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Article

Multi-indices diagnosis of the conditions that lead to the two 2017 major wildfires in Portugal

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Abstract: Forest fires though part of a natural forest renewal process, when frequent and assuming large-scale proportions have detrimental impacts on biodiversity, agroforestry systems, soil erosion, air and water quality, infrastructures, and economy. Portugal (PT) endures extreme forest fires, with a record of burned area in 2017. These extreme wildfire events (EWE) concentrated in few days but with high burned areas, are among other factors, linked to severe fire weather conditions. In this study a comparison between several fire danger indices is performed for a reference period 2001–2021 and 2017 (May–October) for the Fire Weather Index (FWI), Continuous Haines Index (CHI), Keetch-Byram drought index (KBDI), Burning Index (BI) and Fire Danger index (FDI). A daily analysis for the so-called Pedrogão Grande wildfire (June 17th) and the October major fires (October 15th) included the Spread Component (SP) and Ignition Component (IC). Results revealed high above average values for all indices for 2017 in comparison with 2001–2021 particularly, for October. High statistically significant monthly correlations between FWI, FDI and BI were found, along with lower between FWI and CHI. These correlations are depicted in the spatial patterns between FWI and FDI for the two EWE. The spatial distribution of FDI, SC and IC had the best performance in capturing the locations of the occurrence of the two EWEs'. The outcomes allowed to conclude, that since fire danger depends on several factors a multi-index's diagnosis is highly relevant, though calibration and scale adjustment are needed for PT. The implementation of a Multi-index's Prediction System should be able to further enhance the ability of tracking and forecast unique EWE, since the shortcomings of some indices are compensated by the information retrieved by others as shown in this study. Overall, a new forecast system can help ensuring the development of appropriate spatial preparedness plans, proactive responses by the civil protection regarding firefighter's management, suppression efforts to minimize the detrimental impacts of wildfires in Portugal.

Keywords: Fire Weather Index (FWI); Continuous Haines Index (CHI); Burning Index (BI); Keetch-Byram drought index (KBDI); Fire Danger index (FDI); Spread Component (SP); Wildfires; Portugal

1. Introduction

Forest fires are one of the most severe natural disasters that periodically affect Mediterranean countries [1–6], as well as other countries with Mediterranean-like climates, such as California and in south-eastern United States of America (USA)[7–9], or in more dry climates like in Australia [10]. In the Mediterranean region its climate is characterized by Mediterranean hot- (CSa) or warm-summers (CSb) [11], as well as dry summers (B type, following the Köppen-Geiger Climatic Classification [12]) and this is a key factor that influenced by the nature and magnitude of climate change (exposure) and forestry policies partially explains the susceptibility of this region to wildfires. Within the Mediterranean area Portugal is one of the most affected [13 –15] with major losses either in its ecosystems and agroforestry systems [16–17], but also in infrastructures [18] and

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unfortunately, human lives. Therefore, a better understanding of the underlying danger factors and danger indices is of utmost relevance.

The significance of meteorological conditions for the incidence of conditions prone to the occurrence of forest fires is well known [19–23], hence the ability to anticipate their impact on daily fire occurrence and related behavior is one of the major goals of researchers in this area of expertise [24–25]. As a result, several fire danger evaluation indices or methods have been developed and adapted to different regions of the world [26–30]. In Portugal, the Fire Weather Index (FWI) also known as the Canadian Forest Service Fire Weather Index Rating System is the most used danger index [31–35]. Its forecast is given by the Instituto Português do Mar e da Atmosfera (IPMA) [36]. This index is commonly used in several other European countries, for example the European Forest Fire Information System (EFFIS) [37] provides related long-term fire weather forecast. The associated danger is indicated by a scale associated with the FWI further explained in section two that translates the weather conditions, flammability, and dryness of materials, as well as wind conditions that can lead to significant forest fires. That is, it translates surface conditions into the likelihood of occurrence of forest fires.

The wildfire season of 2017 was considered as an extreme wildfire event (EWE), with an unprecedented number of episodes that burned 6% of mainland Portugal area [17, 38] (Figure A1). Within this exceptional wildfire season two events were the most tragic one in June and another in October not only due to the total burned area, but because in two days more than one hundred human casualties were registered. Owing to the impacts of 2017 forest fires, since 2018 in Portugal, the Continuous Haines Index (CHI) has been also operationally used by IPMA [28–30, 39]. This index, which is also going to be further explored in subsequent sections, reflects the conditions of instability and dryness in the lower atmosphere and is associated with explosive and fast-spreading fires. Namely, this index denotes the conditions in the lower atmosphere that are favorable to the propagation of forest fires. However, it still lacks to be further evaluated regarding its potential as a tool to evaluate the danger of occurrence of forest fires in Portugal.

There are other forest fire danger indices that are commonly used in other regions of the world that also experience vast fire events. As aforementioned, USA with its U.S. Forest Service National Fire-Danger Rating System (NFDRS) [40, 41] and Australia with the McArthur's Forest Fire Danger Meter or Index (FFDM/I) [42] in operational use since 1967. These are two examples of countries that use other indices besides FWI, that is not the case of Portugal. Therefore, the main purpose of this work is to assess not only the currently used indices (FWI and CHI) using 2017 has a reference year (extreme), but also other indices that are not used operationally, such as the Burning Index (BI), Spread Component (SC), Ignition Component (IC) and the Keetch-Byram Drought Index (KBDI) from NFDRS [43]; and the Fire Danger Index (FDI) [41, 44] from FFDI also known as MARK5.

In the last thirty years, the tendency for the incidence of wildfires in Portugal, shows a reduction in the number of occurrences, however with high variability of burned area (Instituto de Conservação da Natureza e Florestas – Sistema de Gestão de Informação de Incêndios Florestais (ICNF) ([45], accessed on 31 november 2021). Indeed, it can be observed that wildfires of vast burned areas are concentrated in events of a few days. Fernandes [15] shows that this decreasing trend is particularly noticeable for fires surviving to ≥10 ha and ≥100 ha between 2001 and 2011 (e.g., Table 2 [15]). This is the case of 2017, the year with the biggest burned area within the period between 2001 and 2021, in which 67% of the burned area was the result of fires that have occurred in a timeframe of 10 days in June (11%) and 3 days in October (56%) ([45], accessed on 31 november 2021). As aforementioned, one of the main objectives of this study is to analyze the conditions that lead to these occurrences by a multi-index's diagnosis. Furthermore, the last objective is to assess if the use of these indices would add more useful information in the prevention of forest fires in Portugal.

In this work, a climatology for several indices between May and October for the period from 2001 to 2021, was attained from daily values and is going to presented and compared with the same months for the year of 2017 (EWE) and 2007 (low number of

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occurrences) and possible relationships between them are going to be assessed. The 2017 year was considered suitable for this case study since it presented extreme weather conditions with a severe wave of heat and extreme atmospheric instability in June [38] for which a daily period from June 16th to 20th will be further analyzed. Moreover, due to the influence of the Ophelia hurricane and a record-breaking drought in October the same methodology will be applied from October 14th to 16th. These meteorological conditions favored the occurrence of large wildfires, with several active fronts and explosive fire behavior, which lead to a record burnt area (>500 kha [46]) that have had a severe impact on human lives (as aforementioned, more than 100 casualties), infrastructures [18], and in agroforestry systems [16]. Towards this aim, a more daily detailed approach is going to be further investigated for these two events in section three using a multi-index's assessment, followed by a discussion (section four) and a summary of the main results in section five.

2. Materials and Methods

2.1. Indices description

2.1.1. The Fire Weather index (FWI)

The FWI, as aforementioned was developed by the Canadian Forest Service Fire Weather Index Rating System and is a combination of four weather variables observations (air temperature, relative humidity, wind and rain) that in a recursive way give raise to a set of three fuel moisture codes: the fine fuel moisture code (FFMC), the duff moisture code (DMC) and the drought code (DC); which in turn are used to compute two fire behavior indices: the initial spread index (ISI) and the buildup index (BUI). With these latter indices the FWI is finally attained for a certain day [31, 47] to produce a general fire intensity potential (Figure A2). In Portugal, the FWI is calculated with data from meteorological stations and with analysis and forecast data from the European Centre for Medium-Range Weather Forecasts (ECMWF). In this work, the analysis of the ECMWF operational model was used for 12UTC in the period from 2001 to 2021, with a spatial resolution of 0.125° ×0.125° in latitude and longitude.

The FWI scale, is shown in table 1, which for Portugal classifies regions with FWI values higher than 38.3 has regions of extreme danger. This class, FWI>38.3, is further subdivided into 3 classes: between 38.3 and 50.1, between 50.1 and 64, and FWI values above 64 ([36], accessed on 01 February 2022). It is worth emphasizing that this subdivision was due to the large fires of 2017, in which the values achieved for the FWI were much higher than the average value expected for the region and period (June and October) of occurrence.

Table 1. Fire Weather index (FWI) scale and interpretation.

FWI	Color code	Interpretation
0 – 8.5	Green	Very low
8.5 – 17.3	Yellow	Low
17.3 – 24.7	Light orange	Moderate
24.7 – 38.3	Orange	High
38.3 – 50.1	Red	Very high
50.1 – 64	Dark red	Extreme/Maximum
>64	Brown	

2.1.2. The Haines index (HI) and the Continuous Haines index (CHI)

The Haines Index (HI) combines two key factors to compute the danger associated to conditions prone to the occurrence of wildfires. Typically, this index is computed accordingly to table 2, in which A is the stability term, and B the term associated with the humidity. The HI is the sum of the latter terms. Therefore, the higher the value of A, the more unstable the atmosphere is, whereas the higher B is, the more favorable are the conditions to the propagation of wildfires. Indeed, values of 5 or 6 to HI translate critical conditions towards the formation of convective feathers and higher propagation speeds.

Table 2. Conditions associated to the computation of the Haines Index according to Haines [39], Choi et al. [48] and Potter et al. [30].

Surface elevations	Pressure levels (hPa)	Stability (TP1-TP2) [1]	A	Humidity (TP3-TDP3) [1]	B	HI=A+B
< 305 m (low)	P1=950	<4°C (2.7°C)	1	<6°C	1	Potential for Large fires
	P2=850	≥4°C (2.7°C) <8°C (2.7°C)	2	≥6°C <10°C	2	
	P3=850	≥8°C (6.7°C)	3	≥10°C	3	
305-914 m (mid)	P1=850	<6°C	1	<6°C	1	2-3 very low 4 low 5 mid 6 high
	P2=700	≥6°C <11°C	2	≥6°C <13°C	2	
	P3=850	≥11°C	3	≥13°C	3	
>914 m (high)	P1=700	<18°C	1	<15°C	1	
	P2=500	≥18°C <22°C	2	≥15°C <21°C	2	
	P3=700	≥22°C	3	≥21°C	3	

[1] TPi, air temperatures at the respective pressure levels (in °C); DPi, dew point at respective pressure level.

In this study, the daily values of CHI were computed and are going to be analyzed since this index eliminates the abrupt transitions between categories and provides major contrast at higher values. Furthermore, allows a more realistic assessment of the contributions of atmospheric instability and dew point depression to the overall score [49]. The CHI is also a combination of two terms, a continuous stability term, ca and a continuous moisture term, cb, and is computed by following equations (1) to (3):

$$ca = 0.5\,(T850 - T700) - 2, \tag{1}$$

$$cb = 0.3333\,(T850 - DP850) - 1, \tag{2}$$

$$CHI = ca + cb, \tag{3}$$

in which, T700 and T850 are the air temperatures at 700 hPa and 850 hPa, respectively; DP850 is the dew point at 850 hPa. Regarding the classification scale, the main difference is that now CHI ranges from 0 to 14 (Table 3), since ca and cb have upper limits of approximately 6.5 and 7, respectively.

The calculations were made with reanalysis data from the ECMWF operational model for the period between 2001 to 2021, at 12 UTC.

Table 3. Continuous Haines index (CHI) scale and interpretation.

CHI	Probable fire behavior and fire prediction reliability
<4	Easily controlled fire. Models easily predict the path of the fire.
4 – 8	Fires can be difficult to control, and its behavior can be erratic. It is likely the modeling of the behavior of the fire is close to reality.
8 – 10	Fires will be difficult to control, and the behavior of the fire will be erratic. It is likely that modeling the behavior of the fire underestimate reality.
>10	Fires uncontrollable and extremely difficult to extinguish. Modeling of the fire behavior dramatically underestimate reality.

2.1.2. Burning index (BI), Spread Component (SC) and Ignition Component (IC)

However, these are not the only indices that allows to assess the conditions prone to the occurrence of wildfires. As abovementioned, the NFDRS also provides several indices such as the BI that is analogous to FWI (Figure A3). Since BI directly relates to the intensity of the fire (value 10×feet, when computed by the Oklahoma Fire Danger Model), that can then be scaled such that BI/10 equals the flame length (FL) in feet at the head of the fire. Though related to flame length, which in the Fire behavior Prediction System, is based on the rate of spread and heat per unit area, BI and FL are not the same. Like FWI, this index integrates the SC (how fast a fire will spread) and the energy release component (ERC, how much energy will be produced). Therefore, BI is a function of a fuel model (e.g., live, and dead fuel moistures) and weather conditions. Following the instructions of the U.S. Forest Service regarding the fire behavior and its suppression the BI can be interpreted following table 4, since it will give, a number related to the contribution of fire behavior to the effort of containing it.

Table 4. Burning index (BI) scale and interpretation (adapted from the traditional U.S. Forest Service interpretation of Burning Index [41]).

BI	Fire behavior and suppression
<40	Fires can be attacked at the head or flanks by firefighters using hand tools. Hand line should hold the fire.
40 – 80	Fires are too intense for direct attack on the head by firefighters using hand tools. Hand line cannot be relied on to hold fire. Equipment such as dozers, pumpers, and retardant aircraft can be more effective.
80 – 110	Fires may present serious control problems torching out, crowning, and spotting. Control efforts at the fire head will probably be ineffective.
>110	Crowning, spotting, and major fire runs are probable. Control efforts at the head of the fire are ineffective.

The BI is computed by:

$$F_L = j\left[\left(\frac{SC}{60}\right) 25 \times ERC\right]^{0.46}, \quad (4)$$

where j is a scaling factor, and ERC is the Energy Release Component; hence:

$$BI = j_1 F_L, \quad (5)$$

in which j_1 is the scaling factor of (10/ft).

Regarding the SC, this variable is a measure of the speed at which the head fire will spread and is numerically equal to the theoretical ideal rate of spread expressed in feet-per-minute however is considered as a dimensionless variable. The IC is also going to be analyzed and measures the probability (therefore ranges from 0 to 100%) of a firebrand to require a suppression action. The higher the IC values the higher the probability of a wildfire to require suppression actions. Consequently, an IC of 100% implies that every firebrand will trigger a fire that will require action when in contact with a receptive fuel. Conversely, an IC of 0% indicates a firebrand that will not require fire suppression action under those conditions.

2.1.3. The Keetch-Byram drought index (KBDI) and the Fire Danger index (FDI)

The KBDI is also encompassed in NFDRS indices and represents the net effect of evapotranspiration and precipitation in producing cumulative moisture deficiency in deep duff and upper soil layers. Like CHI the KBDI is a continuous index, linked to the flammability of organic material in the ground and attempts to measure the amount of precipitation necessary in order to the soil return to saturated conditions. It is a closed system ranging from 0 to 200 units and represents a moisture regime from 0 to 20cm of water through the soil layer. At 0 KBDI assumes the point of no moisture deficiency, at 20cm of water assumes saturation, and 200 assumes the maximum drought that is possible. Therefore, at any point along the scale listed in table 5, the index number indicates the amount of net rainfall that is required to reduce the index to zero, or saturation.

Table 5. Keetch-Byram drought index (KBDI) scale and interpretation (adapted from the traditional U.S. Forest Service interpretation of Keetch-Byram drought index [41]).

KBDI	Fire behavior and suppression
0 – 50	Soil moisture and large class fuel moistures are high and do not contribute much to fire intensity. Typical of spring dormant season following winter precipitation.
50 – 100	Typical of late spring, early growing season. Lower litter and duff layers are drying and beginning to contribute to fire intensity.
100 – 150	Typical of late summer, early fall. Lower litter and duff layers actively contribute to fire intensity and will burn actively.
150 – 200	Often associated with more severe drought with increased wildfire occurrence. Intense, deep burning fires with significant downwind spotting can be expected. Live fuels can also be expected to burn actively at these levels.

Lastly, the FDI is integrated within the Australian McArthur Mark5 Rating System or has already stated FFDI and is an index associated to the danger conditions prone to a fire to start, its rate of spread, its intensity, and the difficulty of its suppression. Like other preferred indices it is open ended though a value equal or above 50 is consider as indicative of extreme danger of wildfire in most vegetation. The overall scale and interpretation are present in table 6. The FDI is attained by

$$FDI = 2e^{(-0.45+0.987\ln(DF)-0.0345RH+0.0338T+0.0234v)}, \quad (6)$$

where DF is a drought factor, T the air temperature (°), RH the relative humidity (%) and v the wind speed (km/h) (Luke and MacArthur [50] for further details).

Table 6. Fire Danger index (FDI) scale and interpretation (Adapted from Luke and MacArthur [50]).

FDI	Color code	Interpretation
0 – 5	Green	Low
5 – 12	Blue	Moderate
12 – 24	Yellow	High
24 – 50	Orange	Very High
>50	Red	Extreme

2.2. Datasets and study area

This study comprises a study area covering mainland Portugal for all indices and the 2001–2021 period. The interval includes an extremely high 2017 fire year in terms of burned area, although 2003 and 2005 also have record values; as well as an extremely low 2007, even though 2008 could be also considered (Figure A1) ([51], accessed on 01 February 2022). Individual fire data, such as, date, duration, location, and size can be retrieved from ICNF, the Portuguese rural fire database ([45, 52–53], accessed on 31 november 2021). In this study, all data regarding the burned areas between 2001–2021, but mainly during the days covering the great wildfires of June 16th, 2017, and October 15th, 2017, were all retrieved from ICNF ([45] , accessed on 31 november 2021). For succinctness purposes, the analysis will be focused on the months most prone to the occurrence of wildfires in Portugal, e.g., between May and October for all indices, thus encompassing the fire season.

For the HI and CHI computation, the daily datasets of the air temperature (at 700 hPa and 850 hPa) and the relative humidity at 850 hPa (Table 1) were retrieved from the ECMWF atmospheric model between 2001 and 2021 ([54], accessed on 13 January 2022).

The FWI was computed by using daily values of air temperature (at 2m), relative humidity (at 2 m) attained from the dew point temperature, wind speed (at 10 m) that was computed from the zonal and meridional components; and lastly, the accumulated total precipitation that was calculated from convective rain and large-scale rain all retrieved from ECMWF atmospheric reanalysis ERA5 ([54], accessed on 13 January 2022), also between 2001 and 2021. The remaining daily values between 2001 and 2021 for BI, SC, IC, KBDI and FDI were retrieved from Copernicus datasets ([55], accessed on 03 January 2022).

The period 2001–2021 between May and October, was considered as a 'baseline climate' or reference period. Monthly statistically significant anomalies were then computed by subtracting 2017 to the related data for the reference period for FWI, CHI, FDI, BI and KBDI. Furthermore, for the same time-period, months, and indices a correlation matrix was computed by using the Pearson's linear correlation coefficient. Statistically significant correlations where then attained with a 5% significance level and are shown without an asterisk in the related figures.

3. Results

In this section, first an assessment of the monthly maximum and mean average values between May and October for several indices between 2001 and 2021 is going to be presented. A comparison between the reference period and 2017 and 2007 is also undertaken. Lastly, the outcomes of the massive wildfire events in 2017, referred to as EWE, which have had two major events that have impacted the central region of Portugal are described. This assessment is going to be performed on a daily basis, namely between June 16th to the 20th and between October 14th to the 16th, 2017. Within these time periods the most catastrophic fire events (owing to the total burned area and human fatalities) have occurred on July 17th (commonly known as the Pedrógão Grande wildfire) and October 15th, 2017 (Table 7). During these two days the total burned area that in the case of October have affected a vast number of urban areas, above 500 kha (Table 7; Figure A1), and were concentrated in the districts of Coimbra, Guarda, Castelo Branco, Leiria, Viseu and Aveiro in the Centre of Portugal (Figure 1).

A comparison between the reference period and 2017 (with extremely high number of fire events) and 2007 (extremely low number of fire events) for the main indices FWI, CHI, KBDI, BI and FDI, for both the maximum and mean monthly average values (Figures 2, A1) depicts these anomalous conditions. Between May and October, all indices revealed for 2017 values above the ones of the reference period (with some exceptions). This difference was particularly relevant for October for all indices either for maximum, or the mean monthly average values. The differences between 2017 and 2007 are quite remarkable for

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October in relation to the reference period for all indices and again for maximum and mean monthly average values.

Table 7. List of the total burned areas (ha) by district on the June 17th and October 15th, 2017 (only the major wildfires were considered) ([52, 53] accessed on 01 February 2022).

Date	District	Urban areas (ha)	Bush areas (ha)	Total burnt area (ha)
17/06	Leiria	30359	0.15	30359.18
	Coimbra	9483.3	8037.64	17521.45
				47880.63
15/10	Coimbra	89638.08	11014.75	111582.2
	Guarda	24836.5	17664.23	47649.22
	Castelo Branco	21290.01	12991.67	35790.34
	Leiria	19283.93	984.3961	20741.06
	Viseu	11969.01	4623.15	18013.13
	Aveiro	8787.079	1875.89	11421.33
				245197.3

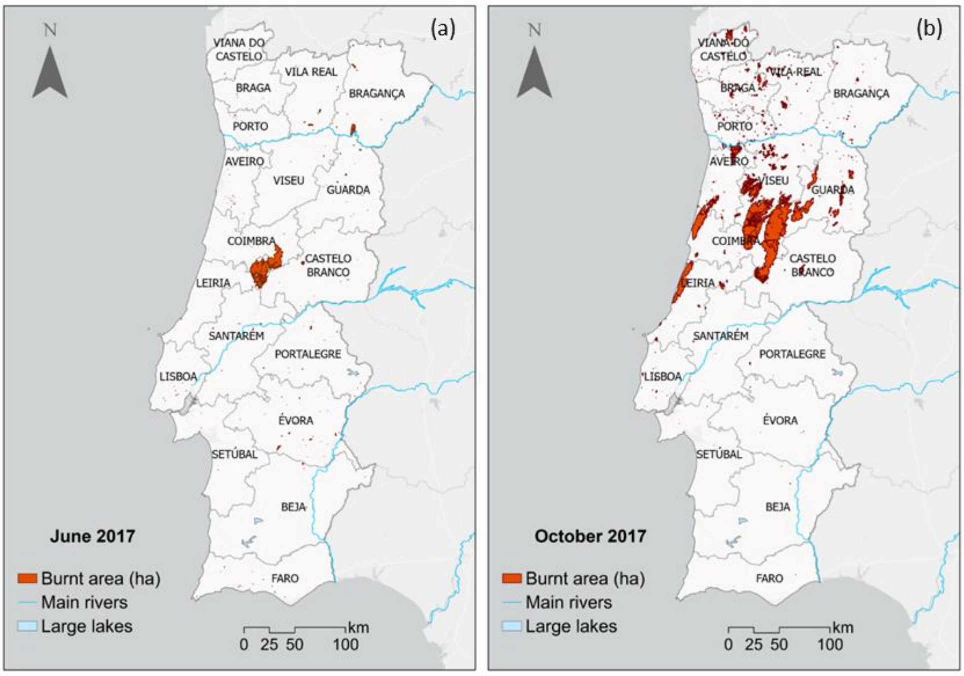

Figure 1. Mainland Portuguese administrative regions (districts) superimposed with the total burned area (a) for June (54 953.2 ha) and (b) October 2017 (313 794.3 ha) (only the major wildfires were considered).

However, the results show interesting variations for the maximum monthly average values of CHI and BI for which the value for 2007 was higher in comparison with 2017 (Figures 2c, 2g). This fact was also depicted for CHI in May (Figures 2c, 2e). Regarding the mean monthly average values, for 2017 the totals are higher in comparison with the reference period, which are higher than the ones observed for 2007 for all indices, except for CHI and BI during May (Figures 2d, 2h).

In this case, the reference period presents higher values when comparing with 2017 and 2007. These results point out to the relevance of using a multi-index methodology to analyze extreme fire events.

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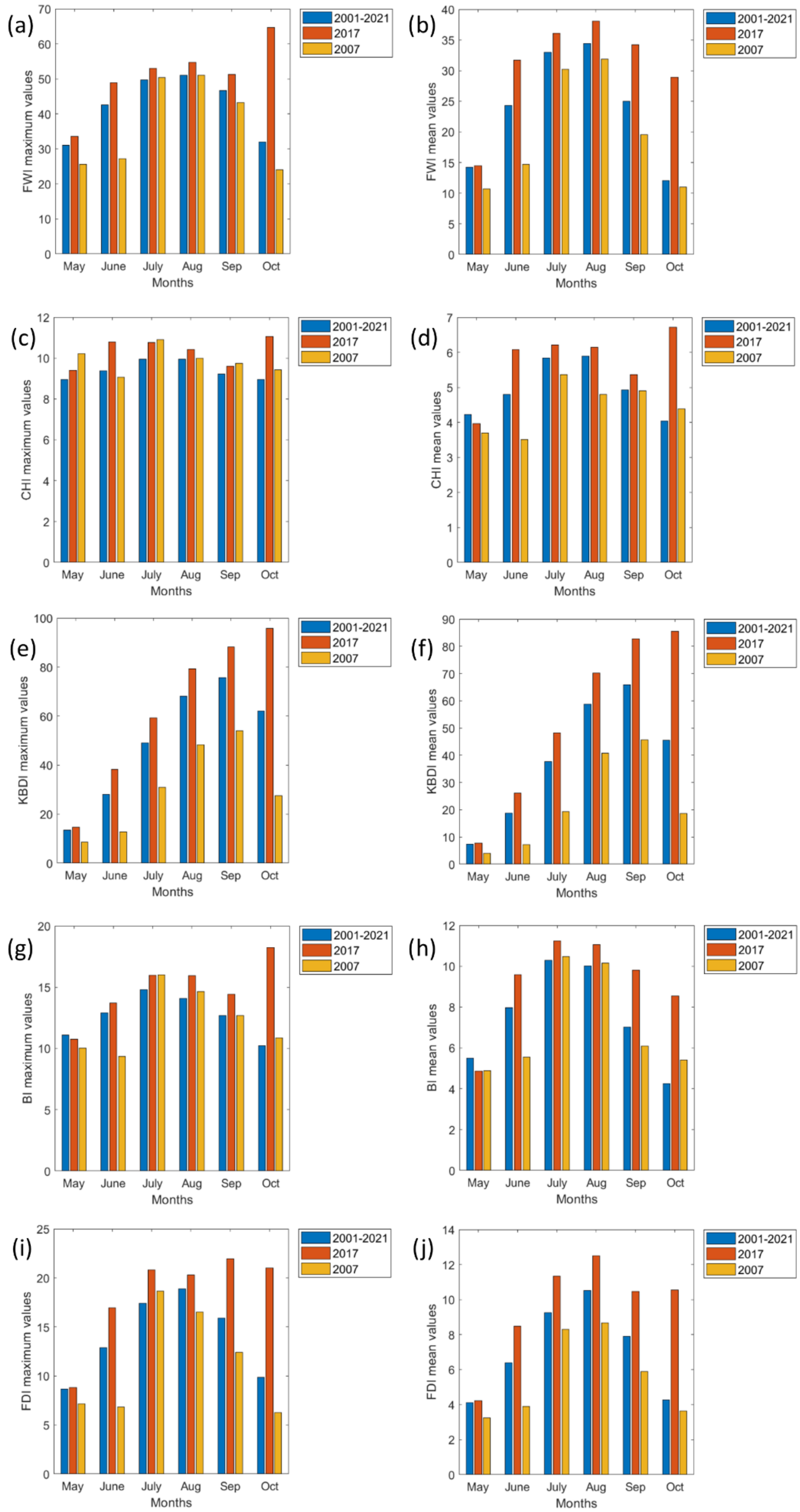

Figure 2. Monthly average values between 2001–2021 (baseline climate) and 2017 for (a, b) FWI, (c, d) CHI, (e, f) KBDI, (g, h) BI and (i, j) FDI for the maximum (left) and mean (right) values, respectively.

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Furthermore, the FWI maximum values for all periods are within the very high class for July, August, and September, and high for June (Figure 2a). Regarding May are moderate for 2007, and high for the remaining period. Lastly, for October are moderate for 2007, high for 2001–2021 and very high for 2017 (Figure 2a). Results show that for the FWI mean values, for May/July are within the low/high class for all periods (Figure 2b). For June, low for 2007, in the transition between moderate to high for the reference period and high danger for 2017. For August for 2017 are in the transition between high to extreme, and high for the remaining periods. For September, for 2007 moderate, 2001-2021 moderate to high and 2017 high danger. Lastly, for October for 2017 high and low for the remaining periods (Figure 2b).

Results show for BI are not highly informative, since only one class can be depicted for both cases and for all months (Figures 2g, 2h). Lastly, for FDI maximum monthly values (Figure 2i) are comprised in the first three classes (low, moderate and high, respectively), whilst for the mean monthly values with the exception of August 2017 (third class) the remaining are in the second, e.g. high danger class (Figure 2j).

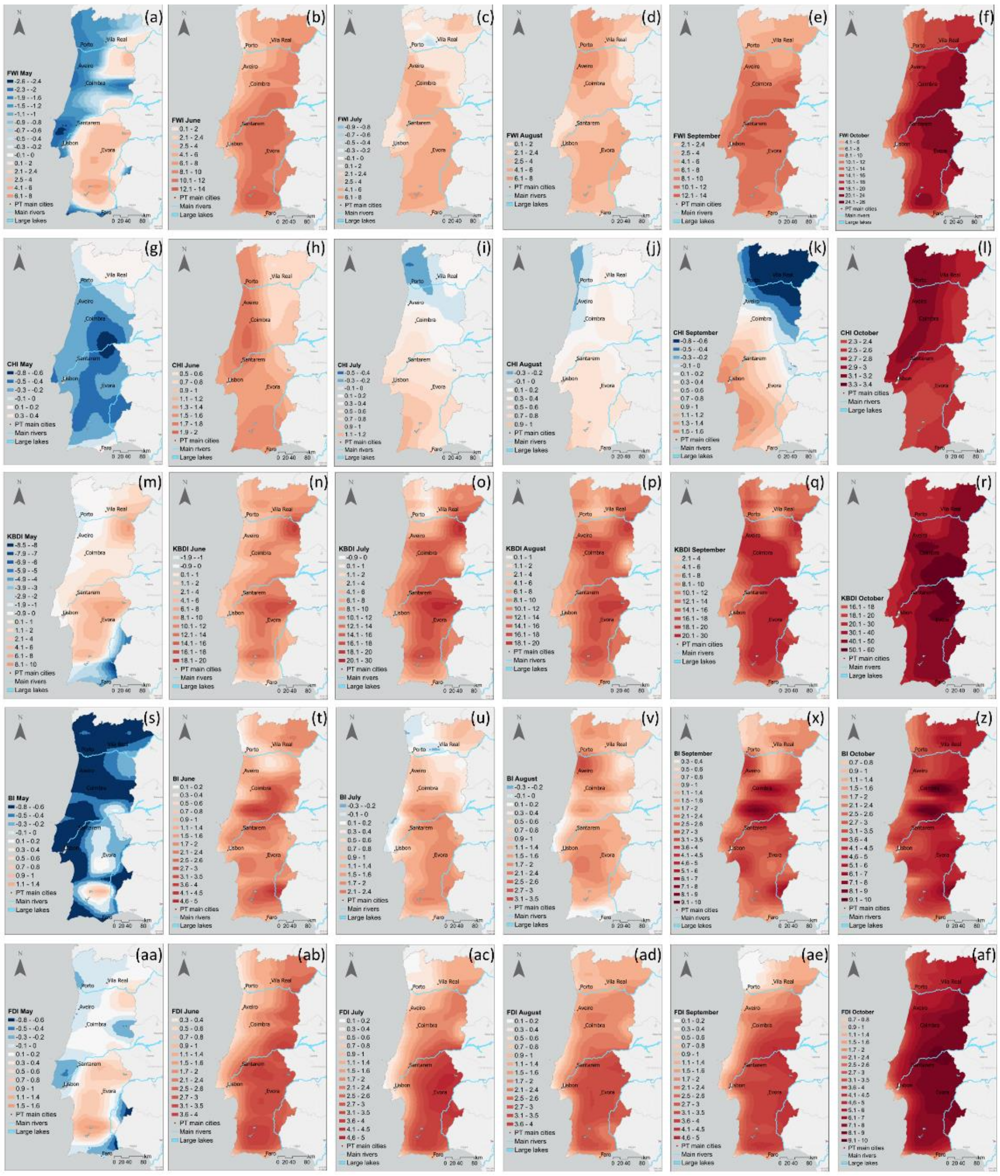

Figure 3. Spatial distribution of the monthly mean anomalies for FWI, CHI, KBDI, FDI, and BI between 2001–2021 (reference period), respectively by row and 2017 for (a, g, m, s, aa) May, (b, h, n, t, ab) June, (c, I, o, u, ac) July, (d, j, p, v, ad) August, (e, k, x, ae) September and (f, l, r, z, af) October (statistically significant at a 5% significance level).

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Results are in clear accordance with the ones previously described. Major positive anomaly values were depicted for October for all indices (Figures 3f – 3af) owing to the fact that 2017 values were above the average in comparison with the reference period. Conversely, May, presents a more heterogeneous spatial distribution with regions with positive and negative anomalies, for which BI (Figure 3s) and CHI (Figure 3g) present negative anomalies almost throughout the country. The northwestern region is the most concordant between all indices with negative anomalies. Moreover, it can also be depicted a similarity in the spatial distribution of May anomalies between FWI (Figure 3a), KBDI (Figure 3m) and FDI (Figure 3aa). For June, with the exception of KBDI (Figure 3n) throughout the country positive anomalies were found. For the remaining months results show a spatial distribution heterogeneity being the positive anomalies prominent. However, for July, negative anomalies can again be depicted in the northern westernmost region of the country (Figures 3b, 3h, 3n, 3t, 3ab). It still worth mentioning that major positive BI anomalies for September and October are located in the areas were the major October wildfire occurred (Figures 3x, 3z).

Since one of the main objectives of this study is to assess the ability of other indices than FWI and CHI to identify conditions prone to the occurrence of wildfires in Portugal, the statistically significant correlations between all indices for 2001–2021 were evaluated for the study area. Results show very high correlations between FWI and FDI/BI for all months, the majority above 0.92/0.94, with the exception of August, with values above 0.89/0.73 (Figure 4d). It is worth mentioned that though statistically significant correlations between FWI and CHI are lower (above 0.68 except for June above 0.51 (Figure 4b)) in comparison with the previous indices (FWI with FDI and BI) but still considered high. Correlations between FWI and KBDI are very heterogeneous, ranging from 0.93 in September (Figure 4e) to 0.55 in August (Figure 4d).

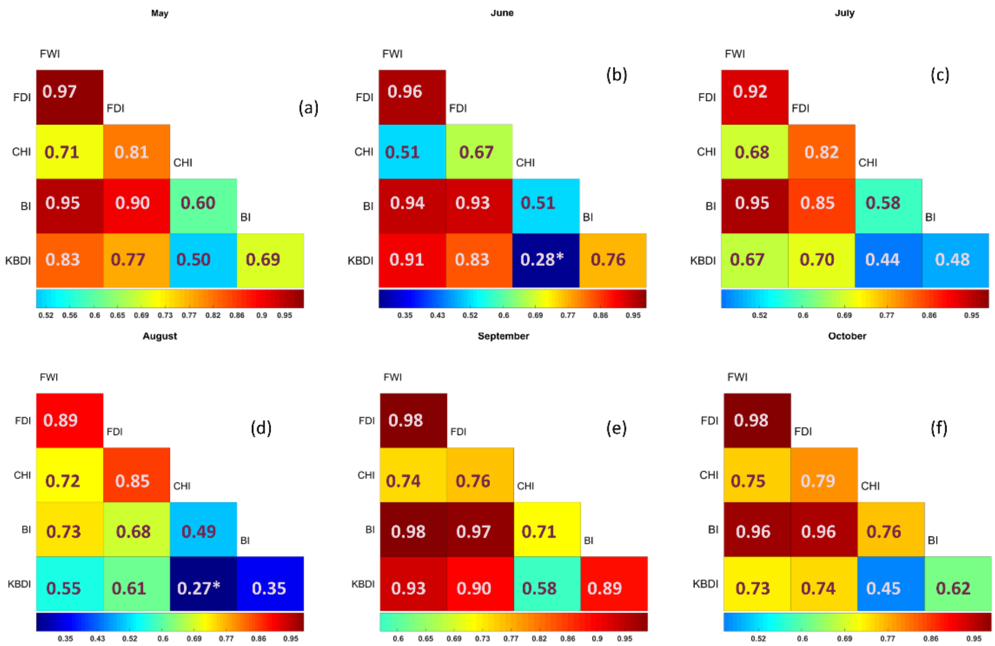

Figure 4. Correlation matrices for FWI, FDI, CHI, BI and KBDI between 2001–2021 (baseline climate) and respective statistically significant correlations for (a) May, (b) June, (c) July, (d) August, (e) September and (f) October (* non-statistically significant at a 5% significance level).

Regarding CHI, results show lower correlations in comparison with the FWI and the related indices. Highest correlations were depicted between CHI and FDI, ranging from 0.85 in August (Figure 4d) to 0.67 in June (Figure 4b). Lower correlations were observed between CHI and BI, ranging from 0.76 in October (Figure 4f) to 0.49 in August (Figure

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4d). Overall, correlations between CHI and KBDI are the lowest among all indices, and non-statistically significant for June (Figure 4b) and August (Figure 4d).

As previously referred, the second part of this study is devoted to the two EWE of 2017, related results are going to be analyzed on a daily scale and are presented herein. Let us remind that the FWI index contains information regarding fuel moisture conditions in the FFMC, DMC and DC codes, consequently the drought situation in June and October of 2017, in Portugal, can be inferred by the high values of the FWI that can be depicted in Figures 5a) – 5e) and Figures 7a) – 7c), respectively. Furthermore, the average value of DC (drought related FWI sub-index) in mainland Portugal, in November 2017, was much higher than the average, being the highest value between 1999 to 2017 (not shown). The average value of the FWI in Portugal was 41.2 (below the 90th percentile) on June 17th and 59.2 (above the 90th percentile), the highest value for 2017 on October 15th.

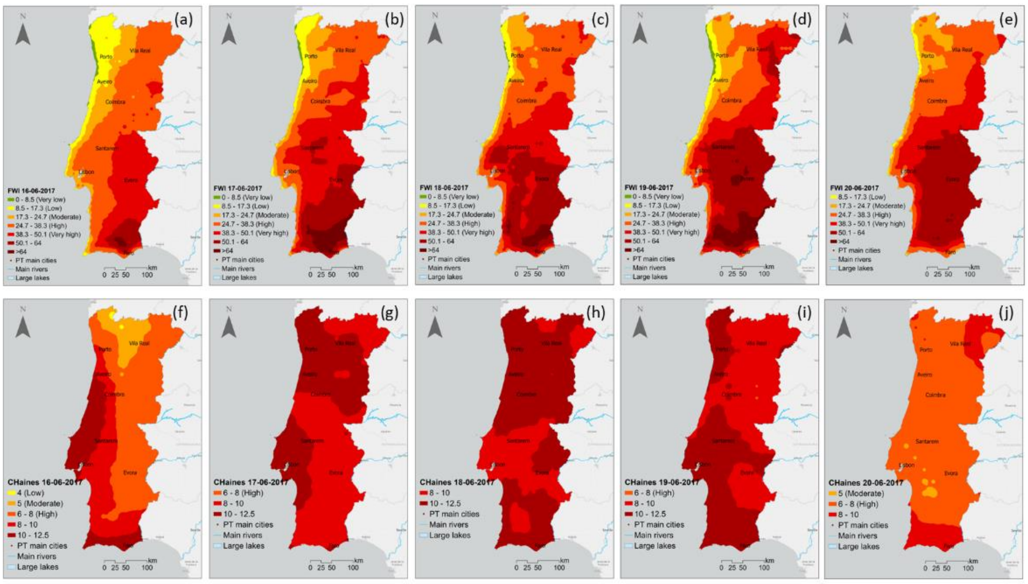

Figure 5. Daily mean values for June (a, f) 16th, (b, g) 17th, (c, h) 18th, (d, i) 19th and (e, j) 20th, 2017, for FWI (upper row) and CHI (lower row).

The assessment of FWI revealed increasing daily values between June 16th until 19th in the central region of Portugal (Figures 5a) – 5d)). This was also depicted for CHI (Figures 5f) – 5h)), and its components linked to instability, namely ca (Figures A4a) – A4d)), and cb associated to the dryness in the lower troposphere (Figures A4f) – A4h)). These factors have contributed to a significant increase in the danger of occurrence of wildfires throughout the country, especially relevant on the afternoon of June 17th, 2017. It is worth mention that this instability give rise to the development of a convective thunderstorm system in the southeastern region of Pedrogão Grande that have produced a large number of lightning [38].

Results show for the KBDI index (Figures 6a) – 6e)), that despite the drought situation that started with a dry spring in 2017, the index only presents values up to 50 in the majority of the territory. Since this was an EWE, the values are not consistent with the actual scale. Therefore, it may be concluded that this index needs to be calibrated for Portugal.

For BI (Figure 6), SC and IC indices (Figure A5), results show that for the same period a significant increase in the central region of Portugal, with the highest values encompassing the region affected by the EWE of June. It can also be concluded that these indices seem to be able to provide additional information that can be useful to identify regions associated to a high danger for the occurrence of rural fires. Results also revealed that the BI index reached values above 30, on June 17th, the highest value registered in the country on that day, in a region eastwards of Coimbra and in a region in the Leiria district (Figures 6f) – 6j); Figure 1a). It is worth mention that the maximum daily average values of BI, in June for the reference period, have fluctuated between 29.9 and 38.5, while in 2017 between 23 and 50.8. The maximum BI value (of 58.125) was observed in 2019 (not shown).

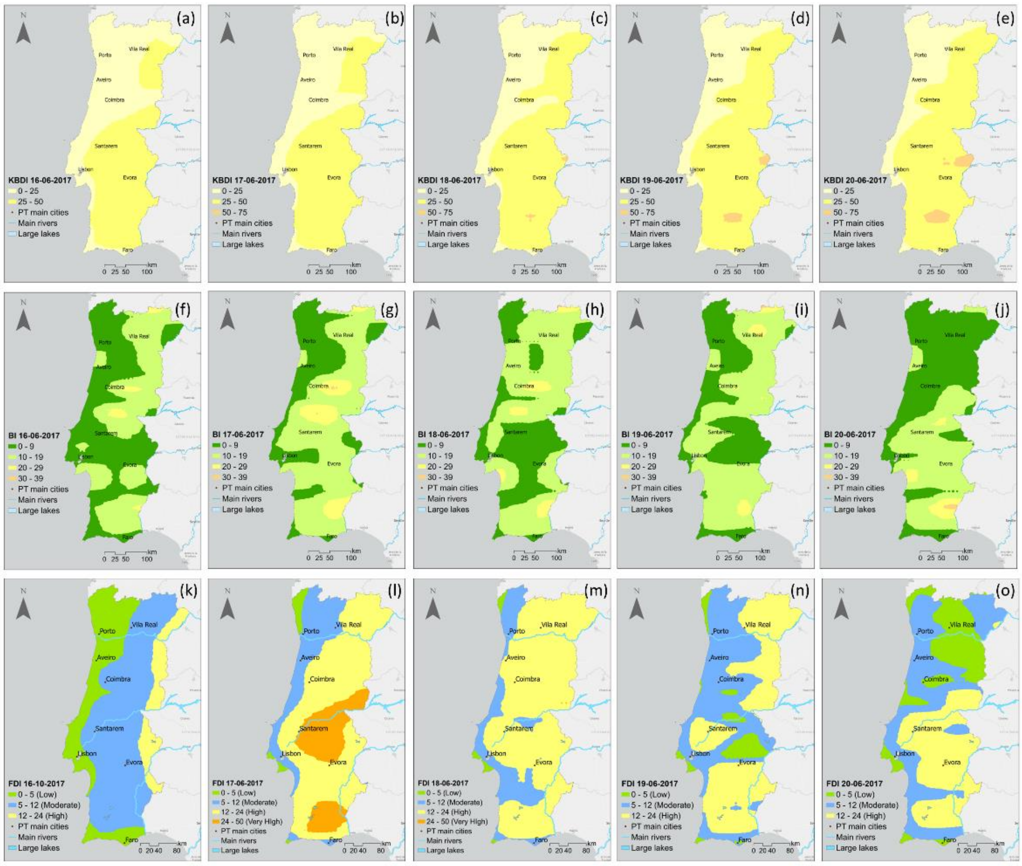

Figure 6. Daily mean values for June (a, f, k) 16th, (b, g, l) 17th, (c, h, m) 18th, (d, i, n) 19th and (e, j, o) 20th 2017, for KBDI (upper row), BI (middle row) and FDI (lower row).

The outcomes revealed that the SC values have significantly increased in the central region of Portugal, again eastwards of Coimbra and in the Leiria district, with the highest values observed on June 18th (Figure A5c). The IC index also showed a significant increase between June 16th and 17th (Figure A5f, A5g) for which the highest values were reached in the vicinity of Pedrogão Grande and Góis regions where the EWE of June has occurred. It is worth emphasizing that the values of these indices are not remarkably high in Portugal, considering the actual scale. On June 17th, the highest values were below 40, which would indicate fires can be attacked at the head or flanks by firefighters using hand tools. Hand line should hold the fire. However, this was not the case in the events in the great fires of Pedrogão Grande and Góis. Also, for the SC and IC indices the values seem quite low for the extreme wildfire event on the June 17th. Again, it may be concluded that also these indices need to be calibrated or re-scaled for Portugal (Figure A5).

The spatial patterns of FDI, reveal a danger variation quite similar to FWI. These results are in clear accordance with the correlations previously analyzed for these indices in the reference period (Figure 4). Between June 16th to 20th, (Figure 6k) – 6o)), a gradual increase in danger from 16 th to 17 th was observed, with values ranging between 22 and 31 (high to very high wildfire danger classes), with the highest values over a vast region in inner center and southern areas (Figure 6l)). Indeed, the increasing values are coupled with an increase in the danger for the occurrence of wildfires. This increase is observed from the coast towards inland, and the behavior of the FDI in the southern regions is clearly as expected within high danger class. In the southernmost regions of Portugal despite the remarkably high FWI values, EWE did not take place. This can be due to the terrain characteristics as well as vegetation type.

After the June 17th (the Pedrogão Grande wildfire), several other fires occurred in Portugal, mainly in the center of the country, but the most severe event took place on October 15th, 2017 (Figure 1b).

Results show that the average values of the FWI in mainland Portugal have gradually increased from October 14th to 15th (Figures 7a) – 7c), having reached the highest value from June to October at 15th. The FWI value, calculated with the ECMWF analyzes, was 62, but values above 80 were observed, consequently, these fires may present serious control problems torching out, crowning, and spotting. In this case, control efforts at the fire head were ineffective also due to the adverse conditions of the terrain and type of vegetation.

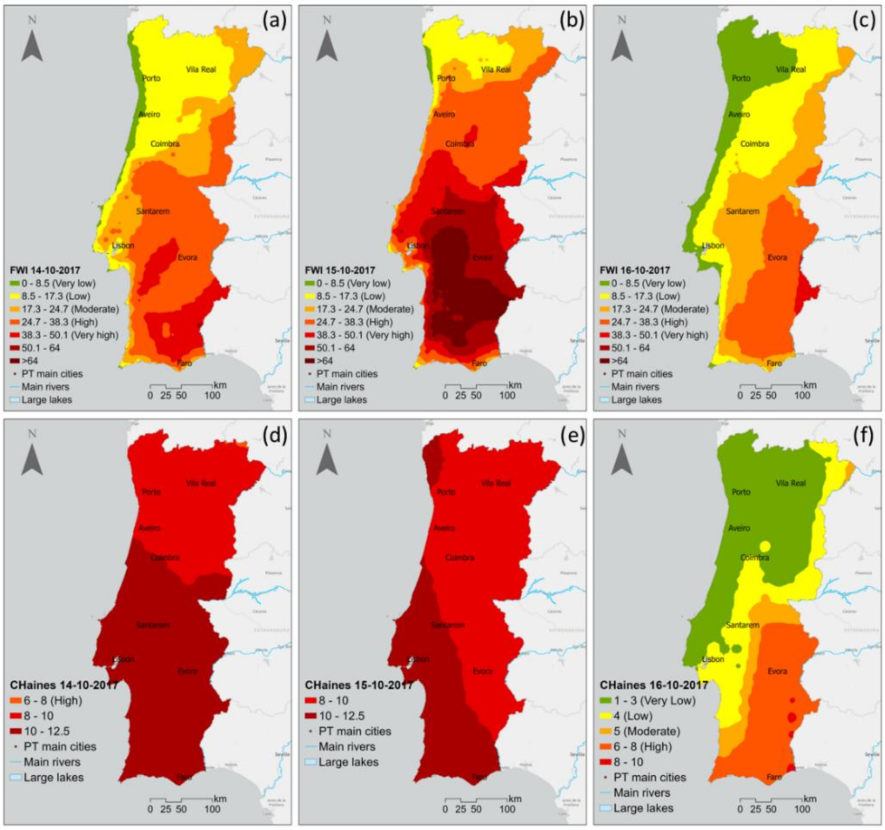

Figure 7. Daily mean values for October (a, d) 14th, (b, e) 15th and (c, f) 17th, 2017, for FWI (upper row) and CHI (lower row).

The CHI index also presented high to very high values, between 8 and 12.5, on October 14th and 15th, decreasing on the 16th (Figures 7d) – 7f)). The component of CHI linked to instability, ca (Figures A6a) – A6c)) showed an increase in severity in the central and northern regions, and a decrease in the southern regions, between October 14th and 17th. The CHI component, linked to moisture in the lowest layer of the troposphere, cb, (Figures A6d) – A6f)) showed higher values in the south; and, lower in the north, with an almost zonal stratification, on October 14th (Figure 7d)) On the 15th, the highest values of CHI were observed on the coast, decreasing towards inland, with a more longitudinal stratification (Figure 7e)). On October 16th results show and overall decrease in all components (Figure 7f)).

Results show for the KBDI (Figures 8a) – 8e)), that despite the drought conditions in October, and the daily variations of the meteorological factors the spatial distributions between October 14th to 16th are quite similar. The index presents values between 100 and

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150 in the inner center and southern territory (Figures 8a) – 8e)). These values portrait the typical conditions of a late summer, early fall. Lower litter and duff layers actively contribute to fire intensity and will actively burn. However, in the surroundings of the major fires KBDI varied between 75 and 125. Since this was an EWE, the values are not entirely consistent, and the actual scale should be adjusted, and the index calibrated for Portugal. It is worth mentioning that the KBDI values for October are substantially higher than the ones attained for the great wildfires in June.

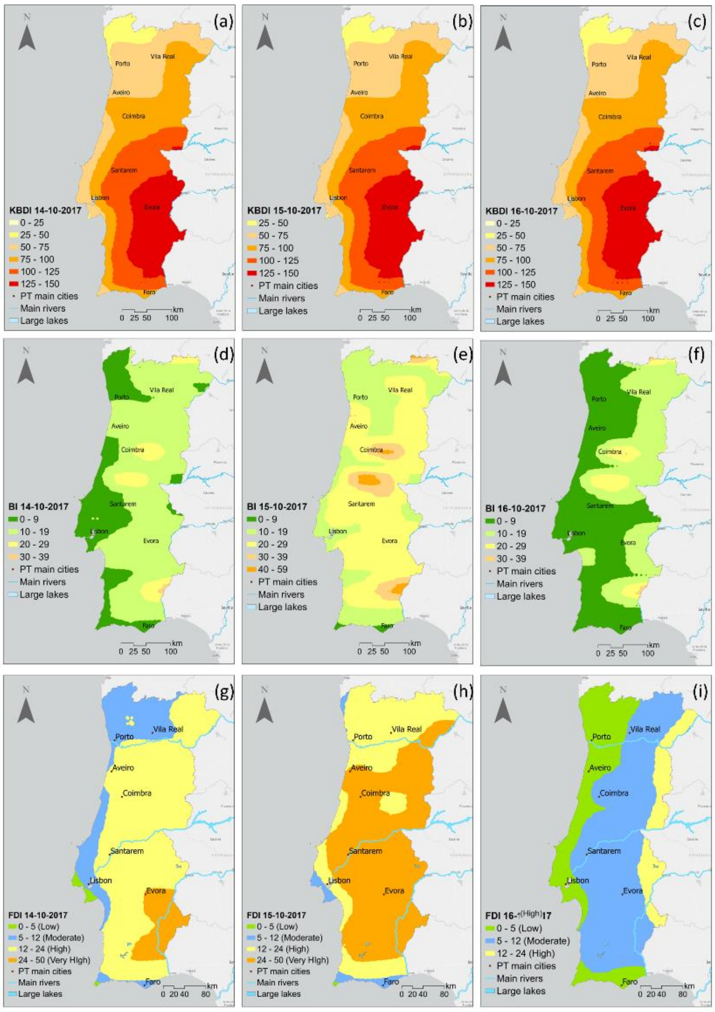

Figure 8. Daily mean values for October (a, d, g) 14th, (b, e, h) 15th, (c, f, i) 16th, 2017, for KBDI (upper row), BI (middle row) and FDI (lower row).

The BI (Figure 8d) – 8f)), SC and IC indices (Figure A7), not normally used in Europe and, particularly in Portugal, showed a similar behavior to the FWI and CHI index. This result is also in clear accordance with the correlations previously presented (Figure 4). In this case, it can be observed a gradual increase of the values from October 14th to 15th, followed by a decrease on the 16th. Major values were depicted in the Center and Southern regions, though in more narrow and defined areas, but close to large, burned areas. This is observed in SC and IC spatial patterns on October 15th (Figures 8b), A7b) – A7e)). On October 15th, 2017, the maximum BI value was 54.104, the highest value observed within the reference period. For the 1st fortnight of October, the BI index values were always well above the average (reference period) for this month. The maximum value of SC in October 2017, with a value of 9.562 took place on 15th, and was the fifth highest value within the reference period series. Results showed for IC, that the maximum value of 54.271 was achieved on October 15th (Figure A7e)). This was the highest value observed within the reference period.

It is still worth mentioning that when comparing the two major EWE in 2017, results showed that for BI, SC and IC higher values were observed on October 15th in relation with June 17th. The BI was above 40, therefore in this case fires are too intense for direct attack on the head by firefighters using hand tools and hand line cannot be relied on to hold fire. The IC exceeded 50 almost every firebrand will trigger a fire that will require action when in contact with a receptive fuel. Lastly, SC exceeded the value 9, which is a measure of the speed at which the head fire will spread. However, due to the known lack of control of the great fires on this day, higher values were expected. Though the location of the areas of occurrence of most of the big fires coincide in locations where these indices reached its highest values, nevertheless a calibration for Portugal is once more advised.

Results showed that the spatial patterns of FDI, reveal again a danger variation quite similar to FWI, which is in clear accordance with the correlations previously analyzed for these indices in the reference period (Figure 4). Between June 14th to 16th, (Figure 8g) – 8i)), a gradual increase in FDI from 14th to 15th was observed, with the highest values ranging between 32 to 39 within the very high wildfire danger class. These maximum values were observed in a major portion of Portugal, particularly in inner central and southern areas, which include the great wildfire of October 15th (Figure 8h)). Moreover, the FDI values for October are higher than the ones attained for the great wildfires in June, and the area within the very high class also much higher. Overall, this index portrays the conditions prone to the occurrence of wildfires.

4. Discussion

The scope of this study was to assess the performance of several fire danger indices for Portugal using as a reference period 2001–2021 and two EWE that have occurred in 2017. To our knowledge only FWI and CHI were used to access the danger conditions to the occurrence of wildfires in Portugal since these are the two operational indices provided by IPMA until this moment.

Drought conditions, especially in Mediterranean countries, are a good example of the relationship between climate and fire [56–58], as the danger of fire rises with increasing droughts their duration and intensity [59]. The drought situation of the year 2017, in Portugal, helps to understand the events of the great wildfires that have occurred that year, bearing in mind, however, that the relationship between drought and wildfires is complex [60]. Actually, there are more factors to take into consideration, besides weather and climate the fuel patterns and the topography of the terrain are the most relevant driven factors in influencing wildfire activity in Portugal [59]. This is one of the reasons for the high concentration of ignitions in the central region of Portugal were the complex topography, the low population density (massively elderly inhabitants) and vast areas of forests with build-up fuel create the perfect settings for propagation linked to very difficult suppression conditions.

The hydrological year 2016/2017 was, in Portugal, the nineth driest since 1931 and the period from April to November 2017 was also the driest since 1931. The dry semester comprised between April to September 2017 was extremely hot and dry, which led to high values of evapotranspiration and significant values of soil moisture deficit ([46], accessed on 01 February 2022). At the end of October and November, the drought situation represented a greater percentage of Portugal's territory in the severe and extreme drought classes (97% of the territory). The maximum temperature presented values above or well above the normal values, especially in April, the second half of June and in the first half of October. During these periods the minimum temperature was above the normal average. These conditions associated to anomalous atmospheric instability in June and the influence of hurricane Ophelia lead to a record of total burned area that can be depicted for June and October in Figures 1a and 1b, respectively. Mainly in October the central region of the country, that encompassed the districts of Coimbra, Guarda, Castelo Branco, Leiria, Viseu and Aveiro, was the most affected, with a total of burned area above 300 kha considering ICNF data and only the major fires or above 500 kha when considering the European Environmental Agency (EEA) [51, 62–63] (Figures 1, A1; Table 7).

The year 2017 presented other extreme weather conditions in June, such as a severe heat wave and remarkably high atmospheric instability conditions [64–66]. The moisture content of fine fuels measured near the Lousã station was 7% [64] which is consistent with extreme fire danger. These conditions impacted FWI and CHI indices.

The ability to supply adequate spatial and temporal forecasts of the potential danger of forest fire ignition and spread is vital. In Portugal the most used index is FWI, that uses surface weather variables. CHI is now also operationally used by IPMA, and in this case provide further information since it is attained from variables at difference pressure levels. This fact helps explain why the correlations between FWI and CHI were not as high as the ones attained for FWI in relation with FDI and BI (Figure 4). However, since current forecasting is limited and mainly based on a few meteorological variables, the use of other indices proves to be useful.

This is the case of CHI, that even when the meteorological variables, fuel and orography are steady conditions, atmospheric instability along with a dry environment aloft can promote the spread of a wildfire. In fact, the generation of convective heat columns within and around the smoke plume, promotes strong air currents which in turn can ignite new fires, and therefore new fronts [67, 37, 38]. This was the case of the Pedrogão Grande wildfire of June, and the results attained are in clear accordance with the findings of Pinto et al. [38] (Figures 5f–5j) regarding the relevance of the atmospheric instability in this EWE.

Conversely, KBDI was designed as a drought index to assess the fire potential [46]. As such, it represents the net evapotranspiration and precipitation in producing cumulative moisture deficiency in deep duff and upper soil layers. Therefore, this index is related to the flammability of organic material in the land. In this study the results attained for KBDI are in clear accordance with the climatological conditions, with lower values for June (Figures 5a–5e) and higher for October (Figures 7a–7c), thus translating the drought conditions. Indeed, the autumn period (from September to November) normally presents a considerable increase in precipitation, which did not take place in 2017. The months of September and October were extremely dry (record breaking-drought in October) and this month was classified as extremely hot, especially the first fortnight. Besides these long-term factors, weather conditions, with the influence of the hurricane Ophelia, that have induced a very strong southerly wind that have transported hot and dry air from North Africa over the majority of the territory, contributed to increase fire danger. These conditions led to a record number of wildfires and the largest burnt area in a single day in Portugal on October 15th. It is still worth mentioning that since this index assumes a ranging between 0 to 200 to express the precipitation necessary in order to the soil return to saturation conditions a calibration having in mind the precipitation regime in Portugal and a new scale is advise. This is a current practice in the USA due to the size of the country that encompasses high climatic, vegetation, orographic contrasts, among other different factors. In this case the United States Forest Services (USFS) and, in particular, the Wildland Fire Assessment System (WFAS) provide regional fire danger rating systems in the USA ([68], accessed on 13 March 2022). This is also the case of the BI, that provides an estimate of the potential difficulty in containing a fire since it relates to the flame length at the head of the fire. The BI also reflects the changes in fine fuel moisture content and wind speed, thus being highly variable on a daily basis. Therefore is more appropriate for short-term forecast of fire danger whilts KBI is for long-term. Furthermore, BI is a function of the ERC and SC (Figure A2) which is proportional to the spread rate. The outcomes for BI point out to a calibration since for 2017 for both EWE the values observed remain below 40 (first class) for June (Figures 5f–7j) and only for October 15th above 40 in the surroundings of the areas affected by the major fire occurrences (Figure 7e). Therefore, when properly calibrated it can be a useful tool for wildfire forecasting and fire attack planning, since it presents an amount for the effort needed to contain a fire for a specified fuel type. In this study, we have opted to use the NFDRS scale, however, the American

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Meteorological Society (AMS) defines a different scale for BI ranging from 1 to 100: from 1–11 no fire danger; 12–35 medium danger and 40–100 high danger. This scale provides further detail in the first class (Table 4), though the interpretation remains the same. Jolly et al. [69], have presented a severe fire danger index attained from ERC and BI percentiles, along with a previous normalization of the data. This technique might be useful in a future work thus helping to adjust BI and other indices to Portugal, since the conversion of absolute values into percentiles considers the local climatology and therefore simplifies comparisons between regions.

Lastly, the FDI provides information related to the chances of a fire starting, its rate of spread, its intensity, and difficulty of supression. This is performed by several combinations of air temperature, relative humitity, wind speed along with short and long-term droughts conditions. This fact helps explaining the statistically high correlations between the FDI and the FWI (Figure 4) as well as similar spatial patterns mainly for the October EWE (Figures 7a–7c; 8g–8i). This results is in clear accordance with the ones referenced in the Technical Report of Dowdy et al. [42] that has compared the performance of these two indices.

Overall, the definition of adequate thresholds for the several danger indices for mainland Portugal, and the combination of different metrics will provide further information that can be used to support decision-making and help create a Fire Behavior Prediction System more complete than the one that is now implemented. This System should also be able to further enhance the ability of tracking and predicting unique EWE, since the shortcomings of some indices are compensated by the information retrieved by others as shown in this study.

5. Conclusions

This study allowed to conclude the advantages of using a multi-index's approach to forecast EWE. Results showed that the maximum and mean monthly average values for all indices when comparing the reference period with 2017 and 2007 (low number of fire events) for 2017 were well above the average, mainly in October (Figure 2). The mean monthly anomalies presented lower values for June, whilst for October high positive anomalies mainly for October (Figure 3). It is worth noting that the highest positive anomalies for BI were located in the areas where the major events of June (Figure 3t) and October (Figure 3z) have occurred. Moreover, in September these anomalies are already depicted though with lower values (Figure 3x). This analysis also allowed to perceive the maximum threshold for each index in order to assess its ability to predict the wildfire danger in Portugal.

High statistically significant correlations were also observed between the FWI, FDI and BI, though lower between all indices in August. Worth notice, were the lower but still rather high correlations depicted between FWI and CHI though the nature of these indices is completely different (Figure 4). Also, there is a large interannual variability in the number of occurrences of wildfires in Portugal (Figure A1), strongly determined by meteorological conditions, but unfortunately, also by human intervention (ignition by humans either accidental or intentional).

The outcomes also allow to conclude that the spatial distribution of FDI has the best performance in capturing the locations of the occurrence of the two EWEs' (Figures 6, 8). The higher IC values for October clearly portrays the areas affected by the October 15th wildfires (Figure A7e) with high values (30 – 59 %) pointing out to a high effort to suppress it. The spatial patterns for SC also indicate high values associated to high velocities in the spread of these fires (Figure A7b) for the same target areas. Though the remaining indices are informative, they lack some accuracy that can be achieved with a calibration procedure, as aforementioned.

Overall, the implementation of a multi-index's methodology might be a highly relevant tool for Portugal, whose complex orography and land cover, along with the projected increase in temperatures and intensification in duration and frequency of drought conditions [70–71] will lead to an increase in conditions prone to the occurrence of EWE. A new forecast system can help ensuring the development of appropriate spatial preparedness plans, proactive responses by the civil protection regarding firefighter's management, suppression efforts, and alert communities in order to minimize the detrimental impacts of wildfires in Portugal. Lastly, the forecast of the spatial distribution of these events can also be a key factor for a better land management policy, as well as the planning of the country's forest cover (more fire resilient species), which should consider prescribed burning techniques (small scale operations) in locations considered critical [72–73] in order to reduce the existing build-up load and thus the intensity of future fires.

Author Contributions: "Conceptualization, C.A. and L.B.; methodology, CA and L.B.; software, C.A. and L.B.; validation, C.A. and L.B.; formal analysis, C.A. and L.B.; investigation, C.A. and L.B.; resources, C.A. and L.B.; data curation, C.A. and L.B.; writing—original draft preparation, C.A. and L.B.; writing—review and editing, C.A. and L.B.; visualization, C.A.; supervision, C.A. and L.B; funding acquisition, C.A. All authors have read and agreed to the published version of the manuscript."

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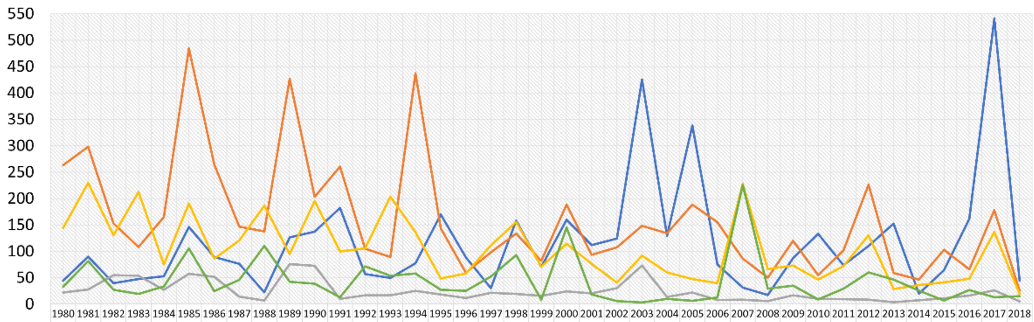
Conflicts of Interest: The authors declare no conflict of interest.

Appendix A



	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Portugal	44,3	89,8	39,6	47,8	52,7	146	89,5	76,3	22,4	126	137	182	57	50	77,3	170	88,9	30,5	158	70,6	160
Spain	263	298	153	108	165	484	265	147	138	427	203	260	105	89,3	438	143	59,8	98,5	134	82,2	189
France	22,2	27,7	55,1	53,7	27,2	57,4	51,9	14,1	6,7	75,6	72,6	10,1	16,6	16,7	25	18,1	11,4	21,6	19,3	15,9	24,1
Italy	144	230	130	213	75,3	191	86,4	121	186	95,2	195	99,9	106	204	136	48,9	58	111	156	71,1	115
Greece	33	81,4	27,4	19,6	33,7	105	24,5	46,3	111	42,4	38,6	13	71,4	54	57,9	27,2	25,3	52,4	92,9	8,29	145

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Portugal	112	124	426	130	338	75,5	31,5	17,2	87,4	133	73,8	110	153	19,9	64,4	162	541	44,6
Spain	93,3	107	148	134	189	155	86,1	50,3	120	54,8	102	226	59	46,7	103	65,8	178	25,2
France	20,6	30,2	73,3	13,7	22,1	7,84	8,57	6	17	10,3	9,4	8,6	3,61	7,49	11,2	16,1	26,4	5,12
Italy	76,4	40,8	91,8	60,2	47,6	39,9	228	66,3	73,4	46,5	72	131	29,1	36,1	41,5	47,9	137	19,5
Greece	18,2	6,01	3,52	10,3	6,44	12,7	226	29,2	35,3	8,97	29,1	59,9	46,7	25,8	7,1	26,5	13,4	15,5

Figure A1. Total burned area (ha) between 1980 and 2018 for Portugal, Spain, France, Italy and Greece (Data retrieved from EEA, https://www.eea.europa.eu/ims/forest-fires-in-europe accessed on 01 February 2022).

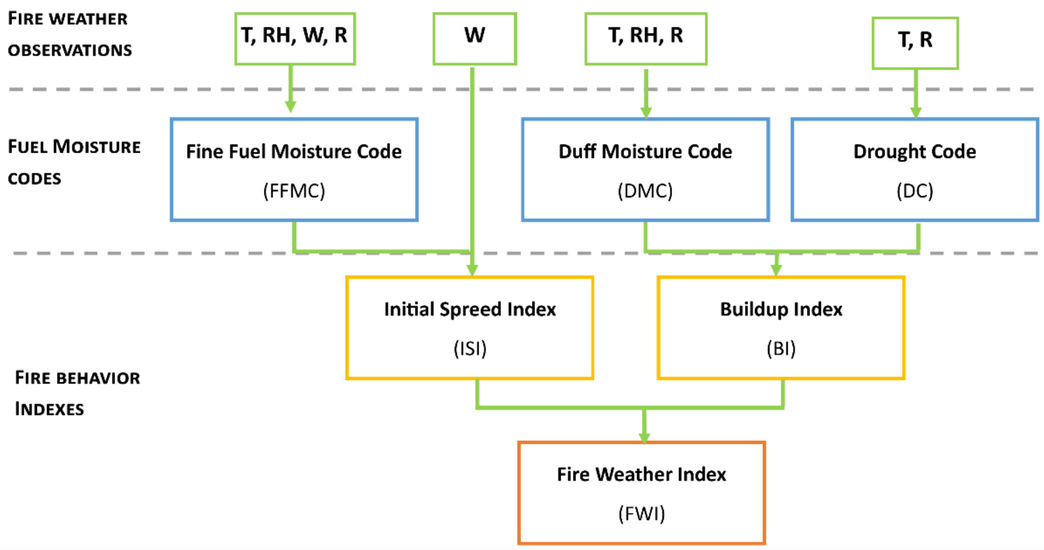


Figure A2. Fire weather schematics in which T (°C) is the air temperature, RH (%) the relative humidity, W wind speed (km/h) and R (mm) rain (adopted from [27]).

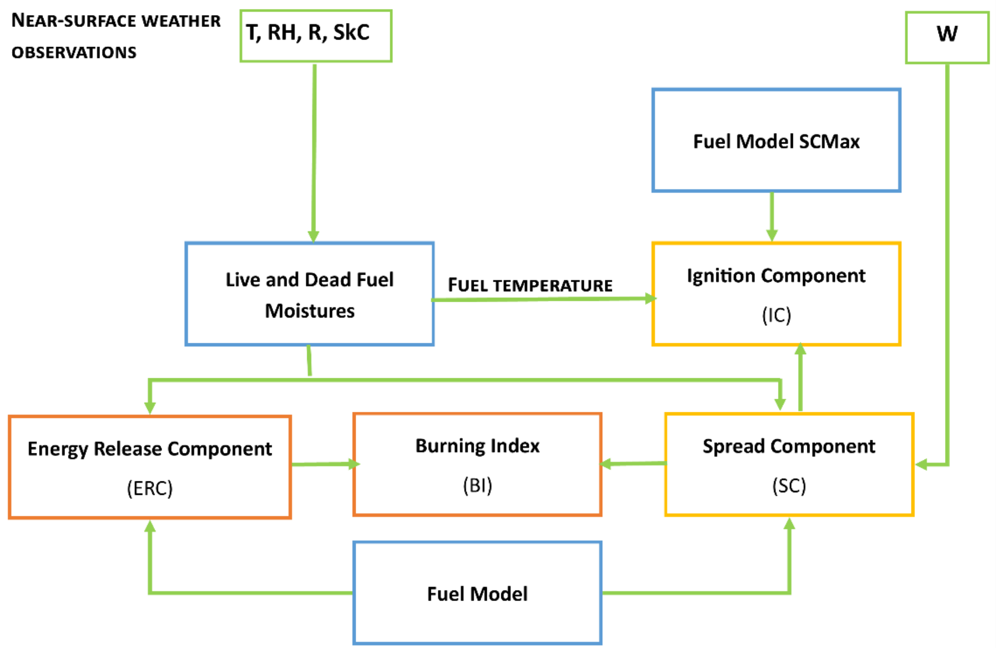


Figure A3. United States National Fire Danger Rating System schematics in which T (°C) is the air temperature, RH (%) the relative humidity, W wind speed (km/h), R (mm) rain and SkC the sky cover (Radiation).

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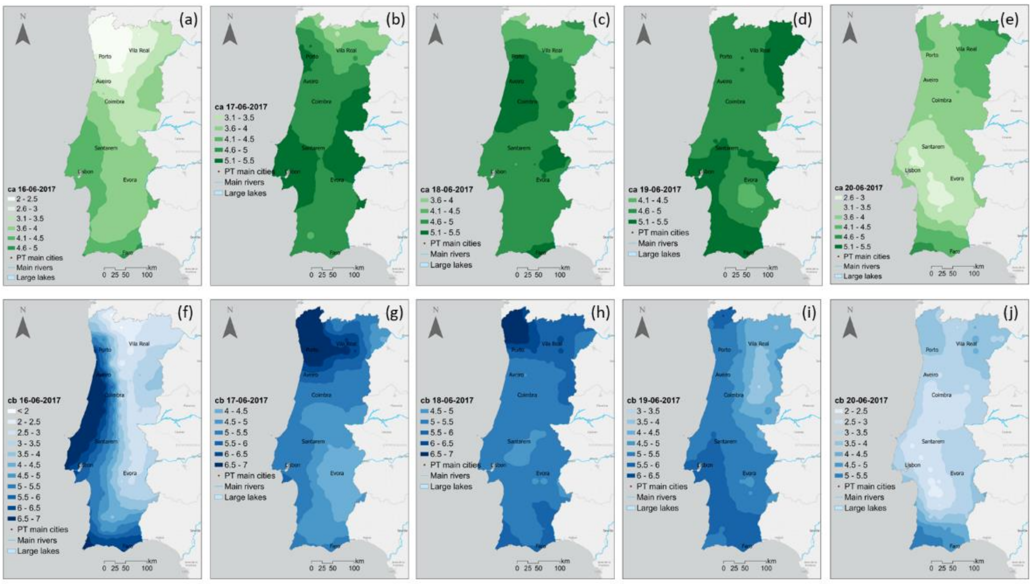

Figure A4. Daily mean values for June (a, f) 16th, (b, g) 17th, (c, h) 18th, (d, i) 19th and (e, j) 20th 2017, for ca (upper row) and cb (lower row).

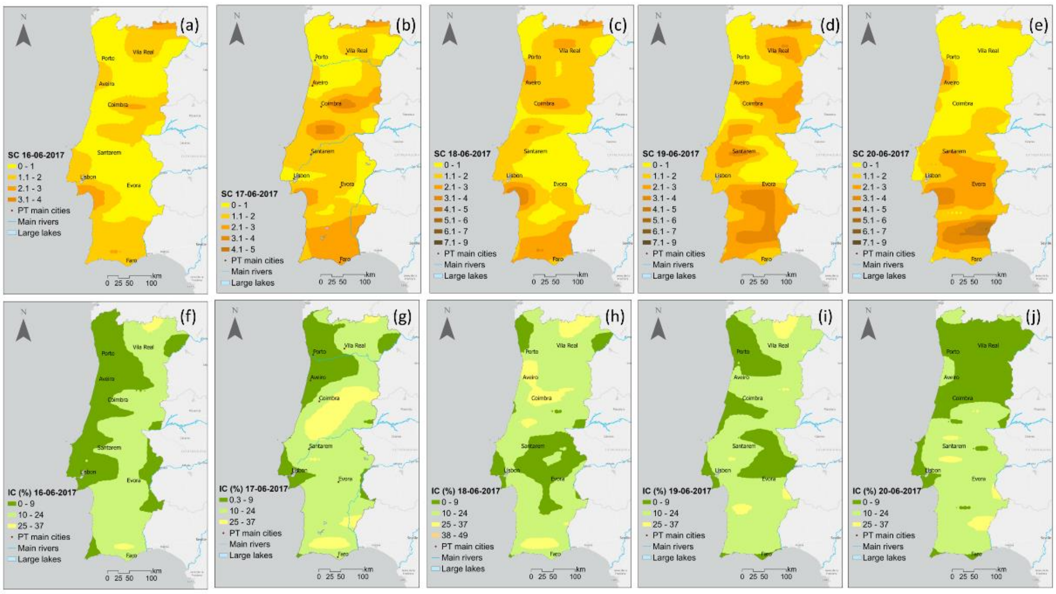

Figure A5. Daily mean values for June (a, f) 16th, (b, g) 17th, (c, h) 18th, (d, i) 19th and (e, j) 20th 2017, for SC (upper row), and IC (lower row).

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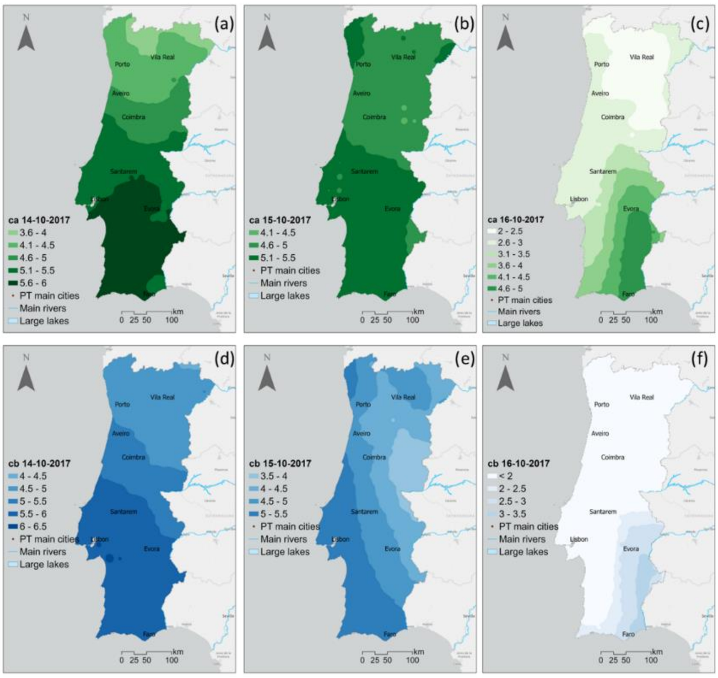

Figure A6. Daily mean values for October (a, d) 14th, (b, c) 15th and (c, f) 16th, 2017, for ca (upper row) and cb (lower row).

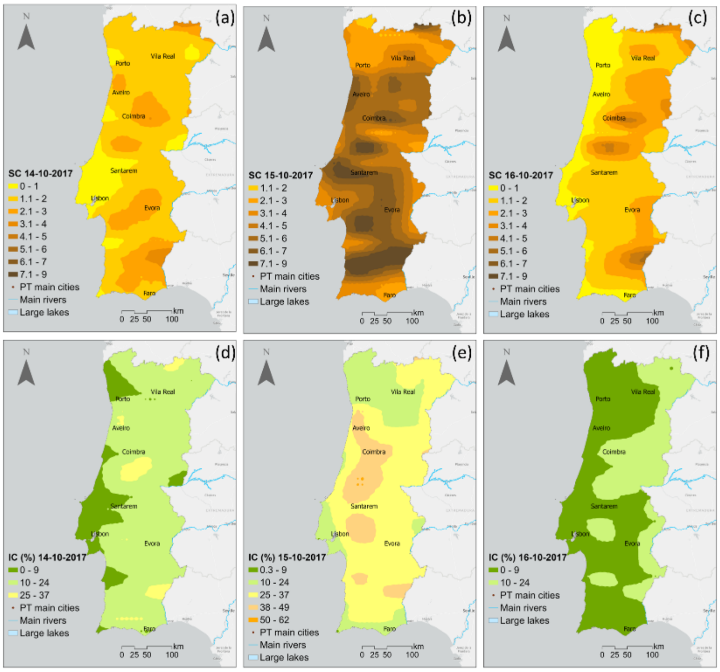

Figure A7. Daily mean values for October (a, d) 14th, (b, e) 15th, (c, f) 16th, 2017, for SC (upper row), and IC (lower row).

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