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Synoptic patterns associated with large summer forest fires in Portugal

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Abstract

Time series of the total annual burnt area in Portugal reveal two main features, a large inter-annual variability and a positive trend since the early 80 s. Here we show that inter-annual variability is partly due to the amount of precipitation in the fire season and in the preceding late spring season and partly to the occurrence of atmospheric circulation patterns that induce extremely hot and dry spells over western Iberia. On the other hand, the observed positive trend of burnt area is mainly related to changes in farming and land use. Meteorological conditions play a fundamental role, both in the ignition and during the fire spread. The description of spatial and temporal variability of wildfire characteristics is performed using the comprehensive fire data set (between 1980 and 2000) from the Portuguese forest service. We show that the vast majority of the burnt area in Portugal (80%) is due to fire events that occurred on in a very small number (10%) of summer days. Large-scale climatic and dynamical meteorological fields were retrieved from the NCAR/NCEP Reanalyses data sets for the 1961–2000 period and composites were then obtained for the 10% of summer days associated with the highest values of burnt area. Anomaly fields of climate variables (e.g. 850 hPa temperature and relative humidity) are interpreted based on physical mechanisms associated with dynamical variables such as the surface wind field or the 500 hPa geopotential height. Overall, one may state that synoptic patterns of most analysed meteorological fields present statistically significant anomalies over western Iberia. In particular, composites of geopotential height for mid (500 hPa) and lower (850 hPa) troposphere show that large forest fires in Portugal occur when the atmospheric circulation forms a prominent ridge over the Iberian peninsula with the flow being dominated by a strong meridional component. Near the surface, wind and sea level pressure anomalies show that these days are associated with south-easterly conditions, with a strong anomalous advection from northern Africa that is further heated when crossing the central Iberian

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plateau. Large asymmetries between minimum and maximum temperatures composites are analysed taking into account the lack of cloud cover and corresponding precipitation. Finally, we present a linear model based on the monthly precipitation and the occurrence of previously identified wildfire prone atmospheric patterns. The developed model gives a correlation coefficient of 0.8 between the observed and modeled extent of burnt area during the summer.

Keywords: Wildland fire; Weather; Rainfall; Temperature; Wind structure; Portugal

1. Introduction

Socio-economic and demographic trends that have prevailed in rural areas of Portugal during at least the last four decades have contributed to high landscape-level susceptibility to fire. Rural areas have experienced a substantial population decrease during the second half of the 20th century, leading to the abandonment of agricultural lands, to the decrease in the size of herds, and to the reduction in the consumption of forest fuels by animal grazing, and by fuel wood harvesting (Rego, 1992). Areas of marginally productive agriculture were converted to forest plantations or abandoned to the natural process of ecological succession, and thus converted to shrublands and woodlands, as in other regions of southern Europe (Pausas and Vallejo, 1999; Moreno, 1999; Lloret et al., 2002; Mouillot et al., 2003). The recent summer of 2003 has seen the most devastating sequence of large fires in Portugal, being responsible for the loss of 20 lives and, additionally, for the largest burnt area in the last three decades. Preliminary results for the year of 2003 estimate the burnt area at approximately 450,000 ha, almost twice the previous maximum (DGF, 2003).

During the period 1980–2000 the mean burnt area by wildfires in Portugal was higher than 90,000 ha per year. In the European context, Northwestern Iberia (i.e. Portugal and the autonomous region of Galicia, in Spain) presents the largest number of fires (50%), followed by southern Italy (10%) and the triangle Provence-Tuscany-Corsica (7%). Northwestern Iberia also has the largest areas affected by wildfires, followed by southern Italy, and Greece (EC, 1996, 1998). Furthermore, during the last few decades some southern European regions have experienced a dramatic increase in fire incidence (Piñol et al., 1998; Moreno, 1999; Pausas, 2004).

Independently from the observed positive trend, a large inter-annual variability in burnt area is also evident. This variability is mostly related to changes in the frequency of occurrence of certain atmospheric conditions favorable to the onset and spreading of large-fires (Viegas and Viegas, 1994). The catastrophic magnitude of the fires in Portugal during the recent 2003 summer, have further emphasized the need to analyze this natural hazard from an atmospheric circulation perspective.

In boreal regions of North America and Russia, fires caused by lightning and extreme fire weather can be responsible for up to 80% of the burnt area (Stocks et al., 1998). However, on a global scale, it is generally accepted that the vast majority (>90%) of biomass burning is human initiated by accident, carelessness, or intentionally (Andreae, 1991). Similarly, studies for both Spain (Vázquez and Moreno, 1995) and Portugal (Vasconcelos et al., 2001) have shown objectively that, in Iberia, the proportion of fires started accidentally or by arsonists vastly surpasses natural causes, such as lightning.

The fire-return interval of a landscape depends on many different variables that can be broadly clustered into three subsets: fuels, weather, and fire management (Hély et al., 2001; Skinner et al., 2002). These factors, fuel loading, the size and shape of fuel particles, and the compactness and arrangement of fuel beds, all affect fire behaviour, namely rate of spread and intensity of the flame front. Fuel accumulation rates, which depend on net primary productivity and fuel type, exert some direct control over the fire return interval. Weather influences fire indirectly, through its effect on fuel moisture, and directly, through the role of wind on promoting convective heat transfer, and affecting the formation of convection columns on large fires. Fire management influences the fire regime by shifting fire size distribution towards a predominance of small fires, and also affects the timing of burning, and types of vegetation burned. The magnitude of the influence of management on fire regimes depends on explicit goals, but also on the effectiveness of fire detection, prevention, and suppression capabilities.

It is widely accepted that meteorological and climatic factors play a crucial role in fire behaviour, affecting both the ignition and spread of wildfires, (Pyne et al., 1996; Kunkel, 2001). Meteorological variables alone or combined with vegetation and topographical information are frequently used to develop fire risk indices, (for a complete assessment see Viegas et al., 1999).

A number of studies have addressed potential linkages between large-scale atmospheric and oceanic circulation patterns, and wildfire activity (Flaningan and Wotton, 2001). Some of these studies have analysed possible teleconnections between the El Niño Southern Oscillation (ENSO) and fire weather in United States (e.g. Simard et al., 1985; Swetnam and Betancourt, 1990; Brenner, 1991). The impacts of atmospheric circulation on fire activity were analysed, with the aim of developing short and long-range forecast models (e.g. Klein and Whistler, 1991; Roads et al., 1991). In particular, Flannigan et al. (2000) explored the relationship between Pacific sea surface temperature (SST) and burnt area in Canada, to build a forecasting model of monthly and seasonal fire activity. Skinner et al. (2002) described the association between large-scale atmospheric circulation patterns (based on 500 hPa geopotential height) and wildland fire severity in Canada.

In Portugal, significant deviations from the mean precipitation regime may imply major consequences in terms of fire risk. Viegas and Viegas (1994) have shown that the mean area of burned forest has a negative relationship with late spring and summer rainfall. On the contrary, winter and early spring precipitation contribute to the development of new vegetation that will increase fine fuel load available in the summer, thus increasing the fire risk. Pereira et al. (1994) identified the most favourable mid-tropospheric patterns associated with large fires in continental Portugal. In the present paper, we intend to merge these two different approaches, incorporating information from both the precipitation regime (before and during the fire season) and the magnitude and frequency of daily large-scale atmospheric patterns that induce large fires.

Thus, the main aims of this paper are two-fold: (a) to analyse the spatial and temporal variability of forest fire activity in Portugal, and (b) to characterize synoptic patterns associated with air masses favourable to high wildfire activity in Portugal. We will stress the different temporal scales associated with the two meteorological phenomena that ultimately control the extent of burnt area in Portugal, namely (1) the existence of long dry periods with absence of precipitation in late spring and early summer (*climate anomaly*) and, (2) the occurrence of very intense dry spells in days of extreme synoptic situations (*weather anomaly*).

We believe that a comprehensive characterisation of synoptic patterns, associated with major wildfires in Portugal, is necessary for two reasons. First, these patterns may provide some guidance to researchers for development of better fires risk indices, with a sound physical basis. Second, some of these atmospheric variables at the synoptic scale are fairly well reproduced by regional circulation models, currently used for operational purposes by the Portuguese national meteorological service (e.g. Almeida and Reis, 2000), enabling their use for fire risk forecasts.

Data and the methodology are briefly introduced in Section 2. Section 3 characterises the spatial and temporal variability of forest fires in Portugal. Section 4 describes in detail the atmospheric synoptic patterns responsible for large fires in Portugal. Section 5 is devoted to the construction of a model for the inter-annual variability of burnt area. Finally, a discussion and some conclusions are presented in Section 6.

2. Data

The present analysis was applied to the summer season in Portugal (here defined as June, July, August and September, JJAS), covering the 21-year-period spanning between 1980 and 2000.

We have used NCEP/NCAR reanalyses data (Kalnay et al., 1996), for the period 1961–2000, to obtain a comprehensive multivariable characterization of the atmospheric circulation associated with high fire activity. In order to identify the most favorable synoptic conditions for high wildfire activity, several surface, low- and mid-tropospheric meteorological variables were considered. Despite the relative small size of Portugal we opted to extract a large window (30°W–20°E and 30°N–60°N) that includes most of

Western Europe, part of Northern Africa and a large sector of the Northern Atlantic Ocean. The meteorological data used are daily time series of:

(a) sea level pressure (hereafter SLP),
(b) 500 and 850 hPa geopotential height (hereafter Z500 and Z850),
(c) 850 hPa level temperature and relative humidity (hereafter T850 and RH850),
(d) maximum and minimum air temperature at 2 m (hereafter $T_{x,2}$ and $T_{n,2}$),
(e) zonal and meridional wind components at 10 m (hereafter U10m and V10m),
(f) precipitation rate (hereafter P_r).

All values correspond to daily mean averages, except for $T_{x,2}$ and $T_{n,2}$. Although based on observational data, reanalyses also depend upon the skill and reliability of the particular forecast model used. In the case of NCEP/NCAR reanalyses, Kalnay et al. (1996) categorise the reliance on the model of different types of variable. According to these authors, variables such as SLP, Z500 and T850 hPa tend to follow the observed variables that were analysed by the model, whereas P_r is most dependent upon the forecast model, thus, susceptible to model systematic errors and should be used with caution. Nevertheless, it is worth pointing out that all the large-scale atmospheric circulation analyses performed in this paper were based on anomaly composites (mean field removed) thus filtering considerably the impact of model inadequacies on obtained results (Trigo et al., 2002). Geopotential height gives the topography of a pressure level and contour lines are to be viewed in the same way as isobars at the surface. The use of 850 hPa height has the advantage of being representative of surface conditions without suffering from contamination from local effects. Information at 500 hPa is representative of the centre of gravity of the column and therefore can be a useful indicator of the entire tropospheric circulation. Typical values of geopotential height at 850 and 500 hPa levels are, respectively 1500 and 5500 m.

In order to characterize the precipitation regime in Portugal, we used monthly precipitation data from 18 stations evenly distributed over Portugal between January 1980 and December 1999 inclusive. The main characteristics of this data set were described previously by Trigo and DaCamara (2000). They found that the precipitation regime reveals a marked seasonal cycle, with an average 70% of the annual precipitation falling between October and March.

The wildland fire database consists of relevant information about each fire event in Continental Portugal within the 1980–2000 study period, such as: ignition date, fire duration, location of fire start and total burnt area. This extensive data set (with over 320,000 individual fires registered) was provided by the Portuguese Governmental Forest Service (Direcção Geral das Florestas, DGF). The database includes information on fire location organised by district (distrito), county (concelho) and parish

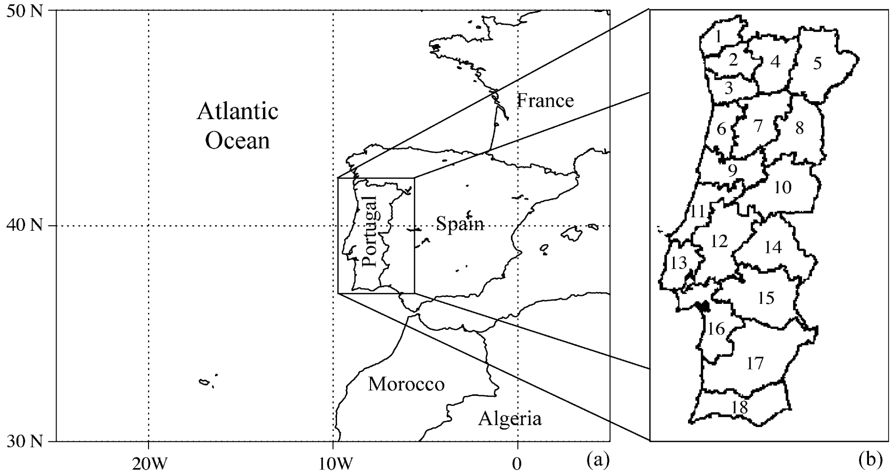

Fig. 1. (a) Location of Portugal in Western Iberia, and (b) the location of the 18 Portuguese continental administrative regions (districts).

Table 1
The main characteristics of the 18 Portuguese continental administrative regions (districts)

Code	District name	DA (km^2)	Population	Rural population (%)	Total BA (ha)	Total FO	BA per year (ha)	FO per year (ha)	BA/DA ha/km^2	BA/FO ha/fire
1	V. Castelo	2219	250275	23.1	98437	19861	4688	946	44.35	5.0
2	Braga	2706	831366	10.6	68086	39452	3242	1879	25.16	1.7
3	Porto	2332	1781836	3.7	83866	68843	3994	3278	35.97	1.2
4	Vila Real	4309	223729	40.5	157646	21548	7507	1026	36.59	7.3
5	Bragança	6599	148883	50.4	91835	10173	4373	484	13.92	9.0
6	Aveiro	2800	713575	10.1	68696	20142	3271	959	24.54	3.4
7	Viseu	5011	394925	29.2	227425	33793	10830	1609	45.39	6.7
8	Guarda	5536	179961	36.5	388314	21305	18491	1015	70.14	18.2
9	Coimbra	3974	441204	16.4	205829	13398	9801	638	51.79	15.4
10	C. Branco	6627	208063	29.6	176331	11888	8397	566	26.61	14.8
11	Leiria	3509	459426	15.9	81882	11276	3899	537	23.33	7.3
12	Santarém	6723	454527	16.2	127701	10864	6081	517	18.99	11.8
13	Lisboa	2801	2136013	2.7	29985	22236	1428	1059	10.70	1.3
14	Portalegre	6084	127018	21.3	14424	1910	687	91	2.37	7.6
15	Évora	7392	173654	13.4	8234	1397	392	67	1.11	5.9
16	Setúbal	5163	788459	3.3	9570	7455	456	355	1.85	1.3
17	Beja	10266	161211	19.4	18019	1588	858	76	1.76	11.3
18	Faro	4995	395218	12.1	58517	5410	2787	258	11.71	10.8
Total		89045	9869343	11.4	1914795	322539				

Characteristics of the 18 Portuguese continental administrative regions (districts) including the district area (DA), total burnt area (BA), fire occurrences (FO), and the ratios of BA to DA (BA/DA) and BA to FO (BA/FO) over the 21-year period. Values refer to the period 1980–2000.

(freguesia), date and time of ignition and extinction, area of forests, shrublands and agricultural crops burned by each fire and land ownership status (public or private) of the burned area. It should be stressed that the DGF data relies on in situ information provided by the Ministry of Agriculture and the National Firemen Service. Therefore, this dataset does not include information from satellite. After being identified a small number of inconsistent entries were eliminated and time series of burnt area (hereafter BA) and fire occurrence (hereafter FO) were produced for each one of the 18 districts of continental Portugal (Fig. 1). Table 1 presents some information about the district area (DA) and the corresponding population as well as data referring to total BA and FO, the ratio BA/DA (which represent the percentage of the district area which is burnt over the 21 years, since BA is expressed in ha and DA in km^2), and average BA per fire, i.e. BA/FO.

3. Spatial and temporal wildfire variability

Fire activity in Portugal presents large values of spatial and temporal variability for both BA and FO time-series. We should stress that the FO series is less reliable than the BA one due to changes in the definition of fire events during the study period. The annual cycle of the variability of average monthly BA for Portugal is shown in Fig. 2. The vast majority of

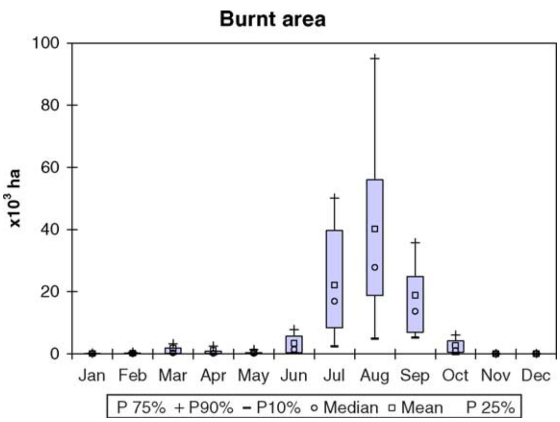

Fig. 2. Box plots showing the annual cycle of the variability of average monthly burnt area in Portugal. Small squares (circles) indicate the mean (median) value for each month, the lower (upper) box limits represent the first (third) quartile and the lower (upper) whisker represents the 10 and 90% percentile of the monthly precipitation.

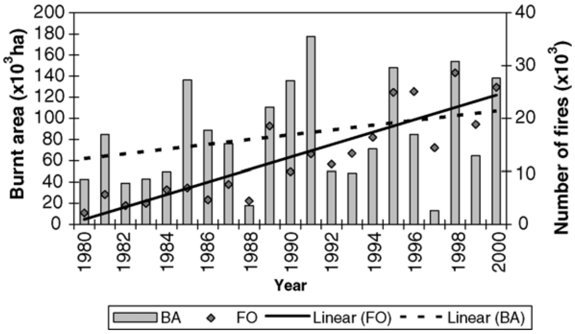

Fig. 3. Long-term inter-annual variability of summer (JJAS) burnt area (BA) and fire occurrences (FO) in continental Portugal and their corresponding linear trend for the period 1980–2000.

fires (266×10^3, or 83% of total) was registered during summer months (JJAS) and were responsible for 1.774×10^6 ha of BA (i.e. 93% of annual BA). As expected, higher values of BA occur between July and September after a relatively long period of dry conditions and high temperatures that constrain the vegetation to a high level of water stress (Chuvieco, 1997). This fact led to restricting our study to the summer months, i.e, June, July, August and September.

The inter-annual evolution of the summer BA and FO is shown in Fig. 3, and both variables reveal an increase over time. However, whereas BA is dominated by large values of inter-annual variability and a relatively small trend, the FO time series presents a significant positive trend (95% significant level as followed from the application of the Kendall test). These results are in agreement with those obtained for Eastern Iberia (Pausas, 2004). Nevertheless, we should stress that part of this increment in FO may be due to fires that were reported more efficiently in the 1990s than in the 1980s.

An analysis of the spatial distribution of FO and BA as well as on the burnt area per district area (BA/DA) and burnt area per fire (BA/FO) may be performed based on the information in Table 1. Regarding FO it is worth noting that two Northwestern districts, Porto (3) and Braga (2), present the higher values, with roughly 69000 and 39000 fire occurrences, respectively. These results are in agreement with those obtained for the contiguous Northern Spanish regions (Moreno, 1999). The remaining districts reveal, in general, a north–south decreasing gradient of FO. A slightly different picture emerges when we consider the spatial distribution of BA. The leading districts are now located south of river Douro; Guarda (8), Viseu (7), Coimbra (9) and Castelo Branco (10), with respectively about 388×10^3, 227×10^3, 206×10^3, and 176×10^3 ha of burnt area. The previous analysis is not affected substantially if based on values of BA/DA and, generally, the higher values of the ratio occur in the same districts where the larger values of BA were registered (last column in Table 1). The larger average values of BA/FO occur in Guarda (8), Coimbra (9) and Castelo Branco (10). Some districts with small BA values, such as Santarém (12) and Beja (17), present relatively high values of BA/FO. On the contrary, northern districts with large BA values, such as Viseu (7), Bragança (6) and Vila Real (4) reveal relatively modest BA/FO ratios. Moreover, the top four most populated districts in Portugal; Porto (3), Braga (2), Lisboa (13) and Setubal (16), present the lowest values of average fire size (<2 ha/fire).

The spatial pattern of FO, BA and mean fire size results from a combination of factors. Coastal districts typically have high population density and possess a complex mix of land use types, with extensive adjacencies between agricultural or industrial lands, and forests, a feature that is responsible for a large number of ignitions. However, landscape fragmentation prevents the occurrence of very large wildfires, and a dense road network facilitates rapid initial fire attack and suppression. This explains the large numbers of small fires in Porto, Braga, Lisboa and Setúbal. In the central and interior districts located north of the Tejo River, topography is rugged, the landscape is dominated by extensive, unbroken areas of forests and shrublands, and population density is much lower than in the coastal region. The reduced number of ignitions in these depopulated areas is, nevertheless, capable of originating many very large fires, due to the spatial continuity of vulnerable vegetation cover, delayed detection, and difficult access to the sites where fires tend to start. Therefore, in comparison with the coastal area, these regions are characterized by a smaller number of fires, which burn a much larger area (Pereira et al., 1998). Besides, orography and typical storm-track trajectories justify the location of the maximum precipitation over the northern part of the country (Trigo and DaCamara, 2000), favoring high net primary productivity and plant fuel accumulation, which is prone to burning under relatively high temperatures and dry conditions typical of the summer season (Viegas and Viegas, 1994).

4. The role of atmospheric synoptic patterns

In this section, we intend to define and analyse the most favourable synoptic patterns of circulation associated with high wildfire activity. For this purpose, we have built up composites of the different meteorological variables that consisted of arithmetic means evaluated for a sub-sample of the original daily values from NCEP/NCAR reanalyses dataset. Here, the sub-sample is based on the 10% of days, i.e. 256 days, with highest values of burnt areas, i.e., those days with burnt areas higher than the 90% percentile of the distribution of all summer (JJAS) days for the 1980–2000 period (hereafter referred to as top 10% composite). In fact, large fire sizes inequalities are a well known fact in Iberia (Vázquez and Moreno, 1995), i.e. a small proportion of fires accounts for a large proportion of the total burnt area. Choice of the 90% for Portugal was motivated by the fact that the daily burnt area distribution is highly skewed, implying, for instance, that only 10% of summer days are responsible for nearly 80% of the burnt area. Anomaly fields were computed based on differences of the composite means to the summer averages computed for the standard 1961–1990 period (hereafter referred to as top 10% anomaly composite).

We provide simultaneous representation of different fields aiming at facilitating the interpretation of climate impacts anomalies (represented in shaded colour) based on dynamical fields (represented by contours). Results are shown in a standard format in Figs. 4–8, i.e. each figure presents composites for the

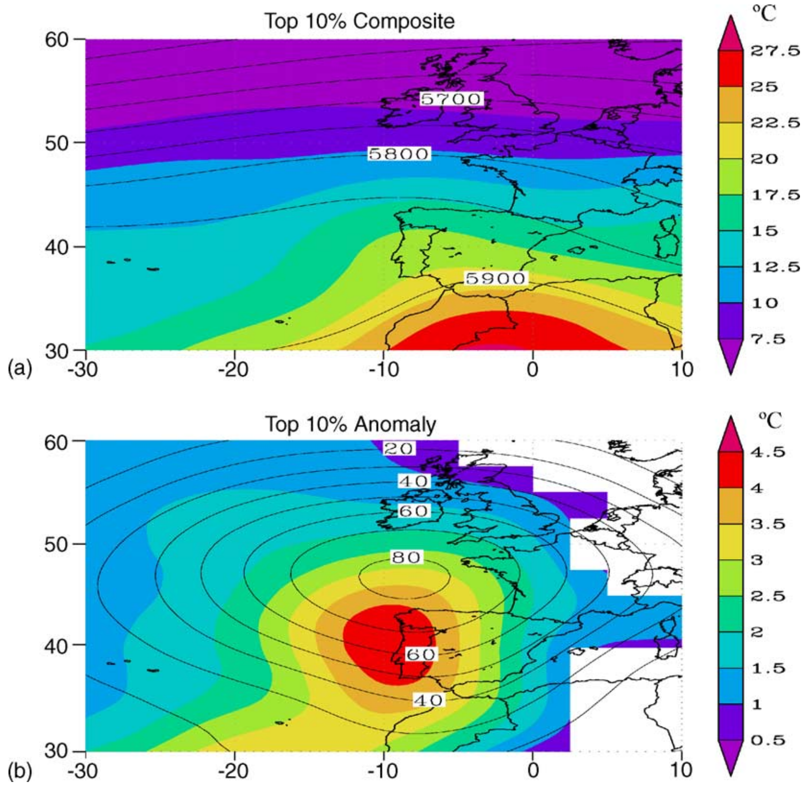

Fig. 4. Air temperature fields (°C), at 850 hPa (T850), for (a) composite for the 10% highest burnt area days in Portugal and (b) the corresponding 10% anomaly. Contour lines show the corresponding geopotential height (gpm), at 500 hPa (Z500). Climate anomaly field (T850) is represented only in those areas where such anomaly is significant at the 1% level (or 99% confidence level) computed with a two-tailed *t*-test.

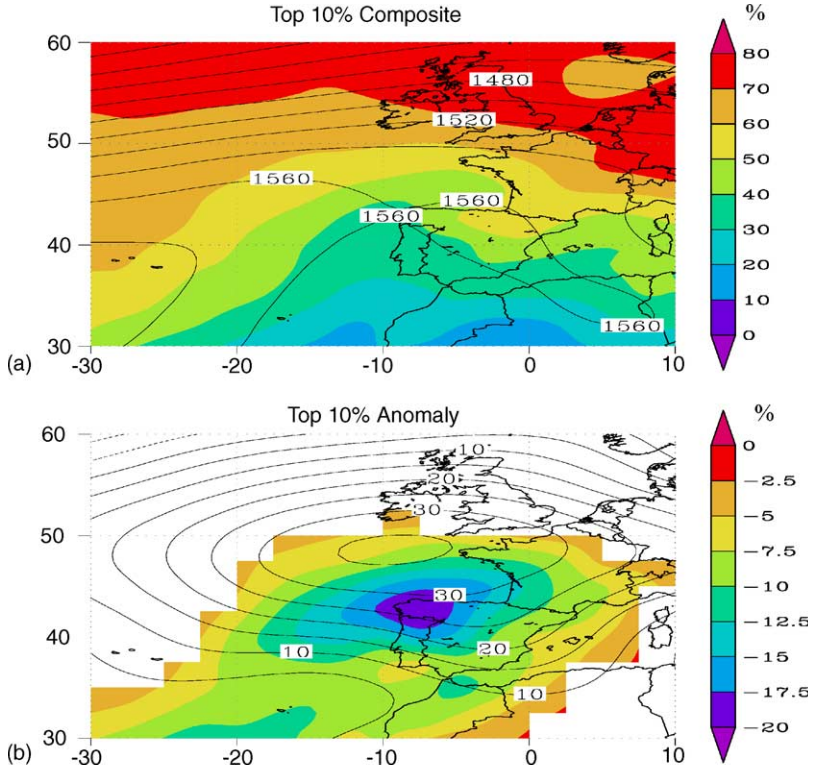

Fig. 5. Relative humidity (%), at 850 hPa (RH850), for (a) composite for the 10% highest burnt area days in Portugal and (b) the corresponding 10% anomaly. Contour lines indicate the corresponding geopotential height (gpm), at 850 hPa (Z850). Climate anomaly field (RH850) is represented only in those areas where such anomaly is significant at the 1% level (or 99% confidence level) computed with a two-tailed *t*-test.

top 10% composite (panel a), and the corresponding top 10% anomaly composite after removing the corresponding summer average (panel b).

It is worth noting that climate anomaly fields are only plotted whenever they are significantly different from the JJAS 1961–1990 climatology at the 1% level (or 99% confidence level) computed with a two-tailed *t*-test. Thus, we emphasize the characterization of climate and dynamical patterns of the synoptic atmospheric circulation that lead to large wildfires, and the significance in the contrast between these patterns and the climatology.

The T850 and RH850 top 10% composite fields are strongly related with the corresponding fields of geopotential height in mid (Z500) and low (Z850) troposphere as shown in Figs. 4 and 5, respectively. Atmospheric circulation, represented by the Z500 (Fig. 4a) and Z850 (Fig. 5a) fields is dominated by a strong ridge with the flow presenting a conspicuous meridional component. The corresponding anomaly fields for these two variables are characterized by rather concentric positive anomaly centres located North of Iberia. Moreover, the corresponding Z850 and RH850 patterns indicate a strong advection of warm and dry air from Spain and Northern Africa. As expected, the top 10% anomaly fields for T850 (Fig. 4b) and RH850 (Fig. 5b) are dominated by intense maximum and minimum values over western Iberia. Both extreme values contribute to high forest fire risk. The anomaly field shown in Fig. 5b reveals significant negative values over a large area; the minimum value is located over western Iberia, with the magnitude of the anomaly decreasing with increasing latitude. In fact, unlike the spread out maximum of T850, the RH850 presents an anomaly with an important north–south gradient, ranging from −7% to −19% from the south up to the North western corners of Iberia.

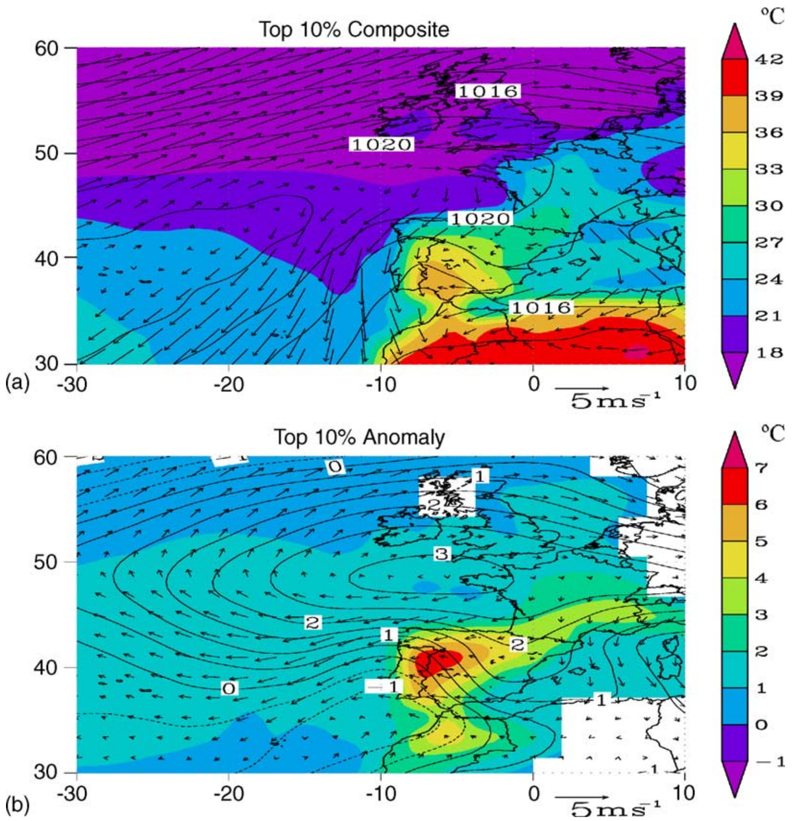

Fig. 6. Maximum temperature (°C), at 2 m height ($T_{x,2}$) for (a) composite for the 10% highest burnt area days in Portugal and (b) the corresponding 10% anomaly. Contour lines and arrows show, respectively, the corresponding sea level pressure (mb) and 10 m height wind fields (m s^{-1}). Climate anomaly field ($T_{x,2}$) is represented only in those areas where such anomaly is significant at the 1% level (or 99% confidence level) computed with a two-tailed t-test.

Figs. 6 and 7 show results for SLP, 10 m height wind (U10m, V10m) and, respectively maximum and minimum temperatures ($T_{x,2}$, $T_{n,2}$). The SLP top 10% may be described as an enhanced typical summer Azores anticyclone pattern, extending further to the east and linking with the high pressure system located over the western Mediterranean (Figs. 7a and 8a). The corresponding top 10% composite for the 10 m wind field is generally in quite good geostrophic agreement with the SLP composite field, with regions of low or very low wind coinciding with the Azores anticyclone and regions with closer isobars being characterized by moderate wind.

The top 10% SLP anomaly field (Figs. 6b and 7b) displays a strong positive anomaly centred north of the Peninsula, and a weaker, negative anomaly located between Portugal and Morocco. Both synoptic features contribute to the anomalous advection of warm (and very dry) air from Northern Africa. This relatively low pressure anomaly centre is a typical summer feature that develops over or near the Iberian Peninsula (Trigo et al., 2002), most often very shallow, without development into the mid/high troposphere. This fact may be easily confirmed by the absence of any corresponding negative anomaly for the Z500 pattern of (Fig. 4b).

The shape of the 10% composite and anomaly fields of $T_{x,2}$ (Fig. 6) is determined mainly by two factors: (1) the strong thermal contrast between continent and ocean masses (as a consequence of their different heat capacities) and, (b) the strong advection of heat from the east after crossing the overheated central Iberian plateau. The $T_{x,2}$ anomaly field (Fig. 6b), exhibits higher values over the Iberian

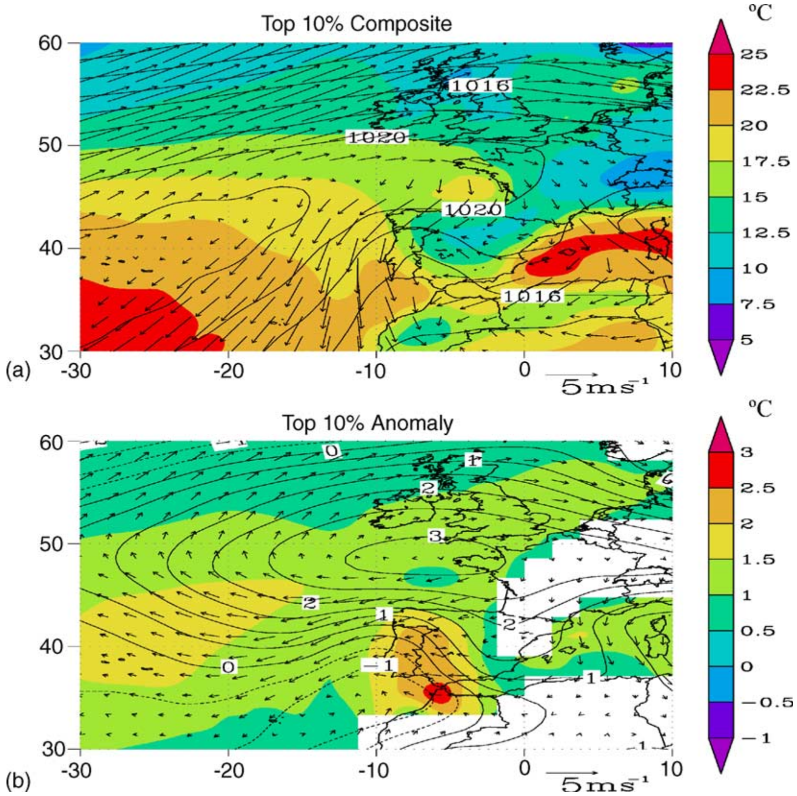

Fig. 7. Minimum temperature (°C), at 2 m height ($T_{n,2}$) for (a) composite for the 10% highest burnt area days in Portugal and (b) the corresponding 10% anomaly. Contour lines and arrows show, respectively, the corresponding sea level pressure (mb) and 10 m height wind fields (m s^{-1}). Climate anomaly field ($T_{n,2}$) is represented only in those areas where such anomaly is significant at the 1% level (or 99% confidence level) computed with a two-tailed *t*-test.

Peninsula, reaching a maximum larger than 6 °C in the central region of Iberia. It is worth noticing that this large positive anomaly encloses the entire Peninsula, even stretching to Northern Morocco (where it still reaches values above 4 °C).

A similar analysis was performed for the minimum temperature ($T_{n,2}$) and results are shown in Fig. 7. Naturally, all dynamical fields associated with the top 10% composite remain unchanged, in particular, the SLP and wind fields represented in Fig. 7. Nevertheless, the impact on $T_{n,2}$ is relatively different from the one described for $T_{x,2}$. On the one hand, the magnitude of the impact is smaller (notice the use of different scales in $T_{x,2}$ and $T_{n,2}$ composite and anomaly fields); on the other hand, the spatial location changes. Whereas for $T_{x,2}$ the region of highest values is mostly confined to the Iberian Peninsula (Fig. 6a), for $T_{n,2}$ the region of minimum values extends from the Alps to central Iberia (Fig. 7a). Furthermore, maximum anomalous values for $T_{n,2}$ (Fig. 7b) are considerably smaller (less than 2.5 °C) than the corresponding values for $T_{x,2}$ (Fig. 6b); besides, they are located further south, over Gibraltar, and not over central Iberia. It has been shown in previous works (Trigo et al., 2002; Trigo et al., 2004) that the reason for these discrepancies is related with the fact that $T_{x,2}$ is registered during daytime (mid afternoon) and $T_{n,2}$ occurs generally before sunrise. Thus, during daytime enhanced solar short wave radiation further increases the heating effect related with the advection of warm air, while during the night the strong clear sky emission of long wave radiation partially offsets that advection by cooling the lower troposphere (Trigo et al., 2002). The discrepancy between the impact on $T_{x,2}$ and $T_{n,2}$ is related to the enhanced anticyclonic circulation that induces a strong reduction of cloud

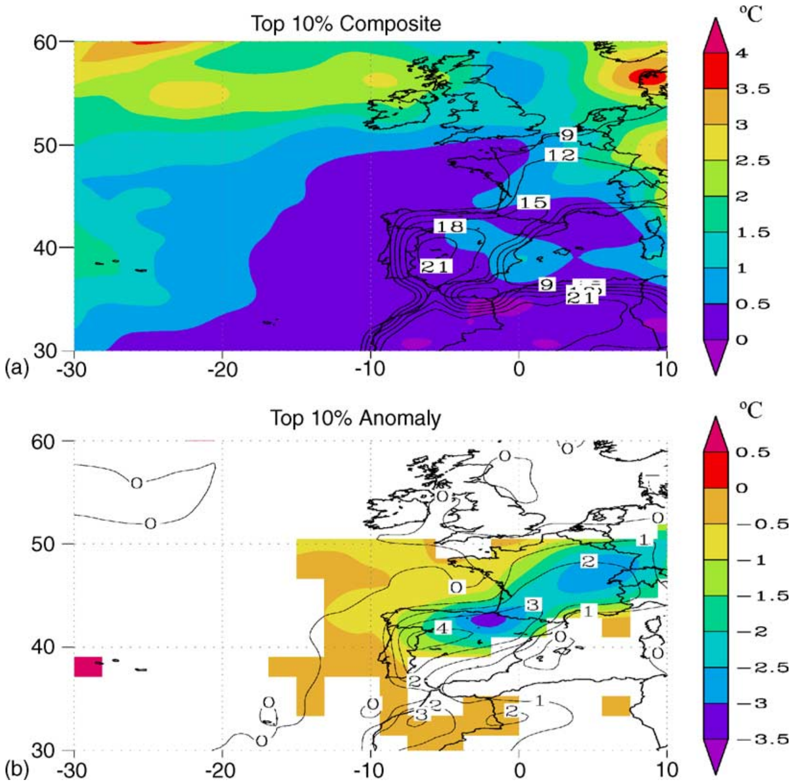

Fig. 8. Precipitation rate (mm/day) for (a) composite for the 10% highest wildfire activity in Portugal, and (b) corresponding 10% anomaly. Contour lines show the corresponding temperature range ($T_{max} - T_{min}$) field (°C), at 2 m height. Climate anomaly field (P_r) is represented only in those areas where such anomaly is significant at the 1% level (or 99% confidence level) computed with a two-tailed *t*-test.

cover over Iberia. In this case, then it should be possible to observe, for the top 10% composite, a strong reduction of summer precipitation.

In the absence of cloud cover data to prove our point, we opted to present simultaneously the precipitation rate (P_r) and the temperature range ($T_{x,2} - T_{n,2}$) fields (Fig. 8). The temperature range composite field is dominated by the land-sea contrast and its anomaly pattern resembles that obtained for the $T_{x,2}$ field, including the location of the maximum center (Fig. 6b). Higher than usual temperature range values could be achieved with an increase of $T_{x,2}$, a decrease of $T_{n,2}$ or both simultaneously, as a consequence of daily (nightly) heating (cooling) by radiation, convection and conduction. Thus, it seems acceptable that maximum temperature range composite values are associated with lower than usual cloud cover regions, and are representative of regions of lower than usual (or even absence) of precipitation. The temperature range anomaly field exhibits a positive anomaly (>4 °C) over Iberian Peninsula that extends into France. On the other hand, P_r presents a relatively small statistically significant negative anomaly extending from Morocco to Northern France (including the entire Portuguese mainland) and its magnitude is most important in Northern Spain and in France, regions where the summer precipitation is usually significant.

5. Modelling the inter-annual burnt area variability

The timing and magnitude of precipitation (or its absence) in Mediterranean regions are among the main factors that control vegetation physiological state and, for that reason; they play a central role on wildfire variability. In a previous work, Viegas and Viegas (1994) explored the relevance of precipitation

Table 2
Correlation coefficients between summer burnt area, BA, (greater than 100 ha) and 10 potential predictors for the 1980–1999 period

	P_{JFMA}	P_{JJA}	P_{JJAS}	P_M	P_{MJJA}	MFR_{RH850}	MFR_{SLP}	MFR_{T850}	MFR_{Z500}
BA	0.36	−0.53	−0.38	−0.57	−0.74	−0.47	−0.37	−0.60	−0.62

Predictors are: January to April precipitation (P_{JFMA}); June to August precipitation (P_{JJA}); June to September precipitation (P_{JJAS}); May precipitation (P_M); May to August precipitation (P_{MJJA}); and meteorological fire indexes based on relative humidity at 850 hPa level (MFR_{RH850}); sea level pressure (MFR_{SLP}); air temperature at 850 hPa level (MFR_{T850}); and geopotential height at 500 hPa level (MFR_{Z500}).

parameters on the high variability of annual burnt area in Portugal for the 1975–1992 period. In particular, the authors have shown that long term winter (January to April) precipitation (hereafter P_{JFMA}) is positively correlated with BA, whereas May and summer (June to September) precipitation (hereafter P_M and P_{JJAS}) show negative correlations.

The present model is based on linear correlation coefficients between different monthly and seasonal precipitation averages and total summer burnt area for fires larger than 100 ha (Table 2). Results in Table 2 show that precipitation between January and April present a positive (albeit small) correlation with BA, because it controls the growth of fine fuels such as herbaceous vegetation and new growth of woody vegetation (Viegas and Viegas, 1994). Both short (P_{JJA}) and long (P_{JJAS}) summer precipitation means present negative correlation coefficients with BA. However, the larger value shown by the short summer approach ($R = -0.53$) highlights the importance of late September precipitation that contributes to the early closure of the fire season. Finally, we stress the importance of the negative correlation value with May rainfall ($R = -0.57$), revealing that its occurrence immediately before summer inhibits the fire ignition or slows down fire propagation. The correlation coefficient between summer (JJAS) BA, just considering values above 100 ha, and P_{MJJA} is $R = -0.74$. If all fires were considered for the evaluation of summer BA, the correlation value would decrease slightly to $R = -0.69$.

Based on the synoptic patterns obtained in Section 4, distinct daily meteorological fire risk indices (MFR) were defined for each considered variable (i.e. SLP, RH850, Z500, T850). These indices were computed, for the entire spatial domain represented in Figs. 4–8, as the Euclidian distance between the synoptic pattern of each day and the average synoptic pattern for the 10% composite (within the space correspondent to each variable). The Euclidean distance between two patterns is simply the mean square deviation (computed for all grid points) of a given field from the respective 10% composite average. Therefore, the Euclidean distance d is given by equation

$$d = \sqrt{\sum (x_i^2 - \bar{x}_i^2)}$$

where x_i is a value of a generic variable at grid-point i and $\bar{x}_i$ is the corresponding average.

Other narrower areas, over the Iberian Peninsula were tested without significant changes in the results. Thus, low absolute values of this distance parameter, for a particular day, denote similar synoptic conditions to those that favour the occurrence of large fires. This approach was applied to all summer (JJAS) days between 1980 and 1999 and seasonal sums of these daily values were computed for each variable.

The meteorological precipitation parameters and the sums of the daily distances for the JJAS months, for the analysed meteorological fields, are tested as predictors for summer total burnt area values, in a multiple regression model. The predictand corresponds to the total burnt area per fire season, however, taking into account the asymmetric nature of fire size distribution we have considered only fires larger than 100 ha. The correlation matrix between the MFR predictors and the predictand is also shown in Table 2. As expected, besides the previously described combined precipitation variable P_{MJJA}, the atmospheric circulation patterns also play an important role, as shown by the MFR based on Z500 and T850 that present statistically significant correlation values with BA ($R = -0.62$ and $R = -0.60$, respectively). One must be careful using all these predictors in any model as they probably present high values of covariability between them, i.e. there is a certain amount of redundancy between some of these variables. In order to build a robust, but parsimonious model we have applied a forward stepwise regression methodology (Wilks, 1996). Results indicate that only

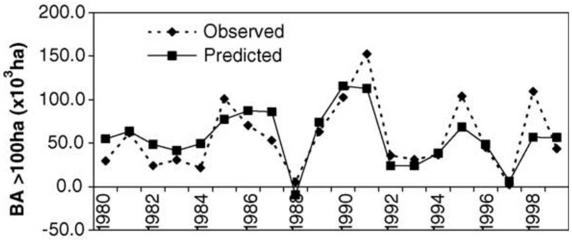

Fig. 9. Observed (dashed line) and modelled (solid line) summer (JJAS) burnt area between 1980 and 1999.

coefficients corresponding to P_{MJJA} (P in the equation model) and the MFR based on Z500 (Z in the equation model) are statistically significant, leading to the following model:

$$B = -402\,P - 2.0\,Z + 342940$$

The correlation coefficient between predicted and observed summer total burnt area (BA > 100 ha) is $R = -0.82$, a value significant at the 99.9% value. The inter-annual variability of observed and modelled BA is presented in Fig. 9 and may be considered remarkably similar. If all fires are considered to compute summer BA, the results are very similar, with a correlation coefficient of ($R = -0.78$). The negative BA predicted by the model to the 1988 summer season has no physical meaning, nevertheless when we adjust it to zeros it does not change the final results in any way. Corrections adjusted to the fact that the summer months have different number of days were also tested with insignificant changes.

6. Discussion and conclusions

The present analysis has shown that large wildfires in Portuguese forests are related to a typical atmospheric circulation pattern dominated by a strong ridge located over the Iberian Peninsula. At lower levels the usual summer configuration is enhanced by the Azores anticyclone extending to central Europe and linking with high pressure in the Mediterranean section, with anomalous advection of hot and dry air from Northern Africa and through central Iberia. It should be stressed that this configuration is relatively rare, as the summer synoptic circulation in Portugal is overwhelmingly dominated by weather patterns with a North or Northwest component (Trigo and DaCamara, 2000). The use of an objective statistical test was an important tool to highlight those specific regions where climatic anomalies are significantly different from the summer climatology.

However, only a very small fraction of all fires is responsible for the vast majority of the total burnt area, a fact that has led us to choose the variable burnt area instead of the number of fires to quantify wildfire activity. We have also shown that there are two main factors controlling the extent of burnt area in Portugal, namely:

(a) a relatively long dry period with absence of precipitation in late spring and early summer (long term precipitation control) and
(b) the occurrence of very intense dry spells during days of extreme synoptic situations (short term heat waves control).

The very different temporal scales associated with these two phenomena should be stressed, as the first issue corresponds to a *climate anomaly* at the monthly or seasonal scale, whereas the second topic may be viewed as a *weather anomaly* with typical temporal scales shorter than a week. A simple example that can be used to clarify the different roles associated with these two temporal scales may be found in the recent catastrophic summer of 2003 in Portugal (approximately 450×10^3 ha of BA). Spring and early summer (March to June) in Portugal were characterised by mild temperatures with a significant lack of rainfall. Thus, from a climate perspective, conditions were favourable for a high risk of summer fire. Nevertheless, the majority of burnt area occurred during a short period of 15 days (between 1st and 15th of August) with extreme synoptic conditions throughout Portugal, Spain and France, being directly responsible, among other impacts, for more than 25×10^3 additional deaths in these countries (WHO, 2004). The control by the precipitation regime on the amount of burnt area per year was addressed previously in Viegas and Viegas (1994). We have focused our analysis more deeply on the second issue, with the aim of constructing models that could account for both factors (long term precipitation deficit and short-term hot and dry spells).

The positive trend of annual burnt area revealed by most Mediterranean countries has been mainly associated with an increase in negligence and criminal behaviour, associated with large-scale rural abandonment. However, one should not forget the likelihood of recent climate change being (at least partially) responsible for such positive trends (Piñol et al., 1998; Pausas, 2004). Information gathered by a recent pan-European project (European Climate Assessment, ECA) has shown evidence of changes in the frequency of extreme temperatures during the second part of the 20th century (Klein Tank et al., 2002). Results obtained for the Iberian Peninsula confirms a steep increase in the minimum temperature and a smaller but, nevertheless, important rise in the maximum temperature (Miranda et al., 2002). According to IPCC (2001), in the future more heat waves are *very likely* over nearly all land areas. However, climate change scenarios of extreme episodes such as summer heat waves are less reliable then those referring to changes in mean temperature, due to the large range of uncertainties involved in their construction. Furthermore, future fire occurrence and associated burnt area might be more dependent on a number of human factors, rather than on climate change scenarios of temperature, humidity and wind. In particular strong efforts to implement better prevention politics such as compulsory forest cleaning use of fire-resistant species or to fund the development of a professional body of fireman specialised in tackling forest fires.

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