Towards an atmosphere more favourable to firestorm development in Europe

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Abstract

Deep pyroconvection associated with the development of firestorms, can significantly alter wildfire spread, causing severe socioeconomic and environmental impacts, and even posing a threat to human's lives. However, the limited number of observations hinders our understanding of this type of events. Here, we identify the environmental conditions that favour firestorm development using a coupled fire–atmosphere numerical model. From climate model projections for the 21st century, we show that the number of days with deep pyroconvection risk will increase significantly in southern Europe, especially in the western Mediterranean region, where it will go from between 10 and 20 days per year at present to between 30 and 50 days per year by the end of the century. Our results also suggest fuel reduction as an effective landscape management strategy to mitigate firestorm risks in the future.

1. Introduction

Fire interacts with the environment at different temporal and spatial scales. On a large scale, climate largely determines global fire activity and, in turn, fire modifies the climate system through carbon dioxide and soot emissions and changes in vegetation [1, 2]. At the local and event scale, weather is one the main factors in wildfire spread (along with orography and fuel structure), but fires can also substantially modify atmospheric conditions through sensible and latent heat fluxes, creating their own weather [3].

The main mechanism by which a fire modifies atmospheric conditions is pyroconvection. The air above the fire warms due to the sensible heat emissions, rises and expands, forming a fire plume. As the air ascends, moisture can condense releasing latent heat, which enhances convection and results in the formation of pyrocumulus (pyroCu) or pyrocumulonimbus (pyroCb) clouds [4]. In cases of deeper convection, the fire may form a firestorm, leading to (a) intense updrafts and downdrafts that can modify surface winds and affect fire spread [5–7], (b) lightning activity that can spark new ignitions [8], (c) the formation of tornados [9, 10] and (d) stratospheric smoke injections [9, 11, 12] that may even alter the atmospheric chemistry [13] and have synoptic weather impacts [14, 15]. The feedbacks between firestorm and surface atmospheric conditions may lead to an unpredictable and hazardous fire behaviour.

The study of pyroconvection has been gaining attention during the last decades, especially in North America and Australia, due to certain catastrophic firestorm events such as the Colorado Hayman Fire in 2002 [5] or the Canberra fires in 2003 [9]. In Europe, the case that raised the alarm about the risks of deep pyroconvection was the destructive Pedrógão Grande fire in 2017 in Portugal [16]. Nevertheless, the environmental controls on deep pyroconvection are still not entirely clear and, in particular, there are uncertainties about the atmospheric conditions conducive to the development of this phenomenon. The limited number of firestorm records, as these events are conditioned by the existence of a fire burning large amounts of fuel, has hampered the study of deep pyroconvection.

Pyroconvective events are associated with large and intense fires [17] caused by interactions between the fire, the local terrain and critical fire weather [7]. Some studies have identified deep flaming (i.e. fires that exhibit sustained and intense flaming over a large
spatial area) as a necessary factor for the development of deep pyroconvection [18, 19].

In addition to high fire intensity, an environment characterised by atmospheric instability is required [17]. Several authors have related the presence of pyroconvective events to an inverted-V atmospheric profile [5, 20, 21], consisting of a dry and unstable lower layer overlaid by a relatively moist middle troposphere. However, upper- and mid-tropospheric conditions also seem to play an important role in the development of deep pyroconvection [12, 17].

Another issue that has been debated in recent years is the role that the moisture released by the fire may have on the convection process. Some authors claim that the fire-released moisture can constitute a large part of the water content in the fire plume [22], having a significant impact on the development of pyroconvection [10]. However, other studies point to fire-released sensible heat and midlevel moisture entrainment as much more relevant contributors [12, 21, 23, 24]. Lareau and Clements [25] measured the relative importance of these factors by comparing the ambient lifted condensation level with the height of the base of pyroCu clouds, finding that the moisture release during combustion is of secondary importance in the convective process.

The uncertainties in the understanding of the environmental controls on the development of deep pyroconvection explain why there is still no standard indicator for pyroconvection risk. The Haines index [26, 27], which identifies unstable and dry lower-tropospheric profiles, has been used in different pyroconvective studies, sometimes in combination with a near-surface fire weather index [4, 28]. However, some authors suggest that the Haines index has limited utility to identify the most extreme pyroconvective events [12, 18]. More conventional atmospheric instability indexes, like the convective available potential energy (CAPE), were also tested [22], although several pyroconvective events have been shown to be associated with little or no CAPE [5, 17].

The first objective of this study is to identify the atmospheric conditions that enable firestorm formation and to select a set of meteorological indices and thresholds that can detect days with a high risk of deep pyroconvection. For this we have conducted an experiment based on idealised numerical simulations of fires spreading under different atmospheric profiles. Once we determine the atmospheric conditions favourable for deep pyroconvection, we create a map of the risk of firestorm development in Europe for the period 1980–2018. We then assess the trend in the risk of firestorm development in Europe for the world. The six locations were selected in representation of the regions with the highest incidence of fires among the southern European countries, as shown in supplementary figure S3. The fire season in these areas is the summer, characterised by being dry and warm [39], and they are generally associated with temperate dry and hot summer (Csa) or temperate dry and warm summer (Csb) climates according to the Köppen–Geiger classification [40]. The locations

2. Methods

To analyse fire behaviour under different controlled fuel and atmospheric settings, we conduct idealized numerical simulations with the fire–atmosphere coupled model WRF-Fire [3], which combines the Advanced research Weather Research and Forecasting Model (WRF-ARW) [29] with a semi-empirical fire spread model [3]. This model has been previously tested in real wildfire case studies [30, 31], even with pyroconvective characteristics [10, 32].

The computational domain is 60 km wide in the x and y directions and the grid spacing is set to 100 m in the fire grid and 1 km in the atmospheric grid with open boundary conditions. The vertical dimension of the domain expands up to 16 km with 60 vertical levels. The microphysics scheme used is the New Thompson et al [33], the radiation scheme is the RRTMG (Rapid Radiative Transfer Model for General Climate Models) [34], the surface layer scheme used is the revised MM5 surface layer scheme [35] and the planetary boundary layer parameterisation scheme is the Mellor–Yamada Nakamishi and Niino Level 2.5 [36]. Convection and cloud formation are explicitly resolved at this resolution without the need for a cumulus parameterisation scheme. Simulations are initialized with a single 400 m radius fire at the centre of the domain, in flat terrain, and atmospheric conditions form a single vertical profile.

To ensure that our model configuration is able to correctly simulate pyroconvection, we have performed a validation using real cases in Europe. We searched for satellite images of cumulus clouds possibly formed by the convection associated with a fire (see supplementary figure S1) and tested the performance of our model setup in simulating these cases. As shown in supplementary figure S2, the model is able to simulate a cloud in all cases except for one (see supplementary figure S2 and table S1).

The idealised runs are initialized with selected real-case atmospheric profiles of wind, temperature and moisture, corresponding to the 100 d of highest fire risk per year during the 2010–2019 period registered at each of the six locations indicated in supplementary figure S3. The atmospheric vertical data for running the model is obtained from the ERA5 database, that is the fifth generation ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis for the global climate [37, 38], which combines model data with observations from across the world. The six locations were selected in representation of the regions with the highest incidence of fires among the southern European countries, as shown in supplementary figure S3. The fire season in these areas is the summer, characterised by being dry and warm [39], and they are generally associated with temperate dry and hot summer (Csa) or temperate dry and warm summer (Csb) climates according to the Köppen–Geiger classification [40]. The locations
in Spain and Turkey are dry enough to be classified as semiarid climate (see supplementary table S2). The altitudes of the selected points vary between 163 and 1096 meters above sea level (see supplementary table S2), which modulates the severity of summer temperatures. The Mediterranean region owes its dry summer to the poleward displacement of the subtropical high during that time of the year. The particularities of the orography and the position to the west or east of the basin condition the different wind regimes at the different sites. However, the lack of precipitation and cloudiness is common to all of them in this season.

For each of the atmospheric profiles (a total of 6000), we perform a suite of paired experiments of an ideal fire spreading through different fuel categories, five in total, from lower to higher fuel load. These fuel characteristics are the same for the different fuel load experiments associated with each selected profile, they do not depend on the site of the profile. A moisture content of 8% is also set to constant in all cases. This moisture content is representative of the high fire activity conditions in the Mediterranean region, where just 12% of the cumulative burned area is associated with fuel moisture contents higher than 10% for late summer and 11% for early summer fires [41]. Each pair of fuel load experiments consists of a control run with interaction between fire and atmosphere and a simulation in which the sensible and latent heat fluxes from the fire are turned off (uncoupled simulation). We assess the role of fire–atmosphere feedbacks by comparing the two experiments.

We first examine how the produced vertical drafts interact with fire characteristics. In particular, we analyse downdraft intensity, now just as an indicator of the existence of pyroconvection, but also of the presence of a strong coupling between the atmosphere and the fire, as it is well known that strong downdrafts behind the head of the fire line can intensify fire spread [42]. According to the results of our simulations, we show in figure 1(a) that the strongest downdraft speeds, higher than around 8 ms$^{-1}$, are associated with the presence of clouds formed by pyroconvection. The intensity of these downdrafts is well correlated with the intensification of surface winds (figure 1(b)), and these stronger winds can multiply the area affected by the fire (figure 1(c)). Strong vertical drafts are also related to the maximum height reached by fire smoke, indicating that when the vertical wind speeds are powerful enough, fire smoke can be easily injected into the stratosphere (figure 1(d)). Similar relations between the fire properties in figure 1 and updraft maximum speeds are found (supplementary figure S4), given that strong downdrafts are always associated with strong updrafts.

Figure 2(a) shows that strong vertical drafts appear only for high fuel loads, above 6 kg m$^{-2}$

![Figure 1](image-url)
Figure 2. Conditions for firestorm development. (a) Three-dimensional representation of lower troposphere (1000 m) downdraft maximum speed, K-index values and fuel load, with each colour representing a different fuel category. (b) Relation between downdraft intensity and K-index, represented by a boxplot for each downdraft intensity interval.

3. Results and discussion

3.1. Present firestorm risk in Europe

We consider a day to have atmospheric risk of deep pyroconvection if it combines a high fire risk at the surface with high atmospheric instability, conditions that are met when certain FWI and K-index thresholds are surpassed simultaneously. We set the K-index threshold at 25 °C, a value that according to our simulations is exceeded by almost 75% of events with downdraft intensities greater than 8 m s⁻¹, but only by 25% of events with weaker downdrafts of less (sensible and latent heat fluxes are directly proportional to the fuel load [3]) and for unstable conditions, with the occurrence spiking when the K-index surpasses about 25 °C. This index is calculated from air temperatures and dew point temperatures, and it estimates the atmospheric static stability as a combination of 850–500 hPa thermal lapse rate, 850 hPa moisture and a measure of thickness of moist layer [43]:

\[ K = (T_{850} - T_{500}) - T_{d850} - (T_{700} - T_{d700}), \]

where \( T \) is the air temperature and \( T_d \) is the dew point temperature of the pressure level indicated by the subscript in hectopascals. High values of the K-index (>26 °C) are associated with environments where thunderstorms are likely to occur [44]. We tested other instability indices, but all show a lower correlation with downdraft intensity (supplementary figures S5 and S6). The reason why the K-index yields a higher correlation with downdraft intensity may be related to the fact that it does not only consider lower tropospheric conditions, but it includes 850 hPa and 700 hPa moisture measures. In addition, it is not based on lifting an unperturbed surface parcel in an environment that is being modified by a fire.

Favourable meteorological conditions for the spread of a fire are also necessary for the existence of deep pyroconvection [17]. These conditions, apart from enabling the ignition and spread of the fire, are also positively correlated with fuel dryness, which allows for more of the available fuel to be consumed, favouring the release of more sensible heat. In this study we quantify fire risk through the widely used Canadian Fire Weather Index [45] (FWI), developed by the Canadian Forestry Service. The FWI consists of six components: three subindexes representing fuel moisture, two subindexes representing rate of spread and fuel consumption, and a final index representing fire intensity as energy output rate per unit length of fire front.

For analysing future pyroconvective risk trends we used data from CORDEX RCM simulations for the (EURO-CORDEX), conducted at 0.11° resolution (EUR-11). From the different combinations of RCMs and General Climate Models (GCMs) available, we used those that provide the needed variables to calculate the FWI and K-index: COSMO-crCLIM-v1-1 and RCA4 RCMs and EC-EARTH, HadGEM2-ES, MPI-ESM-LR and NorESM1-M GCMs. We use the RCP8.5, RCP4.5 and RCP2.6 greenhouse gas concentration model outputs for the future projections. The Representative Concentration Pathway [46, 47] RCP8.5 assumes a scenario in which greenhouse gas emissions continue to increase throughout the 21st century, producing a radiative forcing of 8.5 Wm⁻² by 2100. The RCP 4.5 scenario stabilizes radiative forcing at 4.5 Wm⁻² in the year 2100 without ever exceeding that value [48]. The RCP2.6 scenario is representative of the literature on mitigation scenarios aiming to limit the increase of global mean temperature to 2 °C [49].
than 8 m s\(^{-1}\) (figure 2(b)). 8 m s\(^{-1}\) and above are the downdraft wind speed values that we found suggestive of pyroconvection in our simulations, as discussed earlier. To define a surface fire risk threshold, we use the 90th percentile of the FWI values for the period from 1990 to 2019 at each grid cell. As shown in supplementary figure S7, for most fire-prone areas in Europe fires occur on days with FWI around the 90th percentile. In regions where this 90th percentile corresponds to a very low fire weather index, we set a minimum threshold of 11.2, which is the value that determines a moderate fire risk according to the European Forest Fire Information System, integrated in the EU Copernicus Program. Supplementary figure S8 shows the FWI threshold used for each grid cell from ERA5 reanalysis data.

Figure 3(a) shows the present atmospheric firestorm risk in Europe, obtained by calculating from ERA5 reanalysis data the days per year with both a FWI and a K-index value above the selected thresholds. The Balkan Peninsula, Turkey, eastern Hungary, Italy and northeastern Spain are the regions that present a highest frequency in the occurrence of favourable atmospheric conditions for deep pyroconvection development, with up to 20 d per year of high atmospheric firestorm risk (figure 3(a)). Maps of the number of days per year with each of the indexes (FWI and K-index) above the selected thresholds are shown separately in supplementary figure S9. In southern Europe, the atmospheric risk of pyroconvection is concentrated in the summer months, because this is when the highest fire risk at the surface is registered in combination with an also high atmospheric instability. Around the Mediterranean, atmospheric instability is generally maximum in summer, although some regions, such as the Iberian Peninsula, present a distribution that is more bimodal with peaks in spring and autumn, but maintaining elevated values in summer as well (supplementary figure S10).

Finally, for the atmospheric risk of pyroconvection to materialize into an actual firestorm, in addition to ignition of course, there must be sufficient fuel to burn. The characteristics of the vegetation cover are very diverse across the European continent, so the amount of available fuel also varies from one region to another. Supplementary figure S9 shows an estimate of dry matter productivity (DMP), representing the overall growth rate or dry biomass of vegetation. The areas with the highest productivity are the northwest of the Iberian Peninsula, the half south of France, and most of Italy and the western Balkans. In these regions, it takes only between 2 and 4 years (figure 3(b)) to generate a 6 kg m\(^{-2}\) amount of vegetation biomass, which is the fuel load threshold shown to be associated with a considerable increase in the intensity of pyroconvection in our idealized experiment results in figure 2(a). Some of these regions with potentially high fuel loads, such as central Italy and the Balkans, also have many days per year with high atmospheric risk of pyroconvection, thus the odds of firestorm occurrence multiply. In contrast, there are regions with such low DMP that it may be difficult for fuel to accumulate there to an amount sufficient for pyroconvection to develop, even when the atmospheric risk is high, as is the case of most of Spain and Turkey. These areas need a period of more than 15 years to generate the fuel load of 6 kg m\(^{-2}\).

Most of the real cases of pyroconvection identified to carry out the validation of the model configuration occurred on days that meet the thresholds identified in this study. Specifically, as shown in supplementary table S1, only one event took place on a day with a K-index lower that the threshold (with a value of 22.21 °C, when the threshold is 25 °C), and only

![Figure 3: Present distribution of firestorm risk. (a) Number of days per year with both a FWI and a K-index value above the selected thresholds, averaged from 1980–2018 ERA5 reanalysis data. (b) Minimum number of years required for the accumulation of 6 kg m\(^{-2}\) of fuel load according to the average annual dry matter productivity (DMP) in the 1999–2019 period generated by the Global Land Service of Copernicus, derived from SPOT-VGT and PROBA-V imagery combined with meteorological data from ECMWF.](image-url)
another event occurred on a day with a FWI below the threshold (with a value of 46.61 and a threshold of 49.33). These experiments support the reliability of the results shown in figure 3.

3.2. Future trends under different climate change scenarios

We estimate future trends in pyroconvection risk from EURO-CORDEX model results considering the RCP8.5 scenario [46]. Our calculations indicate that the number of days with high fire risk at the surface (FWI above the threshold set from present data, as discussed earlier and shown in supplementary figure S8) will increase significantly across southern Europe, especially in the Iberian Peninsula and southern France (figure 4(a)), and also in northern Africa, moving from between 30 and 40 d per year at the present (1980–2018) to more than 60 d per year in the 2070–2098 period (supplementary figure S12), which represents a percentage increase of nearly 100%. This increase in fire risk is already appreciable at the present and has been shown to be related to human-induced climate change [50].

Less pronouncedly growing values are obtained for atmospheric instability and with a different spatial pattern (figure 4(b)). The fastest increasing trends are found in Italy and Northern Europe, while Portugal, Spain and Turkey show less significant results. For the Mediterranean region, unstable atmospheres are already quite frequent at the present, more so than in the northern countries, and this spatial pattern will be maintained in the future, although slightly attenuated (supplementary figure S13). Some studies have previously assessed the possible influence of climate change on atmospheric static stability, finding a general increase in the number of unstable environments derived from the predicted rise in surface temperature and low-level tropospheric humidity [51–53].

To analyse the meteorological risk of firestorms and its future trend, we now consider the number of
days in which high fire risk conditions at the surface and high atmospheric instability coincide. Figure 4(c) shows that the occurrence of favourable firestorm environments will increase in southern Europe, especially in the northeast of the Iberian Peninsula. As shown in the time series, this positive trend is mainly driven by the growing fire risk in Portugal and Spain, whereas in France, Italy, Greece and Turkey, the firestorm trend is supported by both increased atmospheric instability and fire risk.

The rise in deep pyroconvection risk is more accentuated in places that already have a higher risk at the present (figures 3(a) and 4(c)), such as the eastern Iberian Peninsula, northern Algeria, northern Italy and the Balkan Peninsula. In these regions the annual number of days with high firestorm risk will double, moving from around 15 d per year in the 1980–2018 period, to more than 30 d per year by the end of the 21st century (supplementary figure S14).

In addition to the worst-case RCP8.5 scenario we have considered an intermediate scenario in which emissions peak in 2040 and then decline (RCP4.5) [48], and a scenario that requires that CO₂ emissions start declining by 2020 and go to zero by 2100 (RCP 2.6) [49]. For the RCP4.5 scenario, the positive trends of fire risk, atmospheric instability and firestorm risk are also significant although less pronounced than for the RCP8.5 scenario (supplementary figure S15). Firestorm risk increases at a rate similar to that of the worst-case RCP8.5 scenario until the 2050s, stabilizing afterwards (supplementary videos 1 and 2). For the RCP2.6 scenario we observe that although atmospheric instability shows significant increases, the risk of deep pyroconvection remains very stable throughout the 21st century (supplementary figure S16 and video 3). We only find a significant positive trend in the firestorm risk in the east of the Iberian Peninsula and in the south of the Balkan Peninsula (supplementary figure S16). This implies that the atmospheric firestorm risk increase can still be controlled with emission reduction policies compatible with keeping the global temperature rise below 2 °C by 2100.

The trends shown in figure 4, supplementary figures S15 and S16 were obtained by linear regressions. The data from the different models were treated independently, and the final result shown in each figure corresponds to the mean of the results from each model output. To quantify the statistical significance of each trend, the p-value is used in the context of null hypothesis testing. In figure 4, supplementary figures S15 and S16, grey shaded regions indicate that one of the model outputs presents a non-significant result (p-value > 0.05) or that at least one of the model outputs shows an opposite-sign trend. The results shown in figure 4(c) are robust to changes in the set of thresholds. In supplementary figures S17 and S18 we show how for different FWI thresholds (from the 80th to the 95th percentile) and different K-index thresholds (from 22.5 °C to 30 °C) the firestorm risk trend undergoes only very slight variations.

3.3. An ongoing process

We use the 1980–2018 ERA5 reanalysis data to check whether the trends determined by climate models for the 1970–2098 period are already noticeable at the present. Significant positive trends in the number of days with high fire risk are already observed for the Iberian Peninsula, France and the region north of the Black Sea and the Caucasus, covering Moldova, Ukraine and southwestern Russia (supplementary figure S19(a)), a wide swath of land where the values surpass those projected by the EURO-CORDEX models for the future (figure 4), but with a greater interannual variability. The pronounced positive trend in the fire risk index in this region north of the Black Sea is related to the fact that this area has experienced the highest summer temperature increase in Europe during the 1979–2019 period (supplementary figure S20), which has also been accompanied by a decrease in precipitation and relative humidity (supplementary figures S21–S23).

Regarding atmospheric instability, Central Europe and the central and eastern Mediterranean regions show the largest increases (supplementary figure S19(b)). This is mainly due to a steepening of the lapse rate between the 850 hPa dew point temperature and the rising of the 850 hPa dew point temperature (supplementary figures S24 and S25). In Greece, Turkey and southern Italy, the trend is further enhanced by a decrease in the 700 hPa dew point depression (supplementary figure S26).

Finally, the risk of deep pyroconvection has been increasing in eastern Spain, most of inland France, Western Turkey and the large region north of the Black Sea (supplementary figure S19(c)). This result is consistent with the projections shown in figure 4 for western Europe, but not so for the east. The significant discrepancies in the region north of the Black Sea are due to the aforementioned large positive trend in fire risk index associated with summer temperatures increases of up to 5 °C and a pronounced decrease in the total summer precipitation in the 1980–2018 period (supplementary figure S23), which models do not capture properly.

4. Conclusions

We have found that two of the three factors that determine deep pyroconvection risk, namely fire risk at the surface and atmospheric instability, will augment significantly in Europe during the 21st century. The spatial pattern of the increase in these two factors is uneven, but the number of days with high fire risk and sufficient atmospheric instability will have the greatest growth in the western Mediterranean region, where these changes are already noticeable at the present.
For the development of firestorms, a high fuel load is needed in addition. Fuel load is determined by the amount and structure of vegetation, but also by its dryness. While fuel dryness is increasing due to climate change, vegetation is the only variable influencing fire behaviour that we can manage [54]. The European landscape has been completely modified by humans, especially in the Mediterranean basin where truly wild environments no longer exist [55]. Although fuel reduction strategies are growingly being used in Southern Europe [55], the amount of fuel has been building up in the last decades due to different processes such as rural depopulation [36], the decrease of farming activities or reforestations [54] and the CO2 fertilization effect on vegetation [57–59]. Fire prevention strategies more focused on fuel management and policies that prevent rural abandonment can help to mitigate the effects of climate change on the incidence of firestorms.

It should be mentioned that this is a study to determine the risk of deep pyroconvection on a broad temporal and spatial scale. This has required some assumptions when identifying the environmental controls on this process, which can be much more complex, especially on a more local scale. Regarding future projections, although we have used different emission scenarios, it is evident that there are still sources of uncertainty related to possible changes in human activity in terms of fuel management or fire ignitions.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.7910/DVN/6V7YHW

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Author contributions

M S R designed the study and drafted the manuscript. D I C and G M M provided critical feedback and contributed to writing the paper.

Conflict of interest

The authors declare no competing interest.

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