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The Performance of ECMWF Ensemble Prediction System for European Extreme Fires: Portugal/Monchique in 2018

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Abstract: At the beginning of August 2018, Portugal experienced a severe heat episode over a few days that consequently increased the probability of wildfire events. Due to the advection of an anomalous very hot and dry air mass, severe fire-prone meteorological conditions were forecasted mainly over southern Portugal, in the Monchique region. Together with the significant fuel amount accumulated since the last extreme wildfire in August 2003, all the unfavorable conditions were set to drive a severe fire over this region. The Monchique fire started on 3 August 2018, being very hard to suppress and lasting for seven days, with a burnt area of 27,000 ha. Regarding the need to have operational early warning tools, this work aims to evaluate the reliability of fire probabilistic products, up to 72 h ahead, together with the use of fire radiative power products, as support tools in fire monitoring and resource activities. To accomplish this goal, we used the fire probabilistic products of the Ensemble Prediction System, provided by the Copernicus Atmosphere Monitoring Service. Among available fire danger rating systems, the Fire Weather Index and the Fine Fuels Moisture Code of the Canadian Forest Fire Weather Index System were selected to assess the meteorological fire danger. The assessment of the fire intensity was based on the Fire Radiative Energy released, considering the Fire Radiative Power, delivered in near real-time, by EUMETSAT Land Surface Analysis Satellite Applications Facility. The exceptional fire danger over southern Portugal that favors the ignition of the Monchique fire and its severity was essential driven by two important factors: (i) the anomalous fire weather danger, before and during the event; (ii) the accumulated fuel amount, since the last severe event occurred in 2003, over the region. Results show that the selected fire probabilistic products described the meteorological fire danger observed well, and the LSA-SAF products revealed the huge amount of fire energy emitted, in line with the difficulties faced by authorities to suppress the Monchique fire.

Keywords: ensemble prediction system; meteorological fire danger; fire intensity

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Citation: Durão, R.; Alonso, C.; Gouveia, C. The Performance of ECMWF Ensemble Prediction System for European Extreme Fires: Portugal/Monchique in 2018. *Atmosphere* **2022**, *13*, 1239. https://doi.org/10.3390/atmos13081239

Academic Editors: Tiago Rodrigues, Miguel Almeida, Diogo Lopes and Carlos Viegas

Received: 14 May 2022
Accepted: 28 July 2022
Published: 4 August 2022

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1. Introduction

Fire danger rating systems are used for many purposes, including preparation for daily deployment of fire suppression resources and evaluation of fire management strategies. They can also be incorporated into different types of models to assess the long-term consequences of specific fire management policies and fire regimes [1–8]. To establish fire danger conditions in a given location, a rating system or a model should be able to simulate short- and long-term variations in temperature, relative humidity, precipitation, and wind intensity, in fuel moisture change, which can be used to predict the occurrence and severity of a potential fire [9–14].

Traditionally, local fire danger assessments rely on meteorological station information, as observations have better temporal resolution and diurnal cycle characterization that may better represent local conditions than numerical weather forecast data [9,10,15].

Nowadays, the improved skills in weather forecasting and numerical weather prediction offer a real opportunity to enhance early warning services' quality [10,16–18]. Recently several international institutions implemented regional fire danger forecasting systems based on their operational weather forecasts to provide fire danger forecasts up to 10 days in advance [10–19].

Under the scope of the Copernicus Emergency Management Service, the European Commission promotes similar fire danger forecasting methodologies by supporting the European Fire Forecast Information System (EFFIS, http://effis.jrc.ec.europa.eu/ (accessed on 1 April 2022)) and the Global Wildfire Information System (GWIS, http://gwis.jrc.ec.europa.eu/ (accessed on 1 April 2022)). These systems rely on fire danger rating systems, namely the Canadian Fire Weather Index (CFWIS) [20,21], to provide forecast fire danger based on numerical weather predictions at the European and global levels [22].

The probability of fire occurrence is assessed through the quantification of the meteorological fire danger, based on metrics obtained from empirical index systems, which evaluate the probability of ignition and the fire spread rate, as well as infer the dryness level of the soil and the available fuels [23]. However, fire danger rating systems are more prone to detecting dangerous weather conditions favorable to uncontainable fires rather than modeling the probability of ignition and fire behavior [23].

The CFWIS was originally designed to evaluate the fire danger in a jack pine stand (Pinus banksiana) typical of the Canadian forests [21,24]. The CFWIS calculation is based on weather parameters; however, no information about biomass accumulation and fuel load, and fuel moisture observations are considered [25]. Short- and long-term variations in temperature, relative humidity, and precipitation occurrence are responsible for the dryness of fuels at different soil levels; on the other hand, fuel inflammability is mainly controlled by wind conditions. The combination of different levels of fuel dryness and inflammability produces an overall meteorological fire danger metric that is a result of the rating system. Moreover, these indices allow the characterization of the likelihood and the anticipation of wildfire events, being used operationally to help fire managers to assess risk to threatened values and prioritize the response [26,27].

Due to the simplicity of CFWIS implementation, it becomes a very popular option in many countries, performing reasonably well in ecosystems very dissimilar to the boreal forest [9,26,28]. With the wide use of weather forecasts instead of observations to predict fire danger, uncertainties/errors can be introduced in the outcomes. Handling random errors in weather forecasts is traditionally completed through the use of ensemble prediction systems, where several simulations are performed starting from slightly different initial conditions and model configurations [29,30]. Thus, weather forecasts are then interpreted as probabilistic rather than deterministic products. Although, the use of probabilistic information contained in an ensemble prediction system might be difficult to interpret for end-users [31].

Nevertheless, ensemble products can boost confidence in the decision process during emergencies since a cost-loss analysis can be linked to the different scenarios available [32]. Ensemble forecast products (ENS) may provide more information than a single deterministic forecast [33,34] since they offer a measure of uncertainty, based on the probability of occurrence. The added value of meteorological forecasts given by an ensemble prediction system to compute fire danger relies on the possibility of having early warning levels of about 10 days in advance; a range of possible scenarios, and predictions where observations are not available, therefore allowing for better coordination of fire resource-sharing and mobilization [9,10].

The increase in weather forecast skills in the last 20 years, lead to an opportunity to use weather forecasts to assess fire danger conditions in advance, as well as the development of the early warning accuracy in environmental modeling of fire management strategies [9,10].

The improved weather forecast accuracy, together with the "high confidence" levels given by an ensemble prediction system, enables the assessment of a range of possible

scenarios, which can lead to a fire danger forecast approach very useful to support extended early warning tools, improving preparedness and mitigation strategies of the countries.

Thus, this work intends to evaluate the performance and reliability of fire danger probabilistic products, provided by an ensemble prediction system, up to 72 h ahead, together with the fire radiative power products, to be used as an early warning tool.

To illustrate our objective, we used as a case study, the severe wildfire that occurred in August 2018, in the Monchique region, southern Portugal, aside from the severe 2017 wildfires. The Monchique fire in 2018 was a consequence of multi-trigger factors, such as climate extremes, fuel accumulation, and increasing human pressure on ignitions [35–37]; belonging to the new generation of wildfires, the so-called megafires, characterized by extreme behavior and being very difficult to suppress [38,39].

Besides the assessment of the Monchique fire danger and its intensity, an atmospheric synoptic characterization of the event is performed to understand the role of the meteorological fire-prone conditions in the fire activity. Fire danger rating systems are mainly based on surface meteorological data, without taking into account atmospheric data on pressure levels that play an important role in the development of very severe fires [38].

Finally, this study aims to develop a joint approach, based on ENS fire products and FRP products to forecast fire danger a few days in advance and follow up on ongoing events, when ignitions occur. Aside to help to monitor fire danger, this work intends to contribute to improving preparedness and mitigation strategies, in southern Europe, where extreme fire events have been increasing in recent years, showing an eruptive or erratic behavior often beyond local suppression capacities [4,8,37–40].

2. Materials and Methods

2.1. Monchique Wildfire Characterization

Due to the record-breaking temperature values observed during the early days of August 2018 [41], the probability of potential ignitions increased significantly over southern Portugal, mainly over the Monchique region. On 2 August 2018, extreme fire danger conditions were predicted for the region, and on 3 August 2018, an ignition occurred, causing a severe event that lasted for seven days, with a total burnt area of 27,000 ha [36,42], hopefully without causalities.

This 2018 fire ignition over the Monchique region mainly resulted from a severe combination of very unfavorable meteorological conditions and fuel accumulation. The present fire occurred over almost the same area previously struck by an extreme fire in 2003 with a total burnt area of 41,000 ha (Figure 1—left panel). Aside from the unfavorable fire weather during the event, this fire was characterized by a severe intensity during its lifetime, when compared with the 2017 Portuguese wildfires [10]. Figure 1, right panel, displays the daily FRE values emitted during the lifetime of those fires, where it can be easily seen that the Monchique event released 3 times more energy and the number of severe fire days doubled the number that occurred in the 2017 wildfires.

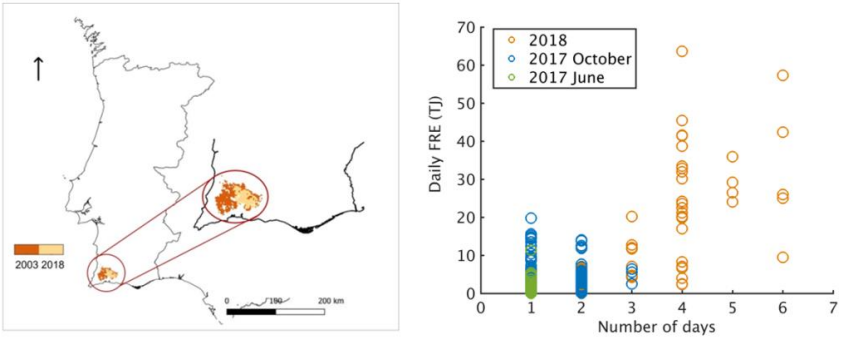


Figure 1. Study area: the Monchique region in southern Portugal, with the total burnt area of 2018 and 2003 wildfires (ICNF, 2018) (**left panel**); daily Fire Radiative Energy (FRE) emitted during the lifetime of the 2017 and 2018 fires (**right panel**).

2.1.1. Synoptic Conditions

The atmospheric synoptic characterization of the event is based on the large-scale and dynamical meteorological fields, retrieved from the ERA5 reanalysis model, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF).

The ERA5 model is the latest climate reanalysis, providing hourly data on atmospheric, land-surface, and sea-state parameters together with estimates of uncertainty, from 1979 up to now. ERA5 datasets are available on regular latitude–longitude grids at $0.25^\circ \times 0.25^\circ$ resolution (~27.7 km grid), with atmospheric parameters on 37 pressure levels, from the surface up to a height of 80 km (https://cds.climate.copernicus.eu/ (accessed on 1 October 2021)).

The ERA5 retrieved fields for this work were the temperature (T), relative humidity (RH), and geopotential at the 850 and 500 hPa pressure levels, namely, T500, T850, RH500, and RH850, hereafter. For sake of simplicity, these variables are interpreted based on physical mechanisms associated with the chosen dynamical variables, by computing the 850 and 500 hPa geopotential heights (hereafter, Z850 and Z500).

2.1.2. Fire Radiative Energy

The assessment of the fire intensity is based on the Fire Radiative Power (FRP) product [43], generated and disseminated in near real-time by the Satellite Application Facility on Land Surface Analysis (LSA SAF), part of the EUMETSAT (European Organization for the Exploitation of Meteorological Satellites) [44,45].

The FRP records information on the location, timing, and fire radiative power (in MWatts) output per pixel of landscape fires detected every 15 min. FRP is disseminated for the full spatio-temporal resolution of SEVIRI (Spinning Enhanced Visible and Infrared Imager) imager onboard the Meteosat Second Generation (MSG) series of EUMETSAT geostationary satellites [46].

The FRP is provided for the whole MSG disk (up to 72° view zenith angle) every 15 min, and each active-fire location is represented at the center of the corresponding SEVIRI pixel, with a 3 km spatial sampling distance at the sub-satellite point (decreasing away from the West African sub-satellite point).

The FRP data provides for each event the geographical coordinates, the date and time, the fire confidence, and the fire radiative power [12]. Since FRP consists of estimates of the radiative power emitted by landscape fires it can be directly linked to the amount of fuel burned and smoke production [47], being useful in fire management and firefighting activities because it can be used as a proxy for fireline intensity [48,49].

In addition, by measuring FRP and integrating it over a fire lifetime, an estimate of the total Fire Radiative Energy (FRE) released can be obtained for each event. A full description of the FRP product and its validation can be found on the LSA-SAF website (http://lsa-saf.eumetsat.int (accessed on 1 October 2021)). The FRE is defined as the emitted radiant energy released during biomass combustion and should be proportional to the total amount of biomass burned during a fire event [12,13]. According to the results of Bowman et al. [50], high FWI values are often related to very high FRP values.

Therefore, the FRP-FRE products are used in this work to assess Monchique fire behavior and intensity, showing the potential of FRE to be used as a management tool, to help authorities monitor and manage resources during ongoing fire events.

2.2. Meteorological Fire Danger

The assessment of Monchique fire danger conditions is based on two steps; firstly, the analysis of the fire weather danger is based on ERA5 reanalysis products, and then is based on the fire danger probabilistic products. Following the rationale that reanalysis data should be seen as the observed conditions during the Monchique fire, enabling the validation of the fire danger probabilistic forecasts' accuracy.

The fire indices datasets are computed using weather forecasts from historical simulations of ERA5 reanalysis model, produced by ECMWF for the Copernicus Atmosphere

Monitoring Service (CAMS) and provided by the Copernicus Emergency Management Service for the European Forest Fire Information System (EFFIS).

Amongst the fire danger rating systems provided by the ECMWF/CAMS, the Canadian Forest Fire Weather Indices System (CFFWIS) was selected, since it is the most suitable for Portuguese fire-prone characteristics [4,6–8,14,37,40,51–53].

Fire danger rating systems like the CFFWIS transform daily meteorological observations into relatively simple indices that can be used to predict the fuel moisture content and consequentially fire occurrence, behavior, and impact; being widely used for public information about fire danger conditions [11,20,21,24].

The CFFWIS is based on a set of six indices, which depend only on daily measurements of air temperature (°C), relative humidity (%), 10 m open wind speed (km/h), and 24 h accumulated precipitation (mm). The first three indices—the fuel moisture codes—are numeric ratings of the moisture content of litter and other fine fuels; the average moisture content of deep and compact organic layers. The remaining four are fire behavior indices, which represent the rate of fire spread, the fuel available for combustion, the frontal fire intensity, or the fire weather index.

The values of CFFWIS indices increase as the fire danger increases [11,21,54]. From the available indices, the Fire Weather Index (FWI), and Fine Fuel Moisture Code (FFMC) were selected to assess the meteorological fire danger of the Monchique event.

FWI is defined as a numerical rating of the potential frontal fire intensity, that indicates fire intensity by combining the rate of fire spread given by the Initial Spread Index (ISI), with the amount of fuel being consumed given by the Build-Up Index (BUI). FFMC is an indicator of the moisture content in litter and other fine fuels less than 1 cm in diameter (needles, mosses, twigs), being representative of the top litter layer less than 1–2 cm deep. FFMC values change rapidly because of a high surface area to volume ratio, and direct exposure to changing environmental conditions [20,21,24,54].

Regarding the fire probabilistic products provided by the Ensemble Prediction System (EPS) of the ECMWF, one ensemble forecast is defined as a set of 51 separate forecasts (i.e., 51 ensemble members), run by the same computer model, with the same starting time. The starting conditions for each member of the ensemble are slightly different, as well as the used physical parameter values that are slightly different too [30]. Thus, each ensemble forecast set provides 51 realizations, from perturbed initial conditions and different model physics, with a spatial resolution of 18 km, a daily temporal resolution, and a lead time of 10 days (https://www.ecmwf.int/en/forecasts/ (accessed on 1 October 2021)).

In practice, the lead time value means that each produced ensemble forecast is extended up to 10 days ahead, with a range of possible scenarios that might occur (namely 50 hypotheses), enabling the issue of early warning levels.

A full description of the modeling components can be found in Di Giuseppe et al. [9].

3. Results

3.1. Synoptic Conditions

To better understand the role of the atmospheric synoptic patterns in the Monchique fire activity, the performed analysis was based on the anomaly fields of the T500, T850, RH500, RH850, Z500, and Z850 variables. To make the interpretation of the observed synoptic patterns easier, the climate anomalies of temperature and humidity fields were represented in shaded colors and plotted jointly with the anomalies of the dynamical fields (Z500, Z850), represented by contours in the respective figures.

The analysis was performed for the two previous days before the ignition (1 and 2 August) and the lifetime of the fire (3–9 August), to evaluate the exceptionality of the synoptic conditions previously and during the event.

Figures 2 and 3 show the spatial patterns of the daily synoptic anomaly values of T850 at the Z500 level; and the daily synoptic anomalies of R850 values, at the Z850 level, respectively.

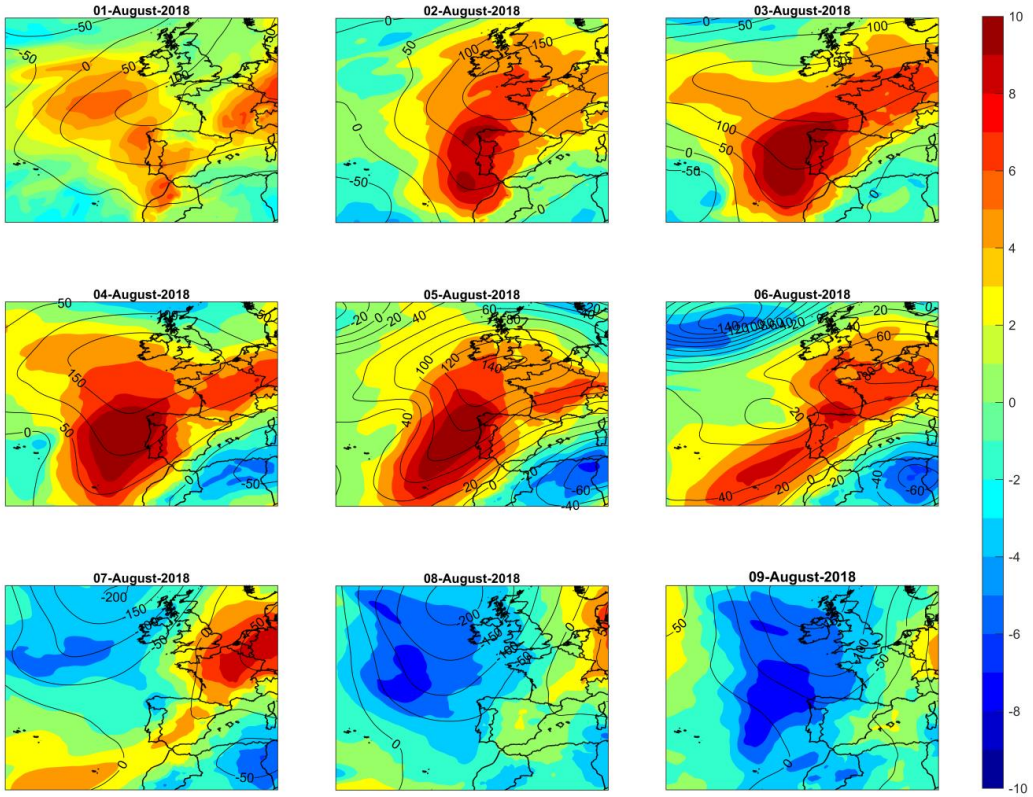


Figure 2. Daily synoptic anomalies for the Monchique fire period of August 2018: temperature at 850 hPa level (colors, °C) and geopotential height at 500 hPa level (lines, m).

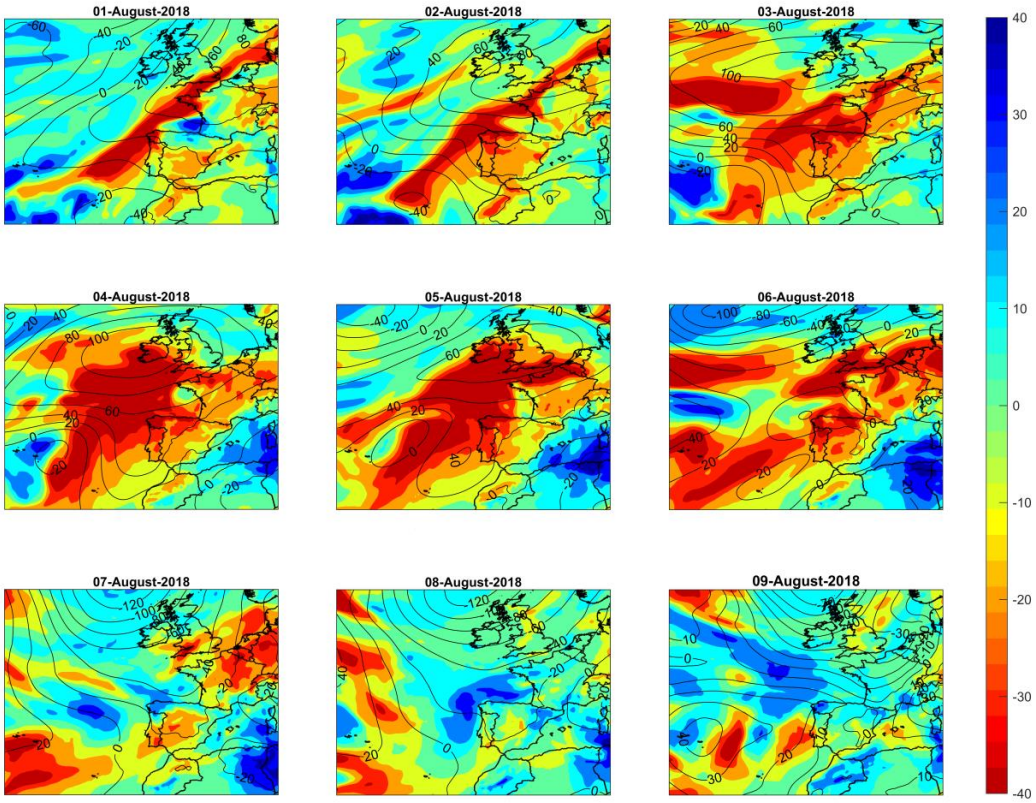


Figure 3. Daily synoptic anomalies for the Monchique fire days of August 2018: relative humidity at 850 hPa level (colors, %) and geopotential height at 850 hPa level (lines, m).

The T850, in Figure 2, is strongly related to the field of geopotential height in the mid-troposphere (Z500) as shown in atmospheric circulation, represented by the Z500 anomaly contours. The T850 anomaly field is characterized by a strong positive anomaly center located over Portugal, along the Portuguese shoreline, mainly between 2 and 6 August.

Moreover, the RH850 and Z850 patterns in Figure 3 show a strong advection of warm and dry air from the Atlantic Ocean, along the Portuguese shoreline, within the period from 2 to 6 August.

The T850 (Figure 2) and RH850 (Figure 3) anomaly fields are dominated by intense extreme positive temperature and negative humidity anomalous values over Portugal during the first five days, with both extreme values contributing to the predicted fire danger and observed fire intensity of the Monchique event. Namely, T850 strong positive anomalies (about 10 °C) can be observed during 3 and 6 August, over Portugal's mainland.

The RH850 anomaly shows significant negative values over a large area; with the minimum values mainly located over the western Portuguese shoreline, with the magnitude of the anomaly decreasing with increasing latitude. In fact, unlike the spread out the maximum of T850, the RH850 presents an anomaly with an important north–south gradient, ranging from about −40% to −20% from the south (Madeira Islands) up to the north (UK) of the Atlantic Ocean Portuguese shoreline.

The anomaly fields of atmospheric circulation, represented by the Z500 (Figure 2) and Z850 (Figure 3), are characterized by a concentric positive anomaly center located over the southern British Islands with a marked valley affecting Portugal, namely from 2 to 5 August.

The observed synoptic conditions played a fundamental role in the Monchique fire activity, namely in the ignition and during the spreading of the fire. Particularly, the 24 h before the fire ignition (on 3 August) revealed exceptional hot and dry conditions that continued till 6 August 2018. These unfavorable weather conditions started ceasing on 7 August; the becoming more favorable conditions consequently contributed to the fire suppression, on 10 August 2018.

3.2. Meteorological Fire Danger

3.2.1. ERA5 Reanalysis

The FWI and FFMC daily anomalies, obtained from ERA5 reanalysis data, for the Monchique fire days are presented in Figure 4. As expected, the highest daily anomalies of both indices occurred between 2 and 6 August.

The observed FWI daily anomaly 24 h before the ignition, was positively high (up to 10) over southern Portugal (Figure 4, left panel), remaining very high over the Monchique region from the ignition day till 6 August 2018.

A similar pattern is observed for the FFMC daily anomalies during the same days, with the highest positive anomaly values (around +5) observed over Portugal's mainland, not only over the Monchique region (Figure 4, right panel).

These exceptional FWI and FFMC ERA5 spatial patterns are clearly illustrated by the respective percentiles map in Figure 5. Accordingly, it can be seen that in the 24 h before the ignition, on 2 August, FWI values are above the 99th percentile over southern Portugal, and on the day that the fire started, the Monchique region was all above the 99th percentile, too. This exceptional FWI pattern lasts till 6 August, as observed previously, and follows the atmospheric synoptic patterns, presented in Figures 2 and 3.

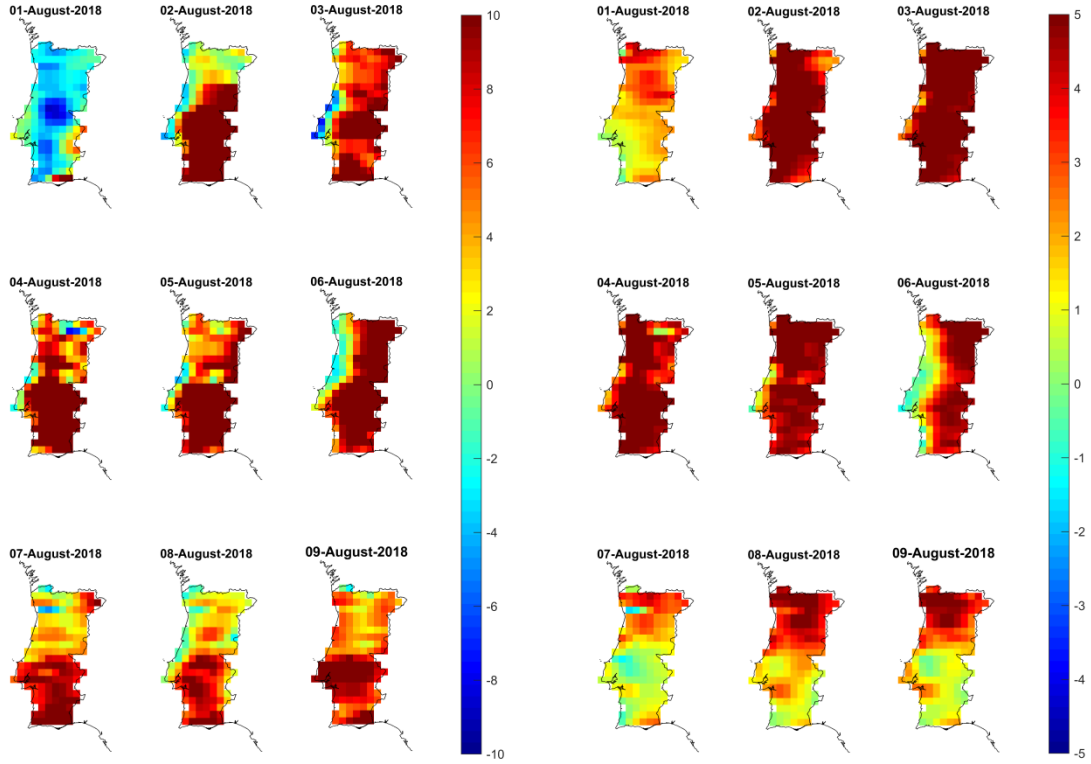


Figure 4. Fire danger daily anomalies of FWI ERA5 (**left panel**) and FFMC ERA5 (**right panel**) over the Monchique fire days in August 2018.

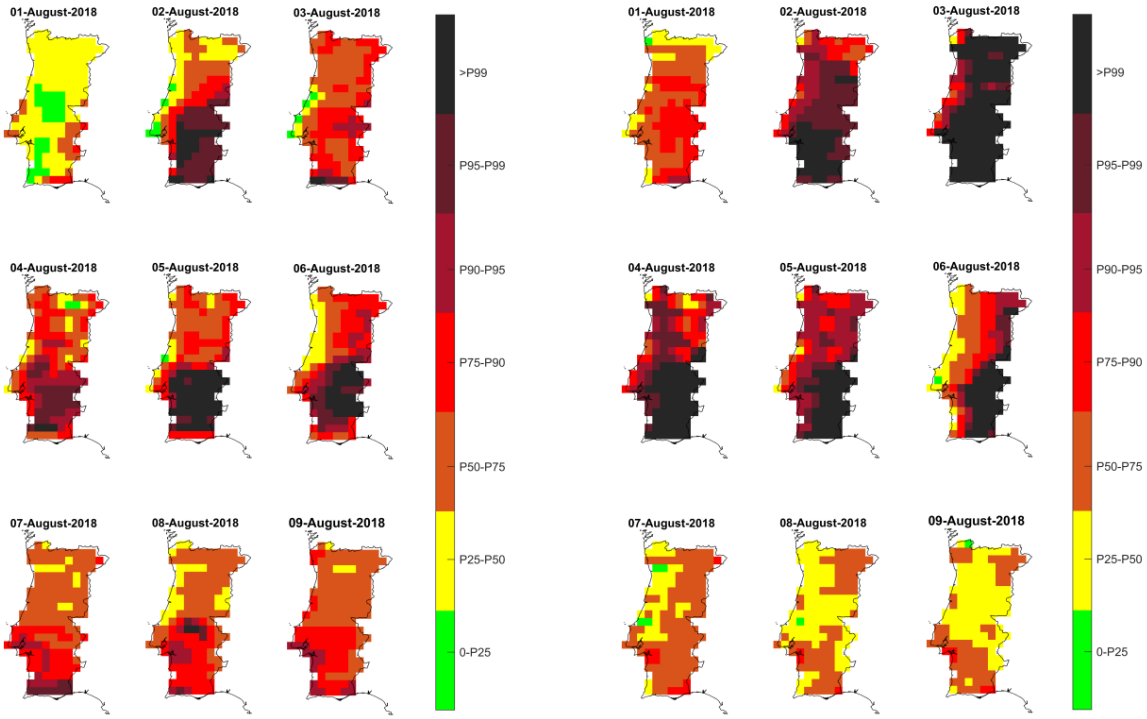


Figure 5. Daily percentiles of FWI ERA 5 (**left panel**) and FFMC ERA5 (**right panel**) for the Monchique fire days of August 2018.

The FFMC percentiles map reveals the most severe pattern, with practically all the Portuguese territory above the 99th percentile during the early days of August, namely on 3 August, and in the following days, over southern Portugal.

Additionally, to complete this characterization, FWI and FFMC ERA 5 classes were obtained with the index values aggregated according to Table 1 and presented as supplementary information (Figure S1). Once more, it can be seen that almost over the Portuguese mainland, in the early days of August, FWI was classified above the Very High threshold, with the southern part of Portugal being classified as Extreme, namely the Monchique area that was classified as Very Extreme, during 2 and 3 August.

Table 1. Fire danger classes of FWI and FFMC indices, following the national guidelines (https://www.ipma.pt/pt/riscoincendio/fwi/ (accessed on 1 April 2022)).

Class	FWI	FFMC
Very Low	0–8.5	0–25
Low	8.5–17.2	25–50
Moderate	17.2–24.6	50–75
High	24.6–38.3	75–90
Very High	38.3–50.1	90–95
Extreme	50.1–64	95–99
Very Extreme	>64	>99

Regarding the observed FFMC patterns, the observed patterns are similar, with almost all of the territory classified above the Extreme threshold since 2 August 2018, with the southern part of Portugal, also classified as Very Extreme over 2 and 6 August 2018, with the Monchique region being classified also as Very Extreme.

3.2.2. Ensemble Prediction System

The daily mean and standard deviation of the FWI ENS dataset (respectively, $FWI_{E\text{-}M}$ and $FWI_{E\text{-}StDev}$) were analyzed to have the first assessment of the FWI predicted values and the magnitude of their dispersion (a measure of the forecast uncertainty) during the period under study. The daily spatial patterns for $FWI_{E\text{-}M}$ and $FWI_{E\text{-}StDev}$ are presented in Figure 6.

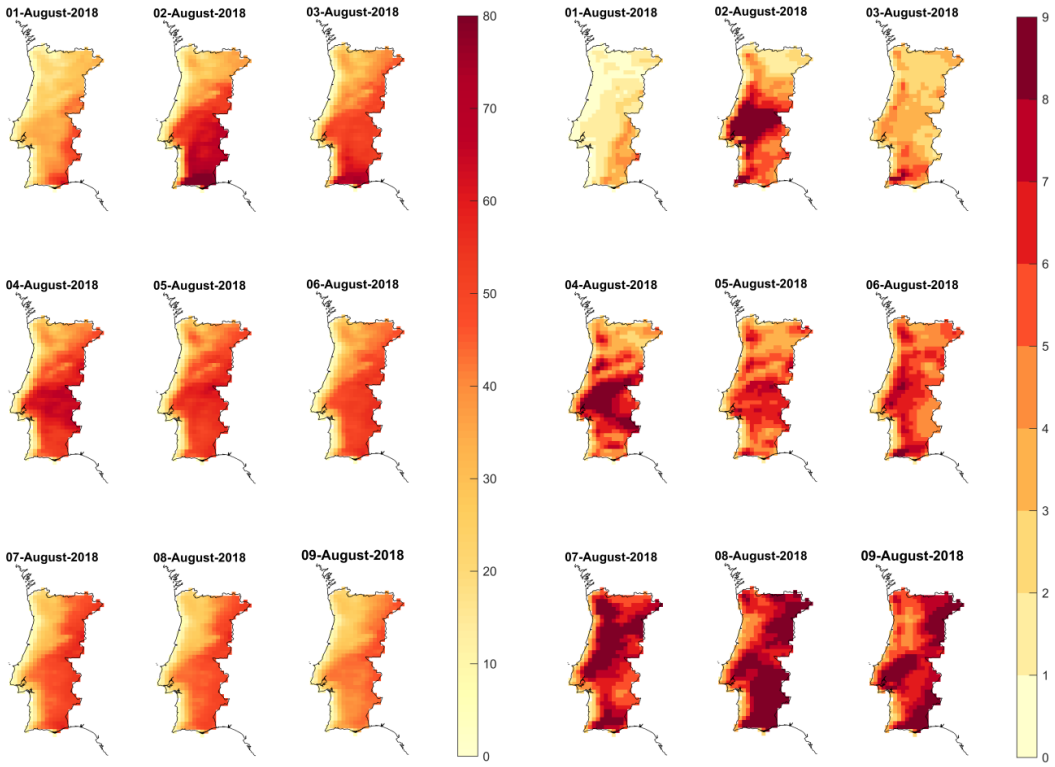


Figure 6. Spatial patterns of the FWI ENS mean (**left panel**) and standard deviation (**right panel**) during the fire (run of 31 July).

Regarding the $FWI_{E\text{-}M}$ values, it can be seen that 48 and 24 h before the ignition, the Monchique region revealed FWI values above 40 (Figure 6, left panel), which can be classified as Very High Danger, accordingly to the national fire danger classification scale (Table 1), where an FWI value ranging from 38 to 50 values corresponds to a Very High Danger class, which are typical values for the occurrence of high-intensity fires (also known as canopy fires).

During the fire period, a significant increase in the $FWI_{E\text{-}M}$ values between 6 and 9 August can be seen, with FWI achieving values around 70, which is classified as an extreme fire danger value according to the national classification, whereas the Extreme fire danger class is defined for an FWI above 50.

These FWI ENS patterns are also in agreement with atmospheric synoptic patterns previously analyzed.

Regarding the $FWI_{E\text{-}StDev}$ patterns, in Figure 6 (right panel), the most variable days are between 6 and 9 August, where the forecasted FWI values show a standard deviation of 8 points not only over the fire area but over the entire country. In practice, this means that the Monchique region could have been classified as Extreme fire danger because it exhibits FWI values above 50. Particular attention should be paid to the very high values of FWI (around 70) that correspond to a standard deviation of 9 over the south half of the country observed for day 2 and clustered in the Monchique region for the day when the fire started.

Concerning the FFMC ENS data, the previous rationale was followed for the predicted values and its results are illustrated in Figure 7.

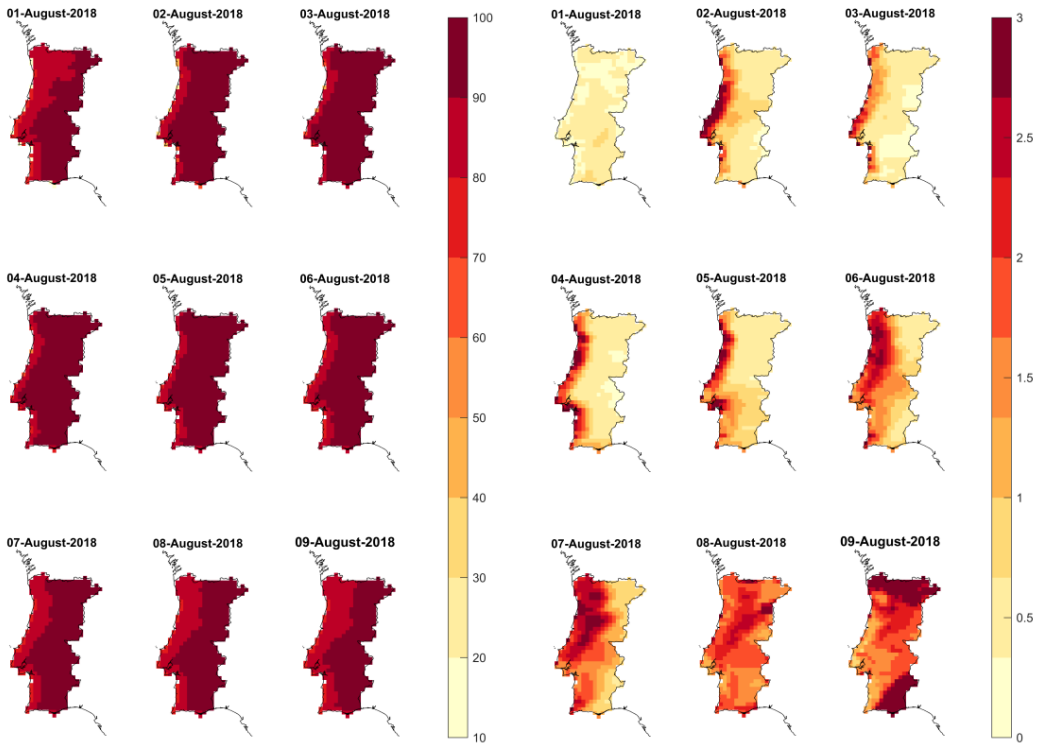


Figure 7. As in Figure 6 but with respect to FFMC ENS.

It can be seen in Figure 7, left panel, that over the entire study period, $FFMC_{E\text{-}M}$ is above the 90 value, which according to Table 1, corresponds to a classification varying from the Very High to the Extreme danger level.

The daily $FFMC_{E\text{-}StDev}$ (Figure 7, right panel) is practically none for the Monchique region from 1 August until 6 August 2018; varying from 4 to 6 points over the days over 7 and 9 August 2018.

The daily maps of the maximum values of the FWI and FFMC ENS ($FWI_{E\text{-}Max}$ and $FFMC_{E\text{-}Max,}$) are presented in Figure 8.

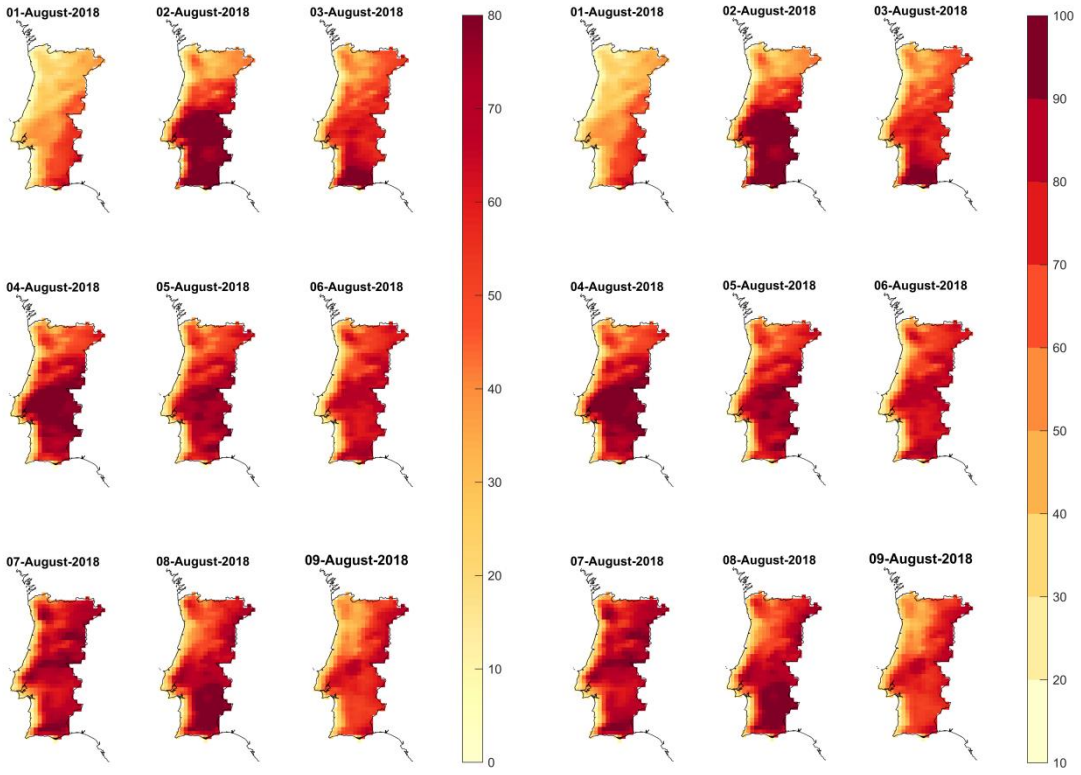


Figure 8. Maximum spatial patterns of FWI ENS (left panel) and FFMC ENS (right panel) over the period 1–9 August 2018 (run: 31 July).

Results obtained for the $FWI_{E\text{-}Max}$ (Figure 8, left panel), highlighted that in the 48 h before the ignition, the Monchique region showed FWI values equal to the maximum values of the ensemble. The increase in the forecasted $FWI_{E\text{-}Max}$ values is seen again over the most severe fire days, comprised between 6 and 9 August 2018.

Analogous results were obtained for $FFMC_{E\text{-}Max}$ (Figure 8, right panel) following what was observed in FWI ENS results. It should be noted that FFMC ENS values vary from 90 to 95, which corresponds to a fuel moisture percentage of 10–5% that is linked to fires burning with high to very high intensity, being likely its propagation in the treetops and ignitions are fast, made by projected sparks.

Typically, FFMC values above 95 correspond to fires burning with extreme intensity and immediate ignition [52,54]. Additionally, the 95th percentile maps of both ENS fire indices revealed the same previous patterns (Figure S2).

3.3. Fire Intensity

The fire intensity assessment, given by the accumulated daily FRE released during the Monchique fire is illustrated in Figure 9. Revealing that very high energy amounts were released, with daily maximum amounts above 10×10^4 GJ, namely throughout the days between 5 and 8 August 2018.

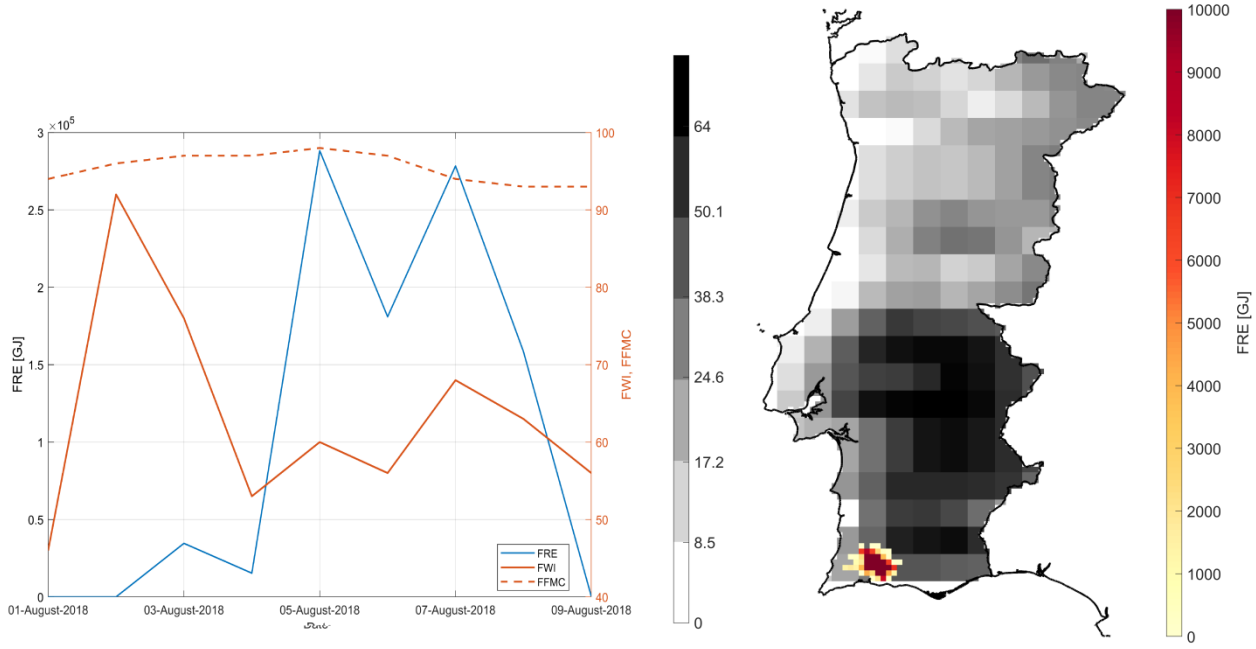


Figure 9. Fire radiative energy (GJ) emitted by the Monchique fire over 3–10 August 2018: Left—temporal evolution of FRE accumulated per day, and daily ERA5 fire danger indices (FWI, FFMC); Right—total FRE emitted by the fire accumulated per pixel, and FWI mean value observed during the fire.

The most severe days registered FRE daily maximum amounts of about 30×10^4 GJ, namely 5 and 7 August 2018 (Figure 9, left panel). However, it should be noted that FFMC values are higher than 95 from day 2 to day 6. The maximum value of FWI observed over the Monchique region was higher than 90 and was recorded on 2 August and remained higher than 75 on 3 August. The FWI values decrease to values lower between 50 and 60 from 4 to 6 August, corresponding to the period with higher FRE values. The values of FRE higher than 2×10^4 (GJ) from 5 to 7 August reflected the extreme fire behavior that was observed in the previous days following the very extreme forecasted fire danger (Figure S3). Total FRE (GJ) of the fire, daily accumulated per pixel for the Monchique fire is presented in Figure S3, where it can be seen that some pixels achieved maximum values of 6×10^4 (GJ).

4. Discussion

The analysis of the spatial patterns of the ERA5 fire indices, the FWI and FFMC, clearly illustrates that the severity of the fire-prone meteorological conditions observed during the early days of August 2018, was directly linked to the ignition of the Monchique fire, consequently driving to it severe spread and behavior.

Highlighting, along with the significant fuel amount accumulated since the last extreme fire that occurred in 2003, all the unfavorable meteorological conditions that were set to drive a severe fire event over this region.

Regarding the fire probabilistic products, the ENS fire danger indices follow the ERA5 fire indices results in general, revealing analogous patterns and being also directly linked to the observed unfavorable meteorological conditions. It should be stressed that the obtained differences between the fire danger patterns given by ECMWF datasets, ERA5 reanalysis, and ENS forecasts, are expected due to the grid resolution of each dataset, ~27.7 and ~18 km, respectively. As well, it should be stressed that ERA5 reanalysis datasets combine model data with observations into a global dataset (data assimilation process), while one ensemble forecast is a set of 51 separate forecasts, with the same starting time, but with slightly different starting conditions for each one [30].

The meteorological fire danger assessed through the FWI and FFMC ENS forecast values revealed reliable results, following the general patterns that had been observed during those early days of August.

The ENS fire products showed a clear signal for very high to extreme fire danger conditions 72 h before the ignition, particularly revealing a very clear signal of the fire danger 48 h before the ignition occurs. The fire intensity results, assessed through the emitted FRE values, are in agreement with the fire danger patterns obtained for the ERA5 reanalysis data. These findings reveal that extreme fires such as this one release huge amounts of energy, that can be directly linked to very high FWI values according to Bowman et al. [50], and followed by very high FFMC values, which correspond to a very dry fuel moisture percentage, and consequently, it can be seen as a measure of the cumulative dry mass available to burn [49].

Considering the monthly distributions of daily energy (GJ) released per pixel, computed by Pinto et al. [12], the total FRE daily amount per pixel is above the maximum absolute value expected for a typical August (~50,000 GJ), being closer to the expected values emitted by fires for a typical July (~70,000 GJ). The observed total FRE daily amount values showed the intensity of this event and how hard the suppression activities developed by Portuguese authorities had been. Taking into account that 2000 GJ is the typical daily amount of energy released by a severe fire, which is very difficult to suppress [12], the obtained results confirm that the Monchique fire was a very severe fire, with almost all of the fire days above this severity threshold, namely within the period, from 3 to 8 August 2018.

5. Conclusions

This work aimed to evaluate the performance and accuracy of ECMWF fire probabilistic products (CAMS), up to 72 h ahead, to be used as an early warning tool, as well as to explore the satellite-derived FRP and FRE products (LSA-SAF) to follow up on ongoing fires and help authorities to manage resources and activities according to its fire intensity/severity.

The chosen event was a fire that occurred over the Monchique region, southern Portugal, which lasted for seven days, from 3 to 10 August 2018, with a total burnt area of 27,000 ha (ICNF).

According to the work of Sousa et al. [41], over the early days of August 2018, Portugal experienced a short record-breaking extreme heat episode due to the advection of an anomalously warm air mass, from Sahara Desert regions, transported abroad under the influence of a strong subtropical ridge pattern. Particularly, extreme temperatures were observed over Portugal, following IPMA monitoring data, with several stations breaking their previous historical maximum temperatures [41].

Despite the anomalous meteorological fire-prone situation observed, the very high fire probability occurrence over Monchique was re-enhanced due to the substantial fuel amount accumulated during 2018 and particularly since the last extreme wildfire, which occurred over this region in August 2003 [3,42,55,56].

To accomplish the proposed objectives, we used the FWI and FFMC indices of the Canadian Forest Fire Weather Indices System, based on two steps; firstly, the assessment of the fire weather danger based on ERA5 reanalysis data, and then based on the ENS fire danger forecasts, produced by the ECMWF and provided by CAMS, for the European Forest Fire Information System (EFFIS).

The assessment of the fire intensity was based on the Fire Radiative Energy emitted by the fire, considering the Fire Radiative Power, delivered in near real-time, by EUMETSAT Land Surface Analysis Satellite Applications Facility.

The obtained results showed that the ENS fire danger products are a useful tool to monitor fire danger and to follow up on active fires, by enabling an overview of the fire danger conditions, after the ignition. As well, these ENS results are in line with the fire behavior during the fire days, as revealed by the FRE emitted during the Monchique fire.

The emitted FRE values are in agreement with the known severity of the event, being also in line with the maximum FWI and FFMC values, namely, the FRE highest values occurred, as expected, in the same period as those maximums were forecasted.

The exceptional character of the Monchique fire is coincident with the new concept of *megafires* that is associated not only with the amount of total burnt area but also with its exceptional intensity [57,58], confirmed by the very high values of fire energy released during this event. The findings confirmed how extreme the event was described by authorities, being very hard to suppress, driven by the extreme meteorological conditions and observed during its lifetime.

Finally, the presented approach revealed that with meteorological conditions such as the ones observed in southern Portugal, in 2018, it is evident that having efficient forecasts, together with the FRP products, is an added value to fire resource activities, namely, to provide timely alerts, operational planning, and emergency intervention before ignitions and during ongoing fire events.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/atmos13081239/s1, Figure S1. Fire danger percentiles for the Monchique fire days of August 2018: Left—FWI ERA5 daily percentiles; Right—FFMC ERA5 daily percentiles, Figure S2. Spatial patterns of the 95th ENS percentile fire danger data over the period 1st–9th August 2018: Left—FWI 95th ensemble percentile; Right—FFMC 95th ensemble percentile, Figure S3. Daily FRE values in GJ emitted by Monchique fire over the period 3rd–10th August 2018.

Author Contributions: Participated in the conceptual design of the study, R.D. and C.G.; All the authors contributed to the interpretation and analysis of the results and the redaction of the manuscript. Defined the datasets and the methodology to be used for the study, R.D. and C.G.; made all the calculations R.D. and C.A.; All the authors made figures and tables; R.D. and C.G wrote the manuscript; Each of the co-authors performed a thorough revision of the manuscript, provided useful advice on the intellectual content, and improved the English language; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable here.

Acknowledgments: This study was made within the framework of the 2021 FirEUrisk project funded by European Union's Horizon 2020 research and innovation programme under the Grant Agreement no. 101003890) and is supported by national funds through the Fundação para a Ciência e a Tecnologia, Portugal (FCT) under project FIRECAST (PCIF/GRF/0204/2017). Authors acknowledged to Claudia Vitolo and Francesca Di Giuseppe (ECMWF) for data support.

Conflicts of Interest: The authors declare no conflict of interest.

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