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Projections of fire danger under climate change over France: where do the greatest uncertainties lie?

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Abstract

Global warming is expected to increase droughts and heatwaves, and consequently fire danger in southern Europe in the forthcoming decades. However, an assessment of the uncertainties associated with this general trend at regional scales, relevant to decision-making, is still missing. This study aims at assessing potential climate change impacts on fire danger over France through the projection of the widely used Fire Weather Index (FWI) and at quantifying the different sources of climate-driven uncertainty associated with these projections. We used daily climate experiments covering the 1995–2098 period under two scenarios (RCP4.5 and RCP8.5) provided by the EURO-CORDEX initiative. Our results show an overall increase in FWI throughout the century, with the largest absolute increases in the Mediterranean area. Model uncertainty was very high in western France, previously identified as a potential fire-prone region under future climate. In contrast, large increases in FWI in the Mediterranean area showed low uncertainty across models. Besides, analyzing the natural variability of FWI revealed that extreme years under present-day climate could become much more frequent by the end of the century. The FWI is projected to emerge from the background of natural variability by mid-twenty-first century with a summer elevated fire danger three times more likely when summer temperature anomaly exceeds + 2 °C.

Keywords Fire Weather Index · Climate change · Projection · Emergence

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1 Introduction

Large wildfires are responsible for human, economic, and environmental losses in the Euro-Mediterranean area (San-Miguel-Ayanz et al. 2013). Accumulating evidence shows that the largest fires occurred under extremely hot and dry conditions (e.g., Turco et al. 2017; Ruffault et al. 2018). Drought has already increased in many regions of the world (Dai 2013), including the French Mediterranean region (Ruffault et al. 2013) and this trend is expected to continue in the future (Kovats et al. 2014). Projections show a substantial increase in fire activity in Europe for the next century (Turco et al. 2018), as already observed in the USA (Abatzoglou and Williams 2016) and parts of Canada (Gillett et al. 2004) during the last decades. A robust assessment of future trends in fire danger and their uncertainties at the regional scales is therefore required for policy making and long-term land management planning in the Euro-Mediterranean area.

To anticipate future climate change impact on fire risk in Europe, many studies have projected meteorological fire danger metrics derived from the Fire Weather Index (FWI) System from regional to continental scales (Dupuy et al. 2019). Amatulli et al. (2013) also projected burnt areas using the components of the FWI System as predictors. All these studies, as well as others using different fire weather or drought predictors (e.g., Turco et al. 2018), predict an increase in fire danger or burnt areas for forthcoming decades. The FWI System (designed by the Canadian Forest Service; Van Wagner 1987) provides an empirical representation of fuel moisture dynamics driven by daily to seasonal atmospheric processes, as well as weather and fuel moisture that are conducive to fire at daily scale. Specifically, the FWI consists of six components: three primary components modeling fuel moisture responses to weather over typically days, weeks, and months; two intermediate components representing the rate of spread and the fuel consumption; and the final FWI value, which aims to estimate expected fire intensity. The FWI System requires four climatic variables as inputs, including 24-h accumulated precipitation, wind speed, air temperature, and relative humidity, at 12:00 local standard time (LST). The FWI System was primarily designed and calibrated on a standard pine fuel type typical of burnable North American forests. However, it has been widely used as a general measure of forest fire danger across the world, including Mediterranean countries (Good et al. 2008; Viegas et al. 1999) and France (Dupire et al. 2017; Lahaye et al. 2018; Barbero et al. 2019), where it is computed daily by the French National Weather Service. Daily FWI values are often aggregated over longer periods (typically the summer season) to characterize the fire danger of that period using different FWI-based statistics.

Among the many sources of uncertainty in fire projections (see Williams and Abatzoglou 2016; Dupuy et al. 2019), the impact of climate-driven uncertainty has received only limited attention so far. Yet, climate-driven uncertainties are inherent to climatic processes (interannual variability), climate models, parameterization of model runs and scenarios of radiative forcing, or the combination of these multiple factors (Deser et al. 2012). Firstly, the scenario uncertainty refers to all external factors influencing the climate system, including greenhouse gases (GHG) emission trajectories or land use changes. Secondly, the model uncertainty arises from differences in the way that climatic processes are implemented in models, yielding different responses to the same external forcing. Finally, natural variability of the climate system occurs on interannual timescales without any changes to external forcing. Such a variability tends to obscure the human-induced climate change signal and to delay the emergence of a given metric from the background of current natural variability. To date, a complete assessment of uncertainties has been undertaken for meteorological variables (e.g., Hawkins and Sutton

2009, 2011) and for some climate change impact studies (e.g., Wada et al. 2013), but uncertainties have been overlooked in the projections of fire weather metrics.

The objective of the present study is to estimate future fire danger realized through the FWI over France and assess the climate-driven uncertainties associated with these projections. We selected different climate model simulations from the EURO-CORDEX experiment (Kotlarski et al. 2014), including two emission scenarios (RCP4.5 and 8.5) and three global climate models. We projected the seasonal mean and extreme daily FWI of these models throughout the twenty-first century. The three sources of uncertainties (model, scenario, natural variability) in fire danger projections are expected to change both in time and space. We seek to answer the following questions: where and when fire danger trends will emerge from the background of natural climate variability? Do climate models agree on the magnitude of future changes? To what extent the scenario involving moderate warming (i.e., RCP4.5) mitigate the fire danger with respect to the RCP8.5 scenario? What are the implications of the estimated trends and related uncertainties for policy and decision-making?

2 Material and methods

2.1 Rating fire danger over France with the Fire Weather Index

France includes different macroclimatic regions, typical of western, central, and southern Europe (e.g., temperate and Mediterranean). Climatic aridity increases moving southwards with a drastic change in fire activity. Aridity reaches a maximum in south-eastern France near the Mediterranean Sea where summer drought and wind gusts (including the Mistral and Tramontane) can facilitate wildfire spread (Ruffault et al. 2017).

In the present study, we used statistics derived from daily FWI to rate fire danger in France. Following Bedia et al. (2014), we computed three metrics for each year and each grid cell between 1995 and 2098, for a generic fire season (June to September, 122 days) including (i) the mean fire season FWI (FWIfs) characterizing the overall danger during a typical fire season, (ii) the seasonal 90th percentile of FWI (FWI90), a fire danger level corresponding to the upper range of fire danger during the fire season, as most large fires usually occur during such periods of high fire weather danger (only 12 days on average exceed FWI90 during the 122-day fire season), and (iii) the frequency-over-threshold 30 (FOT30) expressed as the number of days with FWI higher than 30 during a fire season. This fixed threshold measures the occurrence of very high to extreme fire danger conditions, regardless of the historical range of local FWI. Similar thresholds are used in France to identify high to extreme fire conditions for operational purposes (prevention, fighting).

FWI was calculated using the "cffdrs" R package (Wang et al. 2017). The 12:00 LST meteorological variables required in FWI computation were estimated from daily data (accumulated precipitation, daily mean wind speed, and daily mean temperature with minimum relative humidity, calculated using specific humidity and maximum temperature) following Bedia et al. (2014).

2.2 Model selection

We used daily climate data produced in the frame of the EURO-CORDEX initiative (Kotlarski et al. 2014). Three simulations, based on the GCMs CNRM-CERFACS-CNRM-CM5, MOHC-HadGEM2-ES, and MPI-M-MPI-ESM-LR, were selected to maximize model spread for relevant variables, while keeping computational time within acceptable limits. We focused on two scenarios: RCP4.5 and RCP8.5, developed for the last IPCC Assessment Report and representative of the most-likely radiative forcing trajectories. CORDEX simulations result from a dynamical downscaling by the coupling of General Circulation Models (GCMs) with Regional Climate Models (RCMs). We selected RCMs at 50-km resolution that we then downscaled and bias-corrected at 8-km resolution (see next section). The selection of GCM-RCM couples used for this study was based on (i) FWI-relevant data availability in the archiving system of CORDEX simulations (European System Grid Federation, ESGF), (ii) antecedent model validation for the area of interest, and (iii) maximization of the expected differences between models. Data availability was first evaluated for each model according to the following criteria, leading to a pre-selection of 10 models (i) availability of the 3 daily runs (historical, RCP4.5, RCP8.5), (ii) availability of the variables required for FWI computation, and (iii) European domain at a 50-km grid resolution (EUR-44).

As the major source of variability in regional climate simulations is inherited from GCMs (Glotter et al. 2014), we selected three GCMs among the 10 pre-selected models, which have been evaluated over western Europe and exhibit significant differences in predictions of summer temperature and precipitation (McSweeney et al. 2015). We focused on these two variables because they are two important factors of the FWI and are expected to change under future climate. Regarding the choice of the RCM (among those available in ESGF), we used the widespread RCA4, as well as REMO2009 for which two runs corresponding to different initial conditions were available. The five selected runs, as well as a description of their projected climatic changes, are summarized in Table 1.

2.3 Post-processing climatic simulations: statistical downscaling and bias corrections

A preliminary analysis of raw climatic simulations revealed biases in the five meteorological variables of interest over the past period (1995–2015) when compared to a French reanalysis dataset, used as a reference (SAFRAN, Vidal et al. 2010). When computed from these raw data, FWI was also strongly biased, especially during summer months (Online Resource, Figures S1 and S2, with overestimation as high as 140% during the summer months). Projection studies mostly aim at computing anomalies between current and future periods and differences between scenarios. In this context, such an overestimation is problematic since the response of FWI to input variables is non-linear. Hence,

Table 1 Selection of GCM-RCM couples and corresponding projected climatic changes in summer precipitation and temperature for Europe according to McSweeney et al. (2015)

GCM	RCM	Projected climatic changes for Europe
CNRM-CERFACS-CNRM-CM5	RCA4	Moderate summer temperature increase, slight summer precipitation increase
MOHC-HadGEM2-ES	RCA4	High summer temperature increase, high summer precipitation decrease
MPI-M-MPI-ESM-LR	RCA4	High summer temperature increase, medium summer precipitation decrease
MPI-M-MPI-ESM-LR	REMO2009 (run 1)	Moderate summer temperature increase, medium summer precipitation decrease
MPI-M-MPI-ESM-LR	REMO2009 (run2)	Moderate summer temperature increase, medium summer precipitation decrease

projections based on biased data might critically misestimate anomalies and scenario impact.

Consequently, we performed a statistical downscaling and bias corrections, using the reanalysis as reference observational data (8-km resolution). Bias corrections were performed using standard methods based on monthly mean bias or monthly quantile mapping (Bedia et al. 2014; Ruffault et al. 2014), which strongly reduced the bias in model outputs (Online Resource, Figure S2). Temperature, which essentially showed deviations of its mean, was corrected using a mean bias, whereas precipitation, wind speed, and relative humidity were corrected using quantile mapping, as several aspects of the distribution were biased. More details regarding bias corrections are presented in Online Resource "Bias correction methods." Bias corrections and downscaling were performed with R (R Core Team 2017) using the *meteoland* package (De Cáceres et al. 2018). Potential consequences of bias corrections on fire danger projections are discussed in Section 4.3.

2.4 Analyses of projections and their uncertainties

We first analyzed long-term trends (1995–2098) of FWI metrics averaged over France in order to quantify overall anomalies (differences between historical and future fire danger) under both scenarios. Then, we examined spatial patterns, by averaging FWI metrics for each grid cell over the historical (1995 to 2015) and future (2078 to 2098) periods.

Three sources of uncertainty were quantified for each metric using a method adapted from Hawkins and Sutton (2009). First, the interannual variability is related to the natural variability of a given metric (in our case the FWI-based metrics) in the absence of climate change. It provides a relevant reference for assessing the significance of fire danger trends arising from climate change (anomalies) or differences between scenarios. We computed the interannual variability as the mean of the standard deviations of interannual FWI fluctuations of each model run (i.e., multi-model, multi-scenario interannual variability). For each simulated metric and each model run, climatic fluctuations were computed as residuals from the trend, which was calculated as a 30-year moving average (30-year long periods being considered as climatologically stationary) of the 1995–2098 climate series. Trends and variability are illustrated for MPI-ESM-REMO2009-run1 in Online Resource, Figure S3. Assuming a normal distribution of fluctuations, their standard deviation quantifies the radius of the confidence interval in which 68% of annual fire danger predictions would fall (one standard deviation confidence interval). The upper bound of this confidence interval corresponds to the 84th percentile of the annual fire danger distribution during the historical period (1995 to 2015). The emergence of a given metric is achieved when a model crosses this upper bound (and lies above until the end of the century). For the purpose of the present study, seasonal fire danger above this bound is referred to as "elevated." Still assuming a normal distribution of annual fire danger, quantiles of fire danger can be converted in return intervals, the "elevated" fire danger corresponding to 6.25 years return interval. As opposed to Hawkins and Sutton (2009), this source of variability was estimated on an annual basis—rather than a decadal basis—to better account for most extreme years, which are critical in the context of wildfires, and to ease interpretation in terms of emergence.

The second source of uncertainty was model uncertainty, which was calculated for each scenario, as the standard deviation of model trends (i.e., 30-year moving averages) across model runs. According to the model selection, which aimed at maximizing model spread, this quantity expresses the range in which predictions from a larger set of models should fall (i.e., model spread). This uncertainty incorporates model uncertainties arising from differences between models, model parameterization schemes, and initial conditions. Model uncertainty is illustrated for FWIfs in Online Resource, Figure S4.

The last source of uncertainty was the scenario uncertainty, which expresses the magnitude of change in fire danger, resulting from uncertainties regarding future political decisions (illustrated for MPI-ESM-REMO2009-run1 in Online Resource, Figure S3). It was computed as the standard deviation of the multi-model means, computed for the different scenarios (here RCP4.5 and RCP8.5). The sum of the squares of the three uncertainties corresponds to the overall variance in annual predictions.

3 Results

3.1 Projected trends in fire danger and their relative uncertainties

All fire danger metrics (i.e., FWIfs, FWI90, and FOT30) increased over the twenty-first century in France, albeit with high uncertainty in the magnitude of future changes (Fig. 1). Remarkable differences resulted from the emission pathway, RCP8.5 being characterized by a much steeper increase than RCP4.5 after 2050. By the end of the century, relative changes in fire danger metrics reached + 24%, + 19%, and + 93% for FWIfs, FWI90, and FOT30 respectively for RCP4.5, and + 67%, + 50%, and + 295% for RCP8.5.

Model uncertainty (represented by the standard deviation of model runs in Fig. 1) increased over time during the twenty-first century, especially for FOT30, and exceeded the difference between RCP4.5 and RCP8.5.

The RCP4.5 multi-model trend remained within the standard deviation of interannual variability observed between 1995 and 2015 (Fig. 1, black dashed lines) due to high interannual variability. By contrast, the RCP8.5 multi-model trend rose above "elevated" current fire

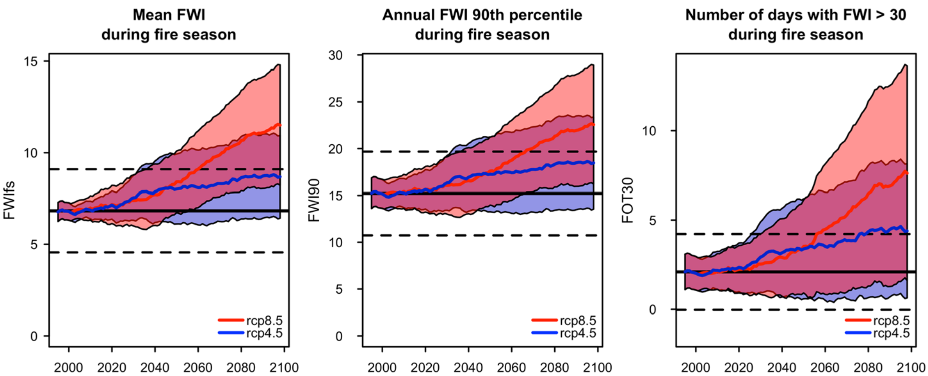

Fig. 1 Trends in fire danger over France between 1995 and 2098, according to three different metrics computed with daily FWI during the fire season (June to September): mean FWI (FWIfs, left panel), 90th percentile of FWI (FWI90, middle panel), and number of days above a FWI of 30 (FOT30, right panel). The multi-model trend (average for a given scenario) is represented in colored solid lines, surrounded by the model uncertainty (shaded areas), expressed as standard deviation between model trends. Horizontal black solid line indicates current mean of each metric during the historical period (1995–2015). The historical interannual variability is represented by dotted lines and can be interpreted as the interval in which 68% of the historical fire danger years fall. The lower and upper bounds correspond to the 16th and 84th percentile of fire danger years, respectively (return interval of 6.25 years), the upper bound being referred to as the "elevated" level

danger levels (upper black dashed lines) by 2060 and emerged from the background of historical variability gauged from 1995 to 2015. The "elevated" level corresponds to the 84th percentile of the historical fire danger, currently experienced only once every 6.25 years. Beyond 2060, the fire danger is expected to match or exceed the "elevated" current fire danger every 2 years, i.e., approximately a 3-fold increase. This date of emergence corresponds to a 2 °C summer warming across France (fire season, June to September) in comparison to the reference period. Dates of emergence and corresponding warming levels for all fire danger metrics are given in Online Resource, Table S2.

By the end of the century under RCP4.5, the fire danger was projected to reach every 2 years the levels occurring only every 4 years for FWIfs and FWI 90, and every 6 years for FOT30, under the present climate. In other words, seasons with "elevated" fire danger will be two times more likely, when measured by FWIfs and FWI90, or three times more likely when measured as FOT30. By the end of the century under RCP8.5, every 2-year levels for respectively FWIfs, FWI90, and FOT30 correspond to fire danger return intervals of respectively 58, 25, and 2765 years under current climate, which means that future fire danger was projected to reach levels that have likely never been observed in France in the past (especially for FOT30).

Figure 2 shows the total variance of each metric as well as the respective contribution of three uncertainty sources. Total variance exhibited for all three metrics a similar increase over time, due to an increase in model uncertainty and scenario uncertainty (after 2060). The variance was clearly dominated by interannual variability in early decades. The total variance then increased slowly until the 2050s due to a progressive increase of model uncertainty. This trend is exacerbated in the second half of the century, as model uncertainty continued to grow and scenario uncertainty appeared. This trend was particularly evident for FOT30, leading to a 5-fold increase in total variance by 2100 compared to the present period (in accordance with Fig. 1).

3.2 Spatial patterns of historical and future fire danger

Figure 3 shows the spatial distribution of mean FWIfs values for the historical (1995–2015) and future (2078–2098) periods under both scenarios, as well as the difference between RCP8.5 and RCP4.5. For conciseness, we focus on FWIfs as results for the other metrics are similar (see Online Resource, Figures S5 to S9). The French territory exhibited strong

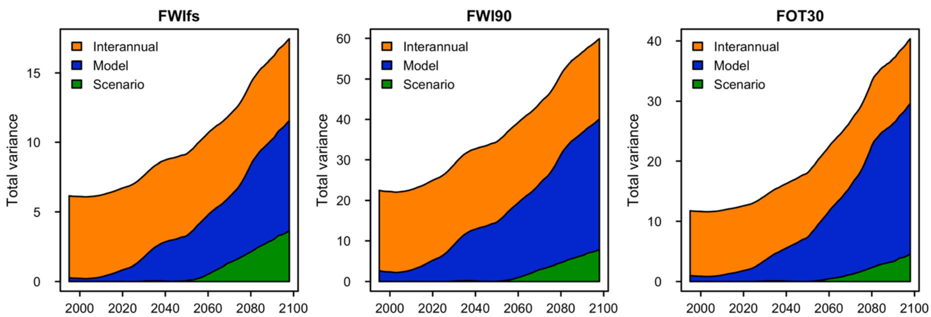

Fig. 2 Temporal evolution of the total variances of three fire danger metrics (i.e., sum of the squares of all uncertainties) and partitions among three sources of uncertainties (interannual, model, scenario): mean FWI (FWIfs left panel), 90th percentile of FWI (FWI90, middle panel), and number of days above a FWI of 30 (FOT30, right panel)

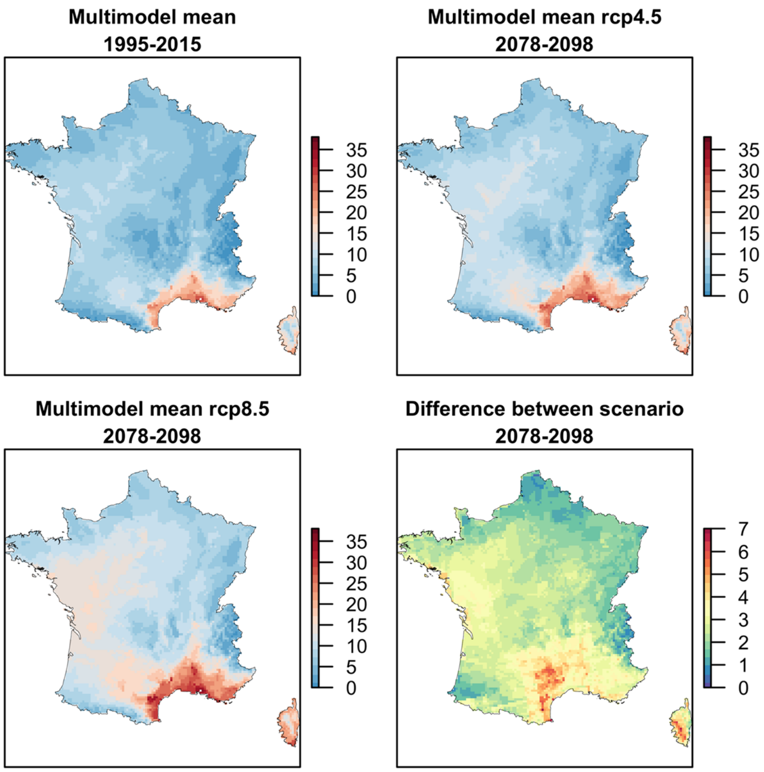

Fig. 3 Evolution of the spatial distribution of the mean FWI during the fire season between historical and future periods under the two scenarios alongside the difference between RCP8.5 and RCP4.5

spatial variations in fire danger, the Mediterranean area being characterized by much higher fire danger than the rest of the territory. Differences between scenarios are visible in most southern and western France where fire danger is or will become significant, the highest differences being observed in the former Languedoc-Roussillon region and the Corsica region. Future anomalies (Online Resource, Figures S6 to S8) for both scenarios indicated a widespread increase in fire danger, despite important regional differences in magnitude. For example, the increase was more pronounced in the Mediterranean area and western France.

Figure 4 shows the differences between future increases (anomaly) under both RCP4.5 and RCP8.5 and each source of uncertainty (model uncertainty and interannual variability) at horizon 2078–2098. When this difference is positive (red colors), the change exceeds the uncertainty. When this difference is negative (blue colors), the uncertainty dominates. When comparing the anomaly to model uncertainty (Fig. 4, left panels), a latitudinal gradient was evident for both scenarios. In northern France, negative values indicate that model uncertainty prevailed over anomalies, because of large model uncertainties (Online Resource, Figures S6 to S8). Conversely, southern France was characterized by low model uncertainty and high anomaly, especially in the Mediterranean area. This is especially true in the RCP8.5 scenario. When comparing the anomaly to the interannual variability for RCP4.5, most of France, including the Mediterranean area, exhibited negative values. Conversely, future increases under RCP8.5 exceeded interannual variability, meaning that climate change-induced signal is projected to exceed that of interannual variations.

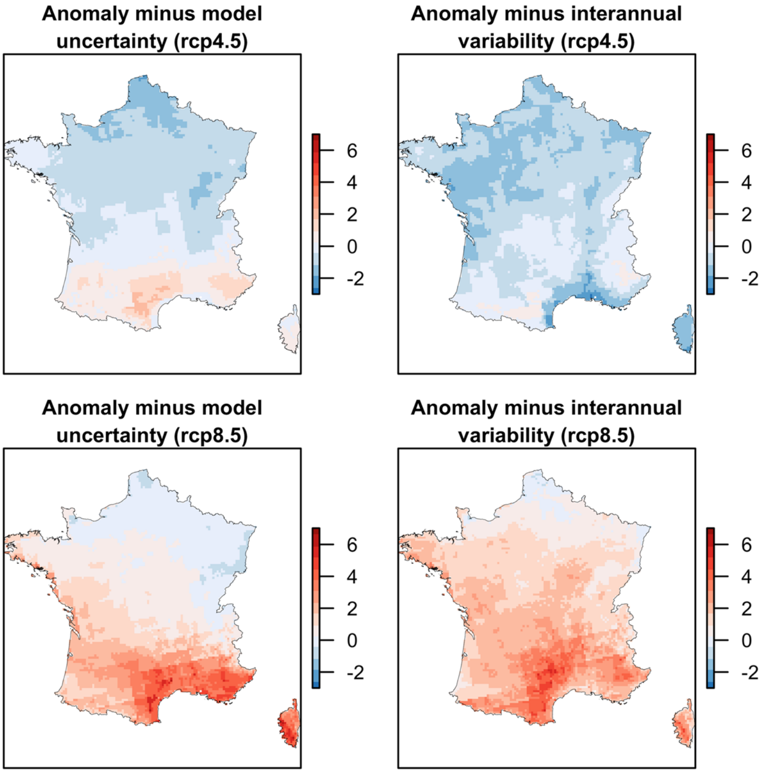

Fig. 4 Difference between anomalies of mean seasonal FWI (FWIfs) and future model uncertainty (2078–2098, left) and the current interannual variability (observed during historical period, 1995–2015, right) for both scenarios. The anomaly is calculated for each grid cell as the difference between future and historical fire danger

The spatial pattern of the scenario uncertainty can also be compared to model uncertainty and interannual variability, to appraise the magnitude of differences between scenarios. This is shown in Fig. 5 for FWIfs and in the Online Resources (Figure S9) for the two other metrics. The highest model uncertainty was mostly visible across north-western France and largely dominated scenario uncertainty in absolute value, indicating that differences between scenarios are of minor importance in this area. Interannual variability shared with the scenario uncertainty a common spatial pattern, similar to the historical pattern of fire danger (i.e., with highest fire danger in the Mediterranean area). The absolute value of interannual variability remained generally higher than the scenario uncertainty, suggesting that differences between scenarios were smaller than future interannual variations.

3.3 Mechanistic insights on trends and uncertainties

To gain more insights into the climatic drivers of FWI trends and associated uncertainties, future changes of the different variables involved in FWI are reported in Online Resource for each model and scenario (Figures S10 and S11). A high increase in temperature concurrent with deficit in relative humidity and/or precipitation was projected by most models at the end of the summer (August and September), especially for RCP8.5, contributing to increased aridity and fire weather conditions. The evolutions of variance partitions reveal two contrasted

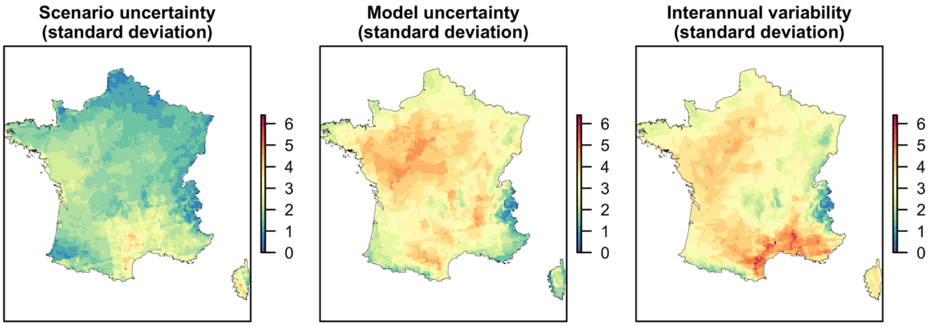

Fig. 5 Range of the different sources of uncertainties for mean FWI during the fire season (FWIfs). Maps display the mean standard deviation of each pixel on the future period (2078–2098)

patterns for summer temperature and precipitation (Fig. 6, similar to Fig. 2): scenario uncertainty overwhelmed the other sources for temperatures for the second half of the twenty-first century, whereas interannual variability remained the major contributor to the variance for summer precipitations. The mean seasonal FWI pattern showed a transition between the characteristics shown for summer temperature and precipitation (Fig. 2).

4 Discussion

4.1 Natural climate variability and emergence

The comparison between FWI projections and its current interannual variability shed light on the impact of anthropogenic climate change on future fire danger and on the differences between scenarios. Our result showed that under the RCP8.5 emission scenario, it is only from 2060s that fire danger projections emerge from the historical background of interannual variability (Fig. 1) in almost all of France (Fig. 4). This implies that a majority of years with "elevated" fire danger level are projected for the post 2060 period. By contrast, under the

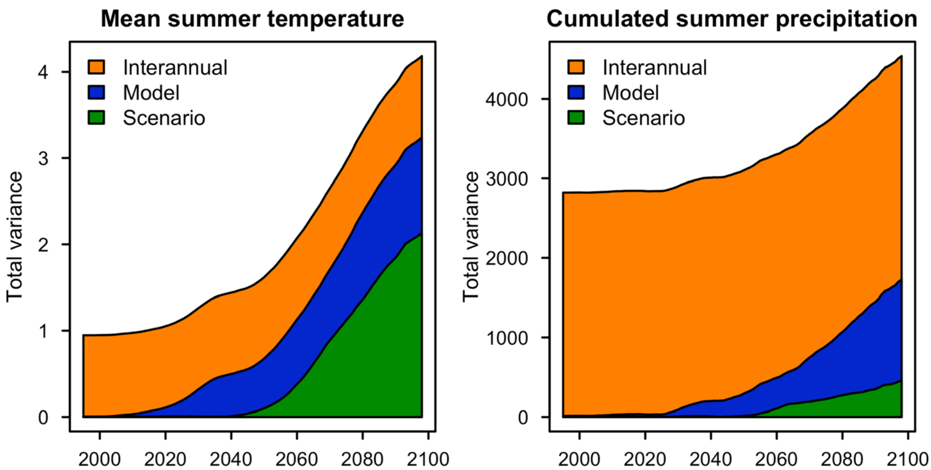

Fig. 6 Contributions of different uncertainty sources to total variance for mean temperature (left) and accumulated precipitation (right) during the fire season between 1995 and 2098

RCP4.5 emission scenario, fire danger projections do not exceed the historical interannual variability by the end of the twenty-first century.

Additional analyses revealed that interannual variability calculated on models runs for the historical period (1995–2015) is often larger than interannual variability calculated from SAFRAN reanalysis data, even after bias corrections of model outputs (with the exception of the second run of MPI-ESM-REMO2009, Online Resource, Figure S12). This overestimation is thought to delay the emergence of the climate change-induced signal in FWI.

Likewise, the choice of the reference period is an important factor contributing to the date of emergence. The increase in FWI signal was estimated relatively to 1995–2015 level. This period, however, exhibits GHG above natural pre-industrials levels. Using another reference period spanning earlier decades would probably lead to an earlier emergence of the FWI. This may explain the later emergence found here with respect to prior FWI detection studies (Abatzoglou et al. 2019).

4.2 Climate model and scenario uncertainties

We found that the main source of uncertainty in fire danger projections came from climate models, with an increasing contribution of models spread on the total climate-induced uncertainty over time (Fig. 2). Model uncertainty is directly related to the variability between models of the four climatic factors used as input in FWI (Online Resource, Figures S10 and S11). An important model uncertainty was expected for temperature and precipitation because climate models were selected to maximize the spread between them regarding these variables. However, we also observed significant spread in the projections of wind speed and relative humidity, which can both substantially affect FWI values through their impact on the ISI and FFMC subcomponents (Dowdy et al. 2010). This advocates for an increased effort to evaluate the projections of relative humidity, as done for wind regime (Najac et al. 2009; Obermann-Hellhund et al. 2018).

Contrary to other uncertainty sources, model uncertainty in fire danger projections exhibits the highest values in regions where fire danger is currently moderate, namely in the north-western part of the French territory (Fig. 5). A similar pattern can also be observed in Bedia et al. (2014), although it was not explicitly pointed out in their study. This result is of major importance when assessing the potential northward expansion of fire-prone climate conditions in the context of climate change. An earlier French study pointed out a potential extension of the fire danger to north-western France, based on the projection of a single climate model (Chatry et al. 2010). Our study confirms this result but also demonstrates that the magnitude of the increase in fire danger remains largely uncertain in this region.

Some FWI metrics were more prone to model uncertainties than others. Specifically, FOT30 (the number of days above a FWI of 30) showed higher model uncertainty at the end of the studied period compared to the two other FWI metrics (Fig. 2), in agreement with the results of Bedia et al. (2014). One explanation for this pattern is that threshold-based metrics of fire danger are more sensitive to the variability in climate inputs and can therefore exacerbate the spread observed between climate models. This advocates for a cautious use of threshold-based metrics in climate projections, which are often used as indicators of critical conditions. We rather recommend the use of FWI metrics based on fire danger levels, such as the annual 90th percentile of daily FWI.

At national level, the impact of scenario uncertainty on the variability in fire danger projections was on average less important than the two other sources of uncertainty (Fig. 2).

Before 2050s, the two scenarios led to a similar increase in all three FWI metrics. After 2050s, however, scenario uncertainty gained importance. The Mediterranean area singles out with a relatively high impact of the scenario associated with a moderate model uncertainty (Fig. 5). This underlines how critical it would be for this region to follow RCP4.5 emission pathway rather than RCP8.5.

4.3 Limitations of the study

In the present study, correcting model outputs bias was justified by the very large departure between FWI computed with SAFRAN and model simulations. This is the case in many studies aiming at quantifying climate change impacts (De Cáceres et al. 2018), in particular fire danger projections (Yang et al. 2015). However, it must be acknowledged that bias correction alters the physical consistency of modeled climate. Quantile mapping makes strong assumptions regarding bias stationarity and can break the co-variation between climatic variables (Cannon et al. 2015; Grillakis et al. 2017). Recent promising techniques accounting for the correlation between variables (e.g., Cannon 2018; Vrac 2018) may be implemented to improve future impact studies on fire danger and fire activity.

Some of the conclusions of our study might be affected by the choice of the fire danger metrics. In this study, three FWI-based metrics were used to evaluate fire danger while being aware that the use of other fire weather indices (e.g., Energy Release Component, McArthur Forest Fire Danger Index) with different sensitivities to meteorological inputs would likely lead to different results, advancing or delaying the emergence of fire danger. Besides, the FWI metrics used in the present study assume a constant fire season length of 4 months across the whole French territory while fire season is likely to expand in the future (Moriondo et al. 2006; Bedia et al. 2014). Likewise, we used spatially and temporally aggregated FWI metrics. However, it should be noted that fire activity might not be linearly related to the FWI, as this was early recognized in the development of the FWI System (see Flannigan et al. 2013) and suggested recently in the development of a fire activity model for southern France (Fargeon et al. 2018).

Finally, apart from climate-driven uncertainties, future fire activity can also be affected by a number of uncertainties related to biophysical and human factors that were not considered in this study (Dupuy et al. 2019). For instance, fire suppression policies or fuel characteristics can both significantly alter the dynamics in fire activity in the Euro-Mediterranean area (Fréjaville and Curt 2017). Comparing how these different sources of uncertainties might impact fire danger projections is a next step towards a better assessment of future fire risk.

4.4 Implications for policy development and decision-making

Fire can be a major threat for humans and ecosystems in Europe and in the Mediterranean. Providing robust estimations of future fire danger levels is therefore a crucial step to set up management options and mitigation solutions. Our results provide further evidence that, regardless of the emission scenario or fire danger metric, fire danger is expected to increase by the end of the century over France, in accordance with previous studies based on FWI projections (Moriondo et al. 2006; Chatry et al. 2010; Bedia et al. 2014) or fire-climate relationships (Amatulli et al. 2013; Turco et al. 2018). However, we demonstrate that a major source of uncertainty in fire danger projection is related to various sources of climate-driven uncertainties. We argue that future projections in fire danger must be analyzed and discussed in light of these uncertainties.

The predominance of natural climate variability on fire danger projections during the coming decades tends to hide the underlying trend in fire weather. A practical consequence of this result is that it might hamper immediate societal choices that would be beneficial for mitigating future fire risk. Model spread appeared as a major source of uncertainty, especially in the north-west of France, which is a potential future fire-prone area. An accurate estimation of anomalies in such areas, which involves a reduction of climate model uncertainties, appears as extremely challenging, but critical to long-term strategies aiming to reduce fire risk. The Mediterranean area singles out with moderate model uncertainty but strong expected increases in fire danger and significant scenario influence, demonstrating the importance of implementing mitigation and adaptation climate policies to avoid a dangerous pathway in this area. Our results clearly advocate for the implementation of climate change mitigation policies to limit the increase in fire danger already observed over the historical period and for preparing adaptation strategies to elevated fire danger in new fire-prone areas. We also encourage French fire prevention policies to give high priority to the already fire-prone Mediterranean area, where most models agree on a much stronger fire danger.

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Author contribution JLD, HF, NM, and FP designed the study. HF conducted the analyses, produced figures, and wrote the first draft of the manuscript. NM and MDC helped on data processing. FP designed the uncertainty analysis. JR and RB contributed to discussing the results and participated in the writing of the text. All authors reviewed the paper.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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