ADVANCES IN FOREST FIRE RESEARCH 2022

Edited by
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Large Fires in Portugal and Synoptic Circulation Patterns: Meteorological parameters and fire danger indices associated to Critical Weather Types

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Keywords :

Circulation Weather Types (WT), Critical Days, Critical Weather Type, Large Fires, NUT III

Abstract

Large fires in Portugal, with a daily burned area equal to or greater than 3000 ha for the entire territory, tend to occur under specific circulation patterns. The severity of the meteorological conditions, expressed by the magnitude of the meteorological parameters anomaly and fire danger indices, associated with these patterns, could be an important tool to enable earlier forecast of fire weather conditions, being a useful support for decision making. However, there are some regional differences that we intend to analyze at NUT III level, contributing to a forecast with greater detail and oriented to support the fight and prevention of forest fires in Portugal. At NUT III level, we considered as Large Fires the 97th percentile of mean burned area of all NUT III, corresponding more or less to 300 ha of daily burned area. To link the synoptic circulation patterns with Large Fires, ten groups or clusters of NUT III were considered and four classes of normalized daily burned area in each NUT III or cluster of NUT III were considered. The six critical Weather Types (WTs) identified (North-easterly, Easterly, Anticyclonic Easterly Quadrant, Cyclonic Easterly, Quadrant, Northerly and Anticyclonic) exhibit distinctive circulation characteristics and mean values and anomalies of the meteorological parameters. The spatial distribution of Large Fires showed preferred regions for some of these WTs. The mean value of the Fire Weather Index (FWI) was computed for each WTs and for Critical Days (days with burned area equal or greater than 300 ha in each NUT III), using the WRF (Weather Research and Forecasting) mesoscale model. The mean value of FWI for each NUT III or cluster of NUT III, showed a few differences according to the WT and region. These values, can thus be taken as historical indicators at regional level of the likelihood of a large fire occurring.

1. Introduction

Large fires are responsible for very significant percentages of burned area every year. In Portugal 92% of the annual burned area is on average consumed during the period June to October, especially in July to September (82%) (Carmo *et al*, 2021). However, even during the fire season, most of the burned area occurs within a few days, these days designated as spread-event days (Lagerquist *et al* (2017), Flanning *et al* (2000), Flanning *et al* 2013). Several studies have pointed out the occurrence of these days associated to specific circulation patterns and associated to weather conditions (Crimmins (2006), Skinner *et al* (2002), Pereira et al (2005), Calheiros *et al* (2020), Duane *et al* (2018), (Dimitrakopoulos *et al* 2011). In the framework of the FireStorm project, a methodology based on circulation weather patterns (Trigo *et al*., 2000) was applied to provide a detailed description of the meteorological conditions during these events in Portugal. This methodology has already been applied to the entire Portuguese territory (Carmo *et al*, 2021). However, some differences amongst the regions of mainland Portugal are expected which can be more significant in certain synoptic patterns and regions. In the present study our goal is to use this methodology to obtain a finer analysis at the regional level of the administrative regions known as NUT III or aggregations of NUT III. Although circulation patterns describe synoptic-scale meteorological phenomena, they imply differences at smaller scales which are associated with fire spread and fire behaviour. The goal of this work is to relate the large fires at the regional level, with the synoptic circulation patterns and search for regional thresholds on the anomalies of the most relevant meteorological parameters and on the values of the Fire Weather index (FWI) and corresponding sub-indices of the Canadian System. Those thresholds could be good tools to establish a warning system that enable an earlier forecast of fire weather.

2. Large Fires in Portugal and Circulation patterns

2.1. Methodology and Data

To determine the relationship between synoptic circulation patterns and large fires, four classes of daily burned area were established, with the burned area being normalized by each NUT III area, whose distribution in each class was based on the daily time series of burned areas above 1 ha, in Portugal mainland from 1980 to 2018 (Table 1). The cases of fires in the class of burned area equal to or greater than 300 ha were considered as LF. These cases correspond to the 99th percentile if the normalized area is considered or the 97th percentile if the average of the burned area in all NUTS III is considered**.** The days with burned area equal to or greater than 300 ha in each NUT III are critical days and each event is associated with a circulation synoptic pattern.

These cases have been associated to mean values and anomalies, of the meteorological parameters, computed using ERA 5 (fifth generation ECMWF Reanalysis) or with the numerical weather prediction model, WRF (Weather Research and Forecasting). The Fire data was obtained from ICNF (2020) and adapted by (Carmo *et al* 2021).

Table 1 – Daily classification according to burned area.

Class ID	Burned area class (ha)	Number of Cases	Number of Cases (%)
1	< 100	45278	95.5
2	[100, 300 [	1434	3.0
3	[300, 1000 [	524	1.1
4	> 1000	194	0.4

2.2. Weather Types and daily burned area classes

The Weather Types (WTs) were built using the methodology of Circulation Weather Pattern (Trigo *et al*, 2000) which is based on computation of a set of indices of the direction and vorticity of geostrophic flow, either pure or hybrid. Here we used a version with 18 weather types: i) 8 directional ii) 2 pure rotational (anticyclonic and cyclonic) and iii) 8 hybrid (4 anticyclonic and 4 Cyclonic). The distribution of the 18 WT shows high frequency of directional WT (56.6%), with NE being the most frequent (20%). The anticyclonic weather types have 32.2%, with the pure anticyclonic WT A the most frequent (17.7%). The cyclonic weather types have a frequency of 11.2%.

2.3. Critical Days and Critical Weather Types

In the fire data series under study (1980-2018), 409 critical days were found throughout the territory, with a much higher frequency (43%) associated with the WT NE, which is one of the most frequent during summer in Portugal. To find out the statistical significance of the predominance of a given WT on critical days, the Chi-square test between observed and expected days within each WT was computed. Three WTs with more significance (p-value< 0.001) and with more cases observed than expected at national level were confirmed: CQE, E, NE (Table 2).

Table 2 – Chi square tests between observed and expected critical days for 9 weather types. In bold p-values (<0.001) and underlined WTs with more critical days than would be expected by chance alone.

Weather Types	**NE**	**E**	**CQE**	**A**	**N**
Summer days **(Critical days)**	1191 **(176)**	247 **(48)**	103 **(19)**	1057 **(31)**	960 **(46)**
χ^2	**<u>< 0.001</u>**	**<u>< 0.001</u>**	**<u>< 0.001</u>**	**< 0.001**	**< 0.001**
	AQE	**AQN**	**CQN**	**C**	
Summer days **(Critical days)**	114 **(11)**	544 **(22)**	96 **(4)**	385 **(24)**	
χ^2	<u>0.25</u>	0.009	0.3	0.6	

This methodology was applied to the Portuguese administrative regions at NUT III level. In order to obtain groups of NUTs III with similar large fire regime, cluster analysis was used for the daily classes of burned area.

The K-means cluster analysis was used, but considering a subjective adjustment to ensure geographic consistency. Ten clusters of NUT III were taken (Table 3*)*.

Table 3 - NUT III Clusters.

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**
NUT III	Minho (111) Cávado (112)	Ave (119) Alto Tâmega (11B)	A.M. Porto (11A) Tâmega Sousa (11C)	Trás-os-Montes (11E) Douro (11D)	Aveiro (16D) Viseu D. L. (16G)
	Cluster 6	**Cluster 7**	**Cluster 8**	**Cluster 9**	**Cluster 10**
NUT III	S. Estrela (16J) Beira Baixa (16H)	Coimbra (16E) Leiria (16F) Médio Tejo (16I)	Oeste (16B) A.M. Lisboa (170)	Lezíria Tejo (185) Alto Alentejo (186) Alentejo Centr (187)	Alentejo Lit.(181) Bx. Alentejo (184) Algarve (150)

2.4. Description of the Critical Weather Types

In Figure 1 the most relevant synoptic patterns related with large fires in Portugal are presented. Figure 1and Table 4, highlight the main meteorological characteristics associated with the aforementioned synoptic circulation patterns. These patterns jointly with Iberian thermal low (TL) and the adjustment to local and regional factors, create the weather conditions that can lead to the occurrence of large fires.

The North-easterly flow WT (NE): it is identified by a high pressure system over Atlantic, located at northwest of Coruña (The North Atlantic Block, Kautz *et al*, 2021), extending in ridge to the western Mediterranean, and the TL centered in southwestern Iberia, defining a northeast flow with a warm and dry air mass over mainland Portugal.

The Easterly flow WT (E): this WT results from a block settled over Western Europe with the Azores high located north of Iberia. In low level, the Morocco´s TL, extending to north over southwestern Iberia defining an east flow with a warm and very dry air mass over the Portuguese territory. This WT, together with AQE (Anticyclonic Easterly Quadrant flow), have the highest, warmest and driest air mass in low and middle troposphere, followed by NE (Table 4).

The Northerly flow WT (N): it is identified by the Azores high located over Azores Islands and the TL located in central part of Spain. In this WT the influence of the sea breeze is well marked. This WT has the coldest and wet air mass, among these six WT, followed by CQE (Table 4).

The Cyclonic Easterly Quadrant flow WT (CQE): it is identified by a high north of Azores and a low system located southeast, breaking the zonal flow (cut-off). At low levels, a low is centered south/southwest of Algarve, defining an east quadrant flow with a warm and slightly wetter air mass over Portugal (Table 4).

The Anticyclonic Easterly Quadrant flow WT (AQE): It is very similar to E, but with the high located a little further south (over western Bay Biscay) resulting in a greater pressure gradient over Portugal.

The Anticyclonic WT (A), "The Sub- tropical Ridge"**:** it is identified by a high over the Azores - Madeira region, extending to northwestern Iberia and a low system over Greenland and UK, defining a zonal flow to the north of Iberia. This pattern, combined with TL, defines a northwest flow over Portugal. This WT exhibits average properties close to the normal Portuguese summer (Table 4).

The southerly or southeasterly patterns with intrusion of Saharan air over Iberia, are very adverse patterns for wildfires, but they are very rare (about 2%) in the Portuguese summer.

Table 4 – Meteorological parameters of critical weather types: ERA 5 mean values at 12 UTC of geopotential height at 500 hPa (Z500), temperature and relative humidity at 850 hPa (T850 and HR850). WRF data, mean monthly anomalies (June to October), 2 m minimum temperature (Tm), 2m maximum temperature (Tx), and 2 m minimum relative humidity (HRm).

Data	Parameter	Critical weather types					
		NE	**E**	**CQE**	**AQE**	**N**	**A**
Mean Values (ERA5)	Z500 (m)	5849	5886	5844	5887	5808	5854
	T850 (°C)	17	18	17	17	14	14
	HR 850 (%)	45	39	48	39	54	49
Anomalies (WRF)	Tm (°C)	0.9	2.1	2.1	1.1	-0.9	-0.9
	Tx (°C)	2.4	4.4	3.5	3.3	-1.5	-0.6
	HRm (%)	-9.0	-15.0	-8.0	-13.0	3.0	0.0

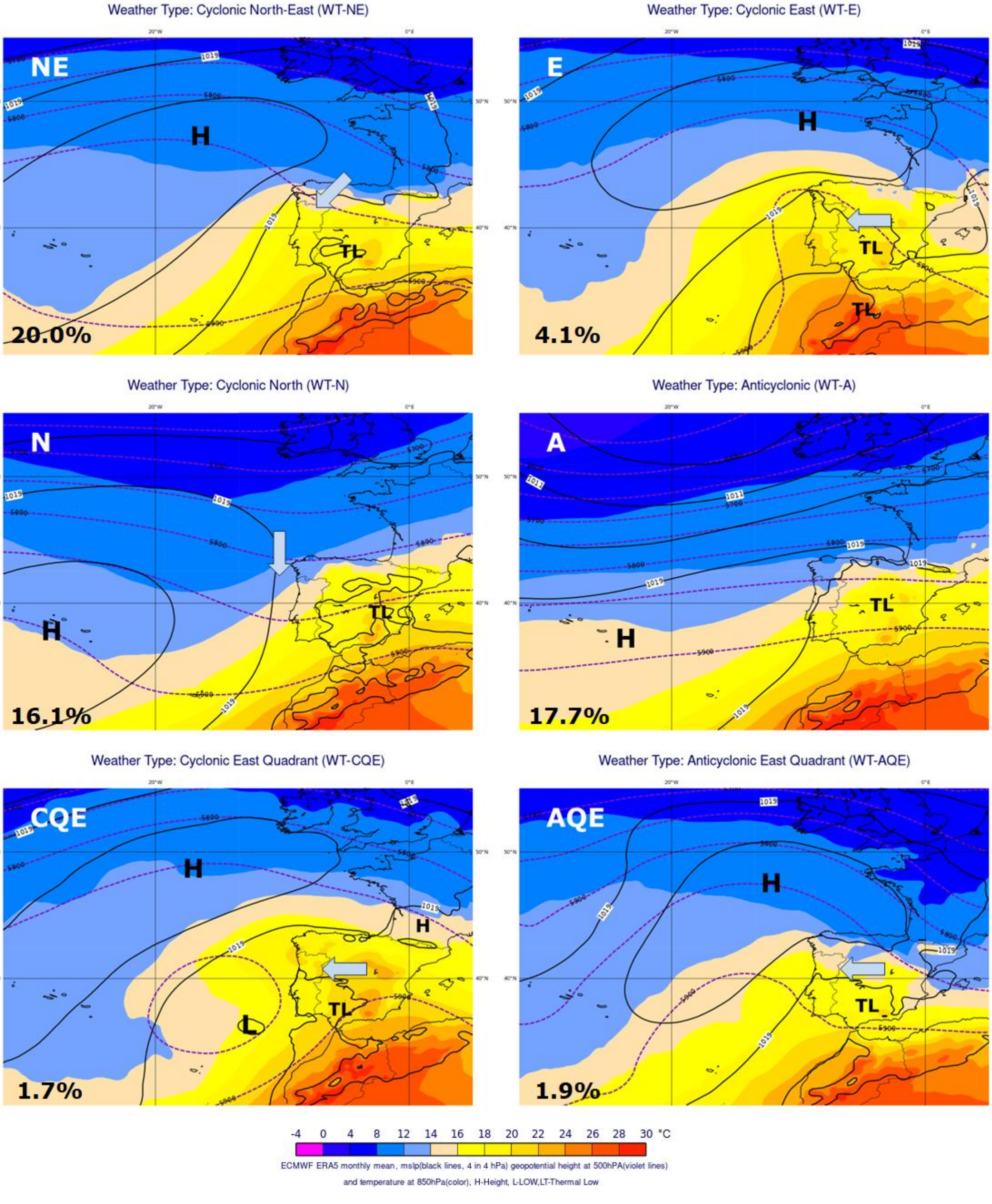

Figure 1- Monthly mean summer (June to October) weather types circulation pattern, from ECMWF ERA5 at 12 UTC in period 1981-2010 and its frequency. NE (Top left), E (top right), N (in middle left), A (in middle right), CQE (bottom, left AQE (bottom right). Mean sea level pressure (mslp, black lines, 4 in 4 hPa), geopotential height at 500

hPa (Z500, lines in violet, 50 in 50 m), temperature at 850 hPa (T850, colour, °C). H – Height, L - Low, TL - Thermal Low, blue arrow - flow direction. WT frequencies (%), June to October, in the bottom left corner.

3. Spatial Fire distribution and Weather Types Frequency

The Figures 2, 3 and 4 shows for each of the ten clusters of NUT III defined in Table 3, the spatial fire distribution for each burned area class in period of 1980-2018, by the six WTs mentioned in chapter 2.2 and 2.3 and three more - AQN, CQN, C - that presented some incidence in large fires in some NUT III. In tables 5, 6 and 7, the frequency of LF in each WT and the respective mean value of Fire Weather Index (FWI) in each of the ten clusters of NUT III is shown.

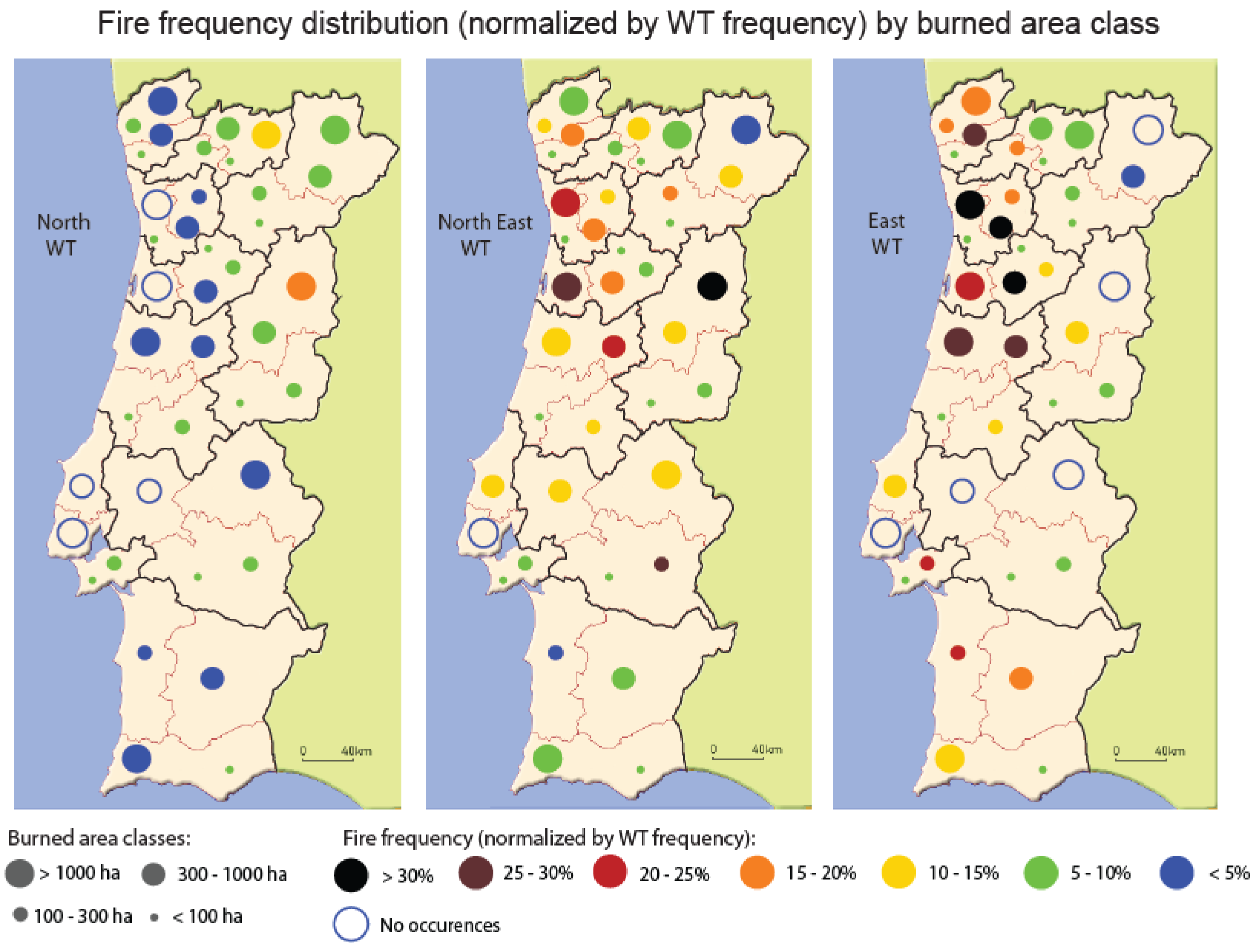

Figure 2 - Spatial Fire Distribution and frequency for each Weather Type in ten clusters of NUT III in Portugal, 1980-2018: N (Left), NE (middle) and E (right).

Table 5 - Fires distribution (%) for the ten clusters of NUT III and for the Weather Types N, NE and E. FWI mean value in NUT III cluster for critical WT and critical days. In bold: Frequency > 25% and FWI > 70.

WT and Burned Area class (normalized daily BA)		Cl1	Cl2	Cl3	Cl4	Cl5	Cl6	Cl7	Cl8	Cl9	Cl10
N [BA] ≥ 300ha] (%)		2.6	7.5	0.8	8.0	2.3	7.4	3.7	0.0	2.8	2.5
NE [BA ≥ 300ha] (%)		13.7	10.9	17.9	10.4	20.6	14.8	16.9	8.5	12.5	6.7
E [BA ≥ 300ha] (%)		22.3	7.1	**35.9**	3.0	**29.7**	12.3	**26.4**	9.4	0.0	13.3
FWI	**WT-N**	35.7	38.1	37.4	44.2	39.1	48.8	43.9	43.7	57.5	53.8
	WT-NE	48.4	49.9	51.1	55.9	53.3	60.4	57.2	56.4	63.8	64.6
	WT-E	59.3	63.1	65.6	69.0	68.0	**71.8**	**70.6**	**70.8**	**77.9**	**75.9**

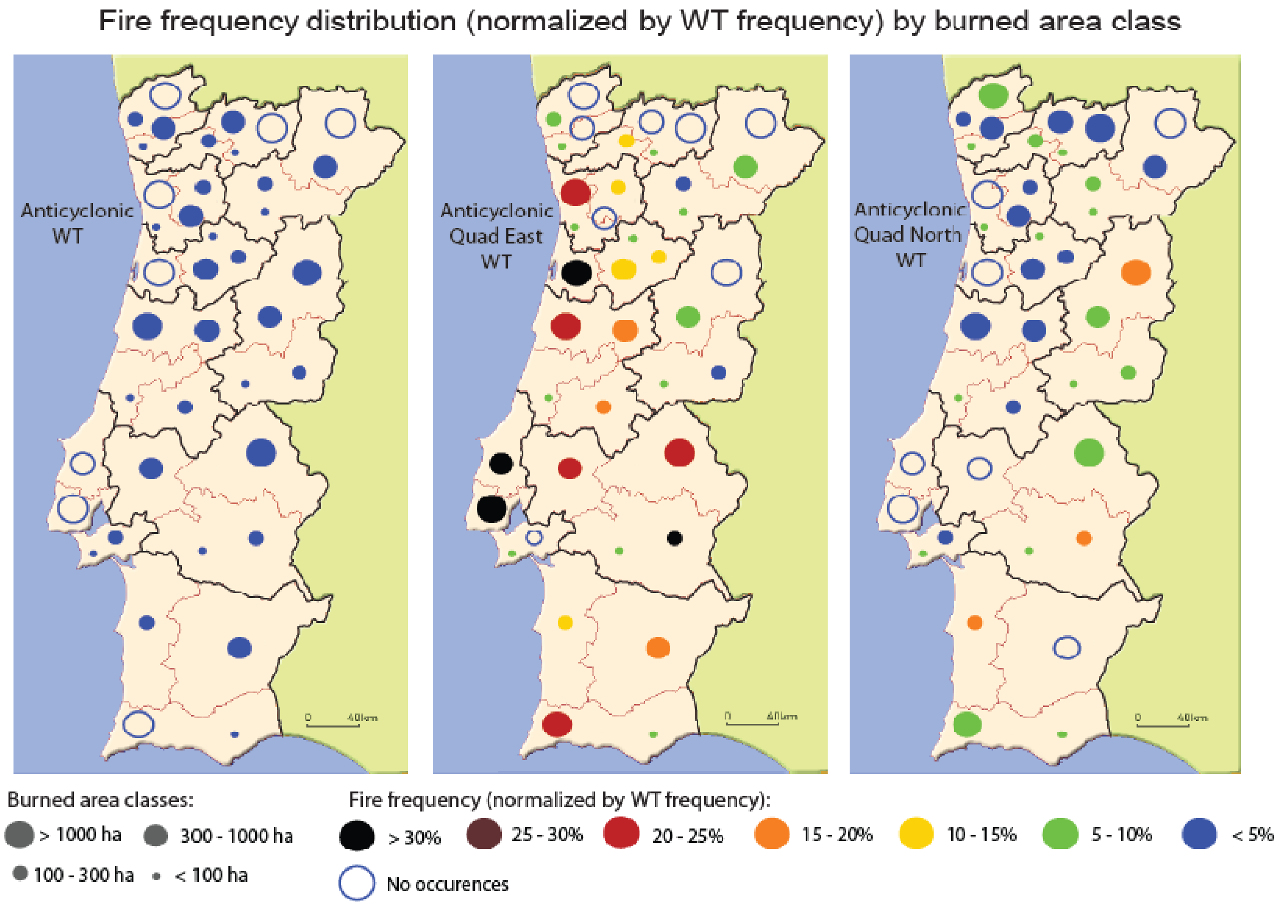

Figure 3 - Spatial Fire Distribution and frequency for each Weather Type in ten clusters of NUT III in Portugal, 1980-2018: A (Left), AQE (middle) and AQN (right).

Table 6 - Fires distribution (%) for the ten clusters of NUT III and for the Weather Types A, AQE and AN). FWI mean value in NUT III cluster for critical WT and critical days. In bold: Frequency > 25% and FWI > 70.

WT and Burned Area class (normalized daily BA)		**Cl1**	**Cl2**	**Cl3**	**Cl4**	**Cl5**	**Cl6**	**Cl7**	**Cl8**	**Cl9**	**Cl10**
A [BA] ≥ 300ha] (%)		0.9	2.0	1.0	1.0	0.7	1.9	1.6	0.0	2.2	0.5
AQE [BA ≥ 300ha] (%)		0.0	0.0	3.3	6.5	17.2	8.6	21.1	**76.0**	**31.6**	**29.3**
AQN [BA ≥ 300ha] (%)		4.0	4.1	0.8	1.4	3.6	9.7	2.0	0.0	6.1	3.0
FWI	**WT-A**	10.1	14.0	12.5	23.7	15.3	27.4	20.6	22.2	30.3	33.0
	WT-AQE	59.0	61.1	62.3	67.3	65.0	73.3	69.7	**70.9**	**75.3**	**80.1**
	WT-AQN	9.1	9.9	11.2	13.5	12.0	14.7	15.6	16.1	20.2	25.5

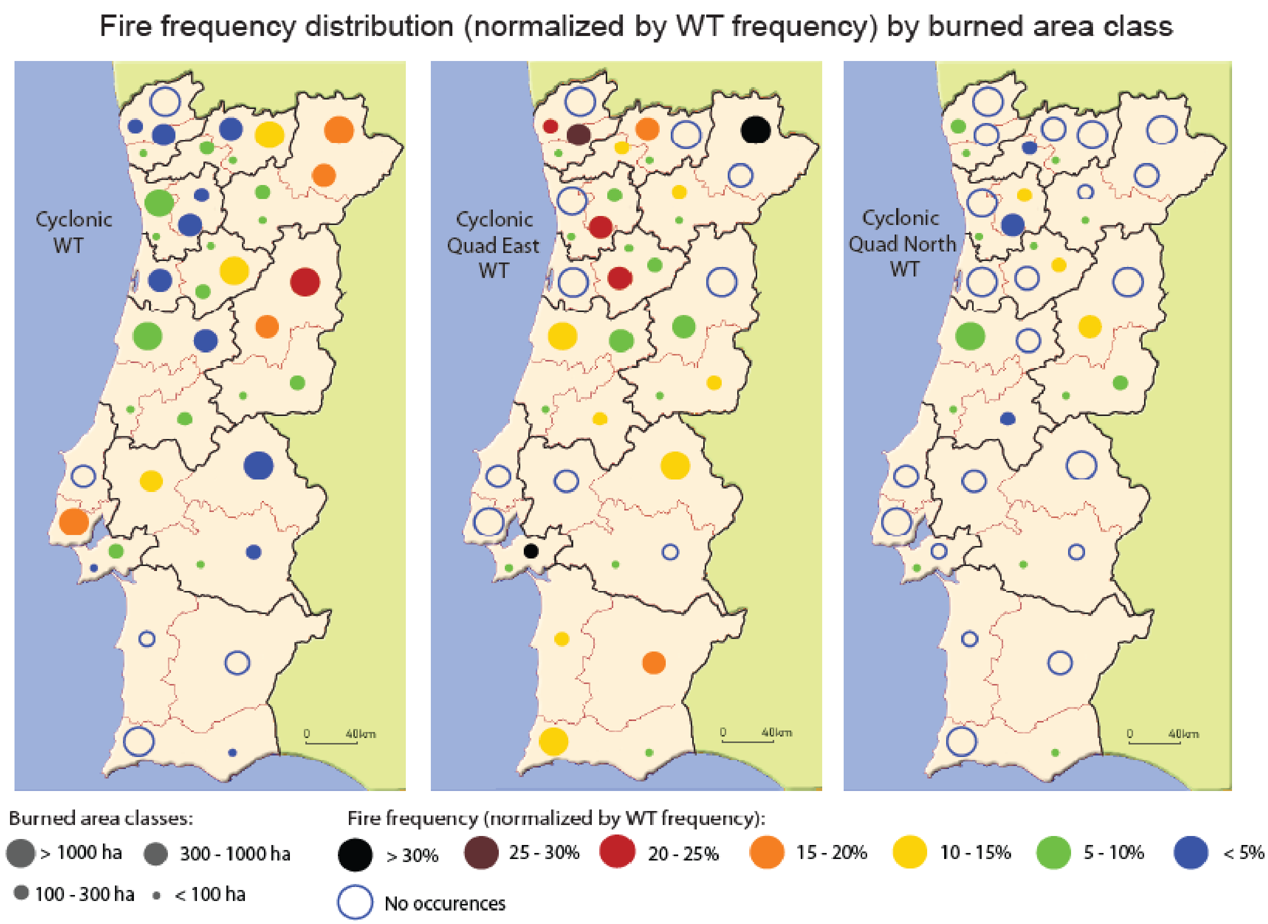

Figure 4 - Spatial Fire Distribution and frequency for each Weather Type in ten clusters of NUT III in Portugal, 1980-2018: C (Left), CQE (middle) and CQN (right).

Table 7 - Fires distribution (%) for the ten clusters of NUT III and for the Weather Types C, CQE and CQN. FWI mean value in NUT III cluster for critical WT and critical day. In bold: Frequency > 25% and FWI > 70.

WT and Burned Area class (normalized daily BA)		**Cl1**	**Cl2**	**Cl3**	**Cl4**	**Cl5**	**Cl6**	**Cl7**	**Cl8**	**Cl9**	**Cl10**
C [BA] ≥ 300ha] (%)		2.5	5.2	5.2	17.6	5.1	16.2	4.3	6.1	6.4	0.0
CQE [BA ≥ 300ha] (%)		16.3	14.5	19.4	17.1	16.4	8.3	9.2	0.0	8.4	15.7
CQN [BA ≥ 300ha] (%)		0.0	0.0	4.0	0.0	0.0	10.2	3.7	0.0	0.0	0.0
FWI	**C**	52.7	52.6	58.5	53.9	61.2	56.8	53.2	61.8	62.2	62.2
	CQE	62.9	64.8	68.5	65.0	69.7	68.2	65.5	**72.1**	**72.9**	**72.9**
	CQN	9.1	9.3	12.0	9.9	12.9	12.2	12.4	15.0	18.4	18.4

A detailed analysis of fires distribution based on Figures 2, 3, 4 and on tables 5, 6 and 7, is presented below:

- Fires in the two lowest daily burned area classes occur with high frequency (about 70%), mean value for all NUT III, in these critical weather types (NE, E, CQE, AQE, A, N), distributed throughout the territory, especially in the north and centre of the territory, with a higher frequency (60'%) in NE WT and for WTs with an eastern component
- Fires in the two highest daily burned area classes showed a high frequency (about 70%), mean value for all NUT III in NE, E, AQE, CQE and C WTs, being about 90% in NUT III near the coast (clusters l, 3, 5, 7 and 8). Considering only the E WT, there is a high concentration of LF (about 30%) in clusters

l, 3, 5 and 7. On the contrary, in clusters 4 and 9 the E WT has low frequency (< 5%). These cases are associated to high values of mean FWI in each cluster of NUT III, in the order of 60 and 75;

- **N WT** shows some LF distributed throughout the territory, with high frequency (5-10%) in clusters 2, 4 and 6 (far north and eastern territory). The mean value of FWI shows moderate values, in the order of 35 and 45, and above 50 in southern;
- **A WT** shows some LF (< 2%) fires distributed throughout the territory, especially in the North and Central regions and no LF occurrences in NUTIII near the coast. The mean value of FWI shows low values, in the order of 20-30, being below 15 in clusters 1, 2 and 3 and above 50 in the south of Portugal;
- **AQE WT** shows the highest concentration (>35%) of LF in the clusters 8 and 9 and in clusters 10. In the cluster 8, most LF (79%) occurred with this WT. The mean value of FWI shows the highest value of 80 in cluster 10 and values above 60 in all clusters, except in cluster 1, that is 59;
- **C and CQE WTs**, these WTs, especially the C, show LF with higher frequency of about 15% in cluster 4 and 6 (the most eastern part of territory), being more frequent (> 15%) the CQE WT, near the coast and in south (Clusters 1, 2, 3, 5 and 10). These WTs, during summer season, are associated to atmospheric instability under warm and wet air conditions. The mean value of FWI shows high values between 50 and 70.
- **AQN and CQN WTs** show a few cases of LF (< 5%) they are concentrated in most eastern part of territory, especially in cluster 6 (*Serra da Estrela and Beira Baixa*) where these WTs showed a frequency of about 20%. The FWI shows the lowest mean values, in the order of 10 to 25 in most of the territory, being below 10 in most northwestern territory. These WTs are associated to cold air mass and for the CQN precipitation is likely.

4. Final remarks:

This study confirmed that large fires (LF) in Portugal are associated with certain synoptic patterns of circulation. The patterns with flow from the east quadrant are the ones with the highest frequency (> 70%), corresponding to most cases of LF in the NUT III, located in the most western part of territory. In this study, the set of critical Weather Types (WTs) are well identified, as well as the differences in the regional distribution of the LF according to these WTS.

The mean value of FWI in each NUT III or cluster of NUT III, showed large differences, according to the WT and region. The highest mean FWI reaches the maximum value of 80 for AQE WT in cluster 10. Nevertheless, the mean values of FWI for A WT are moderate or low (<25) in most NUT III and the north component hybrid WTs (AQN and CQN) exhibit the lowest FWI, below 20 in most NUT III and below 10 in cluster 1 and 2. These values can thus be taken as historical indicators at regional level of the likelihood of a large fire occurring.

The high frequency of directional or hybrid WTs show the importance of wind-driven fires in LF in Portugal. Additionally, orographic effects have to be considered as they can intensify the large-scale flow characteristics. Ultimately, it will be this combined effect that will support a better relation between the synoptic pattern, described by the Weather Types, and the Large Fires regime.

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