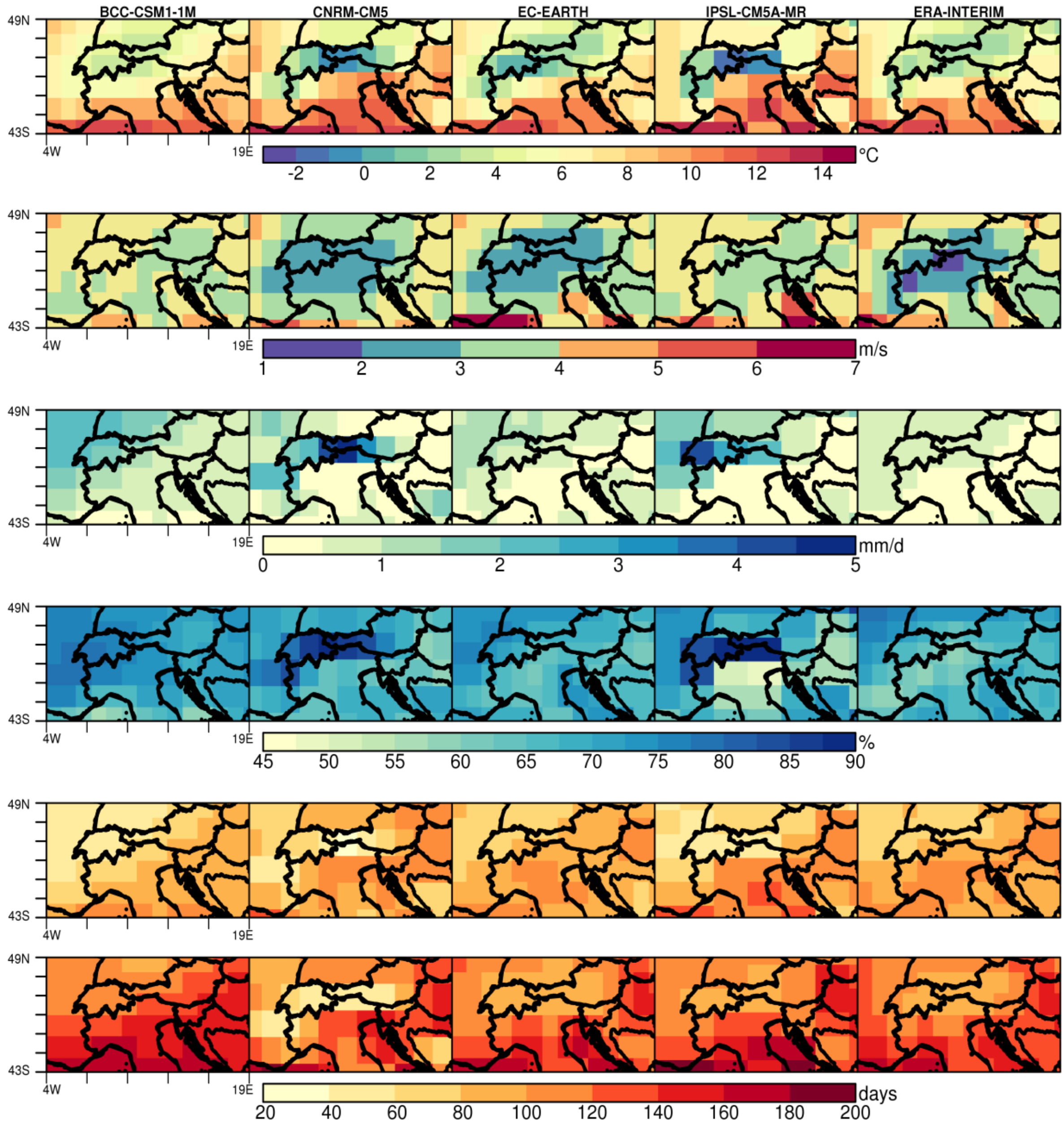

Fig. 1 (a,b,c,d) Maps of 50th percentile values, extracted from daily data - period 1979-2003- non vegetative season (from November to April). From top to bottom: 2m temperature, 10m wind speed, 24h cumulated precipitation, air relative humidity.

Fig. 1 (e,f) Maps of mean number of dry days, extracted from daily data -period 1979-2003. upper panel: non vegetative season; bottom panel: vegetative season

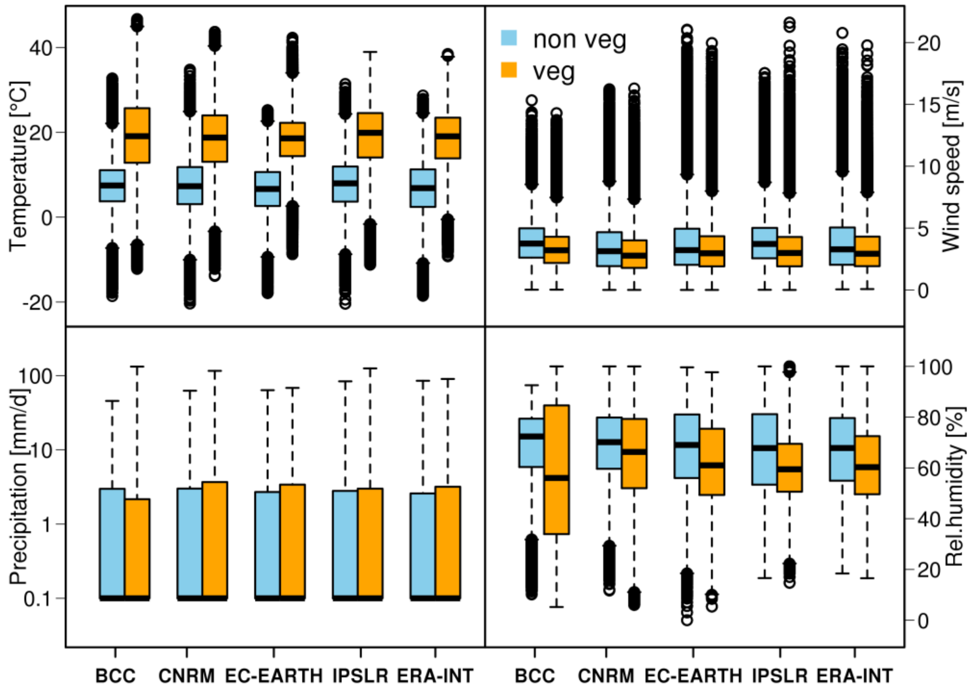

Fig. 2 Boxplots of daily distributions - period 1979-2003. Top left: 2m temperature (2a); top right: 10m wind speed (2b); bottom left: 24h cumulated precipitation (2c); bottom right: air relative humidity (2d). The box is divided in the middle by the median; the extremes represent the first (Q1) and third interquartile (Q3). Outliers locate data point outside of the whiskers of the boxplot (i.e. outside 1.5 times the interquartile range above the upper quartile (Q3) and below the lower quartile (Q1): [Q1-1.5(Q3-Q1),Q3+1.5(Q3-Q1)]

Figure 3 (a,b,c,d) shows the monthly average values of the main weather variables, averaged over the entire domain. For temperature, the curves display a very good agreement across the entire set of models, even though, particularly in summer, most models are slightly hotter than the reanalysis (mainly owing to overestimation over the Mediterranean coasts, not shown). Wind speed confirms the model shortcomings in matching the expected range of values and indicate high variability between models, even if the overall range of observed wind variability is well reproduced. Model fields display considerable difficulties in correctly describing precipitation seasonality: most of simulations cannot reproduce the ERA-Interim peaks and seasonality. The model output that is most similar to the reanalysis is provided by EC-Earth, while the model presenting the largest differences is BCC-CSM1-1M. Air relative humidity displays a better agreement: only the BCC-CSM1-1M simulation presents a significant discrepancy that reaches about 20% in the warmest months.

4. FIRE RISK INDICES IN THE CONTROL PERIOD

Figure 3 (e,f) report the seasonal dependence of the Fine Fuel Moisture Code and of the Fire Weather Index, averaged over the domain of interest. When fire indices are compared, all models, except for BCC-CSM1-1M, reveal good skill in describing the seasonal variability of fires: the curves do overlap over the year and reveal a clear correspondence in replicating both the range of values and the summer peak.The weather indices selected in our study are commonly interpreted to be directly proportional to the increase of fire risk. To estimate fire risk, one should focus on the highest percentiles of the indices extracted from the daily data: low values of FFMC and FWI indicate unfavourable conditions for fire ignition, whereas the high tails of the distributions (say, above the 90th percentile) are associated with very high fire risk.

To assess the model ability to reproduce high fire risk, Figure 3 (g,h,i,l) shows the probability of exceedance of the simulated FFMC and FWI time series extracted from daily data, distinguishing between non-vegetative and vegetative season. The probability of exceedance is defined as 1-CDF where CDF is the cumulative distribution function.

The spatial maps of the 90th percentiles of the FFMC and FWI indices simulated by the CMIP5 models are reported in figure 4.

For the non-vegetative season, the FFMC curves (figure 3g) reveal a good agreement with ERA-Interim values: besides a general slight overestimation of the lowest values of the distribution (actually connected to conditions not favourable to fire ignition), at the highest percentiles, which are usually regarded as thresholds for severe and extreme fire risk conditions, the distributions from the CMIP5 models almost overlap with the ERA-Interim results. The only exception is the BCC-CSM1-1M model: the overestimated frequency of values in the range of the 40th-90th percentiles is caused by relative humidity and precipitation overestimation, particularly in the North-West regions of the domain (figure 4a). This problem can also be noticed in the median values reported in figure 1(1c, 1d) and in the number of dry days , also displayed in figure 1(1e, 1f). In addition, it is clearly evident from the minimum peak during the period October-December (figure 2c, 2d). The general overestimation displayed by the IPSL-CM5A-MR model is caused by a general overestimation of wind speed in the whole spatial domain during winter months (figure 2b, figure 3b) and of temperature in the regions South of Alps (figure 1a). The highest percentiles of the FFMC distributions are better reproduced, except for a negative bias across the Alps (figure 4a).

The CMIP5 control simulations of FWI in the non-vegetative season (figure 3 g) show a rather good agreement with the reanalysis, except for the IPSL-CM5A-MR model: the shortcomings already described for FFMC cause an overestimation of the whole range of middle and high percentiles values, mainly South of Alps (figure 4c) The overestimation of wind speed produces a more relevant overestimation of FWI compared to FFMC (figure 4a). The FWI index is more sensitive to wind, that highly enhances the spreading of fire, than the FFMC index that only expresses the suitable conditions for fire ignition.

In the vegetative season (figure 3i), most models are able to reproduce the FFMC results obtained with the ERA-INTERIM forcing, with the main exception of the BCC-CMS1-1M model, which shows a complete shift of the distribution towards higher values than expected (see also figure3). This difference is related to the different summer weather regimes represented by this model, characterized by an overestimation of summer temperature and an underestimation of summer precipitation, causing a larger evapotranspiration and drying rate of the surface layer of litter and fine dead fuels (figure 1f, figure2).

Figure 4b shows that this overestimation of simulated FFMC values affects the whole domain. In addition, the FFMC curve obtained from the CNRM-CM5 model reveals a shift towards lower values, as can be again noticed also from the median seasonality reported in figure 2. In this case, besides the overestimation of relative humidity and precipitation fields, the key factor is represented by a general slight underestimation of wind speed across the whole domain, and in particular over the Alps; the highest percentiles are instead overestimated by this model, across Central Italy and East Europe (figure 4b).

The FWI probability of exceedance during summer months (figure 3l) is consistent across almost all the models. The different summer weather regimes described by the BCC-CSM1-1M model is responsible for out-of-range values, as already seen in figure 2. In this case, the highly underestimated water vapour content of the air in the simulated weather conditions derived from the BCC-CSM1-1M model results in significant dryness of even the deepest fuel layers: together with the summer temperature overestimation, the final weather conditions would be suitable for very intense and long lasting ground fire, causing the complete shift of FWI values so obtained.

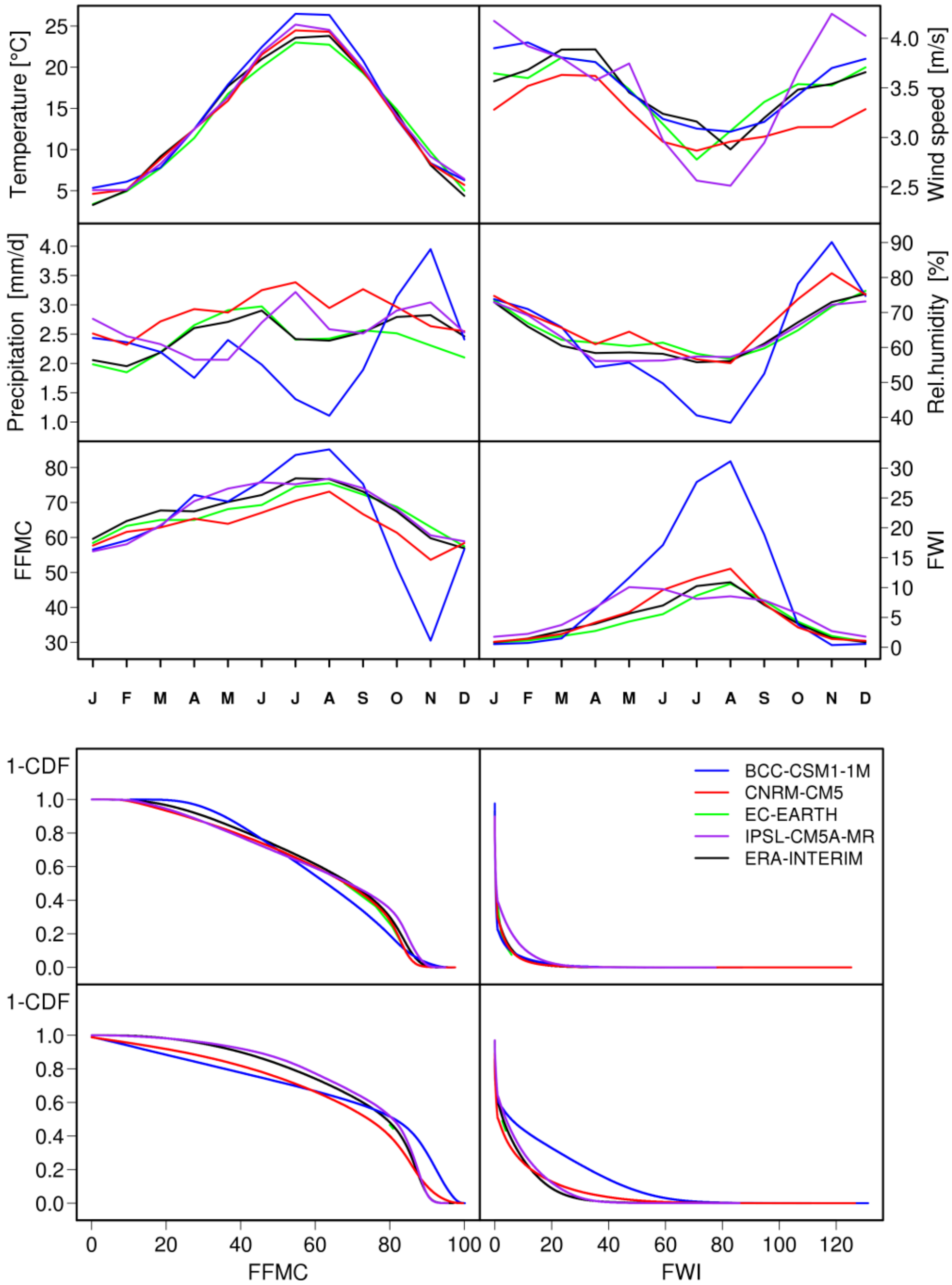

Fig.3 Top panel (a,b,c,d,e,f).Seasonal cycle of the weather fields. Values are calculated from monthly means, averaged on the period 1979-2003. From left to right and from top to bottom: 2m temperature (3a), 10m wind speed(3b); 24hour cumulated precipitation(3c); air relative humidity(3d); Fine Fuel Moisture Code (FFMC)(3f); Fire Weatehr Index (FWI)(3g)

Fig. 3 Bottom panel (g,h,i,l). Probability of exceedance (1- Cumulative Distribution Function), extracted from daily data - period 1979-2003. Top left: FFMC, non vegetative season(3g); top right: FWI, non vegetative season(3h);bottom left: FFMC, vegetative season(3i); bottom right: FWI, vegetative season(3l)

As a general overview, the maps depicting the FFMC and FWI 90th percentile (figure 4) reveal FFMC and FWI geographical differences are rather limited and uniform across the simulations, with the exception of the shortcomings of the specific models discussed above.

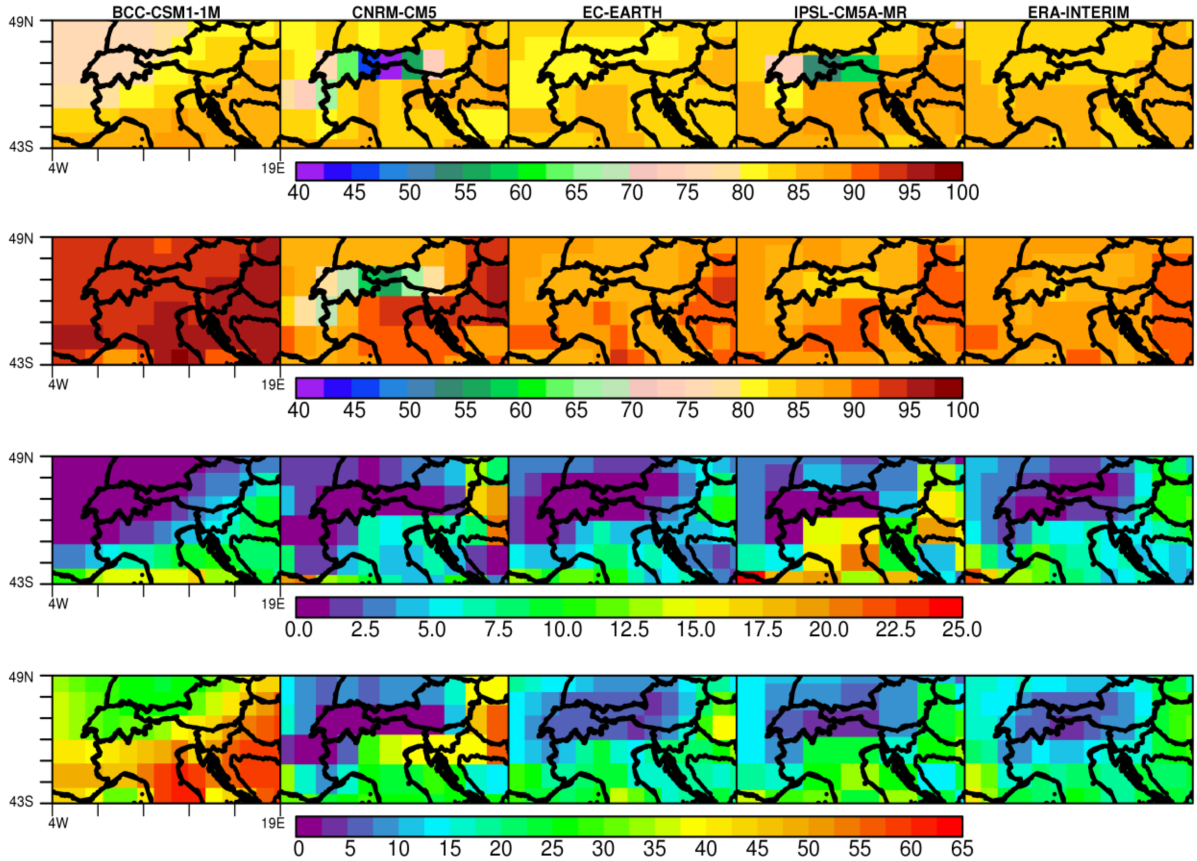

Fig. 4 Maps of 50th percentile values, extracted from daily data - period 1979-2003. From top to bottom: FFMC , non vegetative season (4a), FFMC, vegetative season (4b), FWI ,non vegetative season (4c), FWI, vegetative season (4d),

To summarize the capability of the different models to reproduce the highest percentiles of the simulated fire indices, at each grid point we compute the value of the 90th percentile extracted from the ERA-INTERIM FWI time series over the period 1979-2003 and we determine to which percentile it corresponds in each simulated time series. Table 2 shows the probability of exceedance of the ERA-INTERIM 90th percentile value of FWI in the CMIP5 model's simulations of FWI, averaged over all grid point values. The averaged probability of exceedance is in agreement with the expected 10% during the non-vegetative season for most models, with the exception of the overestimated value derived from the IPSL-CM5A-MR model which mainly affects the regions placed South of Alps. In the vegetative season, deviations from 10% occur for the BCC-CSM1-1M model and, to a small extent, the IPSL-CM5A-MR model, as we expect from the comparative analysis. If we take into consideration the probability of exceedance averaged on all the models' s values, it reveals a very good correspondence during the non-vegetative season (table 2, column "all"). During the vegetative season the unique distribution reveals a higher probability of exceedance of extreme fire danger conditions.

We verified that the differences between the distributions obtained for the models and those obtained for the reanalysis are significant by applying a bootstrap technique (Efron et al. 1994; Efron and Bradley 2003) (1000 bootstrap replications). In particular, for each model, we calculate the difference between the probability of exceedance obtained from the model and the expected probability of exceedance (i.e 10%). We compare this difference with the corresponding value obtained by randomly shuffling the values between the model and reanalysis datasets. Comparing these with the original difference we can assess whether the difference is significant at the 5% level, against the null-hypothesis of no difference.

Table 2 Probability of exceedance of the ERA-INTERIM 90th percentile value of FWI extracted from daily data in the CMIP5 model's simulations - control period 1979-2003. For each model and each grid point, the ERA-INTERIM 90th percentile value is searched in the corresponding grid point model distribution: the probability of exceedance is obtained by averaging the grid point values within the domain.

FWI 1979-2003	BCC-CSM1-1M	CNRM- CM5	EC-EARTH	IPSL-CM5A-MR	ALL
non veg seas	9.0 %	8.9 %	6.5 %	18.9 %	10.8 %
veg seas	35.3 %	13.4 %	9.2 %	14.1 %	18.0 %

5. FIRE RISK PROJECTIONS

So far, our description has dealt with the evaluation of the skill of CMIP5 models to reproduce input climate variables and the resulting fire weather indices in the control period 1979-2003, in order to gauge the capability of the models to reproduce past conditions affecting forest fire regimes and to identify the shortcomings of the selected CMIP5 models. In this section we use the model projections from the same models, in the RCP 4.5 scenario, to formulate future projections of fire weather indices. To assess the possible fire risk variations on short-mid term decades, consider the differences between the conditions in the period 2026-2045 and the conditions on 1981-2000. To assess the variations projected by the CMIP5 models, we conduct the same type of analysis as we did for model verification.

We compared the 2026-2045 FFMC and FWI probability of exceedance curves with the 1981-2000 values (not shown). For winter, the present and future probabilities of exceedance overlap across almost the distribution range, except for a slight increase in the range of median and highest values. The FWI displays a slight increase in the period 2026-2045 for the values corresponding to the highest percentiles; all CMIP5 models show a similar behaviour with the exception of the BCC-CSM1-1M model, which displays a slight increase also in mean values. In the vegetative season, both FFMC and FWI projections reveal a more pronounced shift in the same range of values related to the winter months: again there is good agreement among all the models.

Maps of the differences of the medians between the future and reference period for the fire weather indices (not shown) reveal that projected FFMC median values increase, slightly but significantly, South of Alps particularly during summer months. For FWI, during the non-vegetative season, most projections display no significant differences in the median over the whole domain. During the vegetative season, these differences become significant and larger for all models, and for both indices.

These results suggest that future mean weather conditions will be more suitable for forest fire ignition, in particular in the vegetative season, even if the FWI projections suggest that the spread and intensity of these fire events may change only slightly.

To quantify the impact of future weather conditions on extreme fire events, Figure 5 shows the spatial variations of the probability of exceedance the 90th percentile value between the 2026-2045 and the reference period 1981-2000 for FFMC and FWI. For each grid point we extract the 90th percentile from the 1981-2000 daily time series and we calculate the probability of exceeding that value in the projected daily data over the period 2026-2045. To test the significance of the expected changes we apply a bootstrap technique (Efron et al. 1994; Efron and Bradley 2003).

The maps reveal rather similar results for both indices, showing significant and positive changes over most of the domain. The expected changes are larger in the summer season (figure 5b, 5d). Some models show no significant changes North of the Alps.

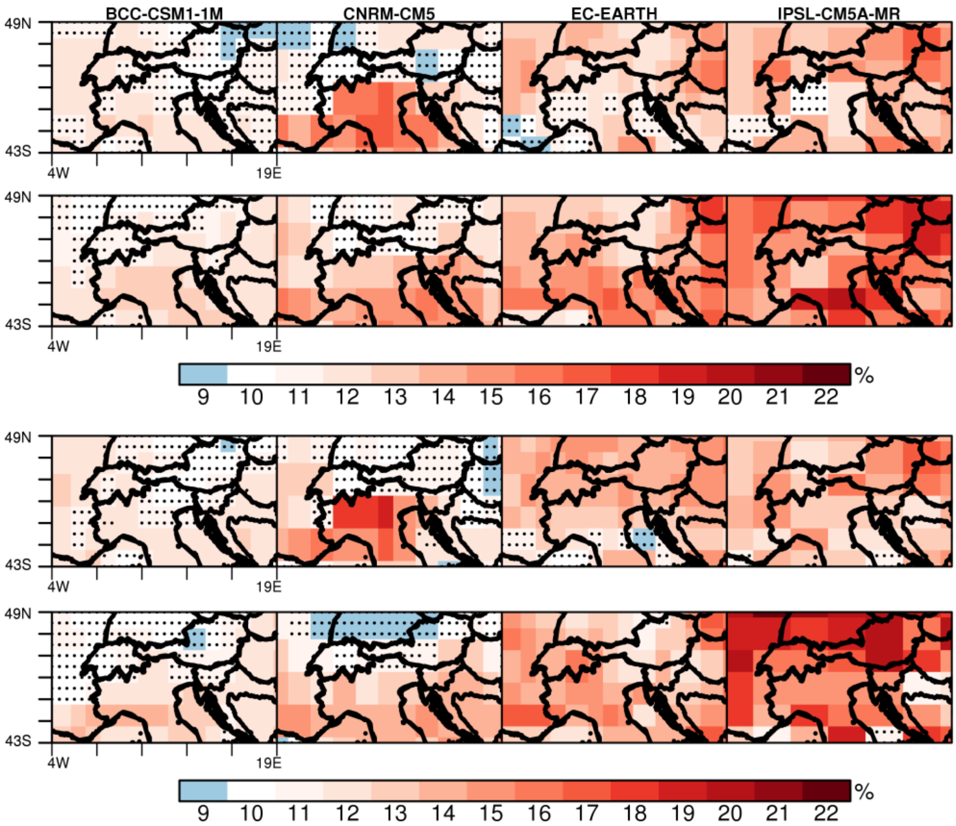

Fig.5 Probability of exceedance of 90th percentile value, extracted from the daily data of the CMIP5 present-day runs (1981-2000), in the daily data of the RCP45 scenario for 2026-2045. From top to bottom: FFMC, non vegetative season (5a), FFMC, vegetative season (5b), FWI, non vegetative season (5c), FWI, vegetative season (5d).

Significance of the expected variations are tested by applying a bootstrap technique (1000 bootstrap replications): black dots mark non-significant variations

To summarize the results for all models, we computed the probability of exceedance, in the period 2026-2045, of the 90th percentile computed for all models in the control period for the FWI and the FFMC indices.

The results, reported in table 3, confirm that both the FFMC (not shown) and the FWI projections present an increased probability of exceedance of the the 90th percentile over the period 2026-2045. These increases lie in the same range as the differences shown in the control period (table 2) for the most of models, but all values are statistically significant.

Table 3 Probability of exceedance of the FWI 90th percentile extracted from the CMIP5 model's daily data – period 1981-2000, in the CMIP5 RCP45 scenario daily data – period 2026-2045. For each model and for each grid point the 90th percentile value is searched in the corresponding grid point scenario distribution: the probability of exceedance is obtained by averaging the grid point values within the domain.

FWI RCP45 2026-2045	BCC-CSM1-1M	CNRM- CM5	EC-EARTH	IPSL-CM5A-MR	ALL
non veg seas	11.4 %	12.3 %	13.6 %	13.7 %	12.7 %
veg seas	11.5 %	12.3 %	14.0 %	16.6 %	13.6 %

It is important to note that only projected temperatures show significant differences in the 2026-2045 period with respect to the 1981-2000 runs (not shown). During the vegetative season, the increase in the highest percentiles of the temperature distribution is more pronounced, is uniformly distributed across the whole spatial domain, it is statistically significant (bootstrap technique, N=1000 replications) and it is revealed by all models analysed. This temperature variation can be considered the cause for the FFMC and FWI changes in the 2026-2045 period.

Overall, we find that future projections of fire risk obtained by the selected CMIP5 models show stable and reliable simulations: the changes are found to be uniform and coherent across the different models and occur in the same geographical areas.

6. SUMMARY AND CONCLUSIONS

This work focused on the verification of a subset of the ensemble of global CMIP5 climate models from the point of view of the evaluation of fire risk over the Alpine regions. The bias-corrected CMIP5 simulations reveal a good skill in reproducing recent climate for forest fire danger assessment purposes. The range of values indicating conditions suitable for moderate and high forest fire danger are well reproduced by the majority of the models, allowing to use them for future projections. On the other hand, large variability between the models still persists, together with a precipitation overestimation during the non vegetative season and a cold bias over the Alpine chain. For future projections, the RCP 4.5 scenario simulations provide rather uniform results for all the models considered, indicating a general increase of fire risk and fire potential across the Greater Alpine Region in the period 2026-2045 with respect to current conditions.

The mean future weather conditions are projected to be slightly more suitable both for forest fire ignition and spreading over the vegetative season. In addition, suitable conditions for the occurrence of extreme fire events, characterized by intense spreading, display a strong and significant increase over both seasons: the probability of exceedance of the current FFMC and FWI 90th percentiles nearly doubles across wide portions of the domain, even if not all the models are in agreement about the sign of projected changes over the regions at the highest latitudes.

The fire risk increase could be even more severe, taking into account non-climate-related factors such as the poorly implemented devolution of forest management (Lung et al. 2013), with severe impacts both on ecosystems and ecosystem services availability, air quality worsening associated with fire emissions and widening of the areas most prone to erosion, due to increased surface runoff.

As confirmed by many works on climate change impact and long-term prevention strategies (see for example Millar et al. 2007), the level of knowledge achieved in current climate research allows us to assess that future environments are projected to be more suitable for forest fires. The new generation of regional climate models, starting from the current global simulations here analysed, will be essential to make more accurate projections, identifying both the size of changes and the geographical regions most prone to such variations, thus providing details about the different effects related to climate change on forested ecosystems. These projections will allow to plan medium and long-term preventive actions to limit the diffusion of forest fires and to adapt fire fighting and forest management to the changing climate of the Alpine regions.

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