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Recent change of burned area associated with summer heat extremes over Iberia

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ABSTRACT

Owing to climate change-induced global warming, the frequency and duration of extremely hot events over the Iberian Peninsula (IP), such as heatwaves, are expected to continue to increase. This study shows the change of individual and monthly concurrent extremely hot events and burned area in the IP in the recent period of 1998–2015, compared with the reference period 1980–1997. Results show a dichotomic behaviour, with June and August showing an increase in extremely hot events and July and September showing many regions with a decrease, both in individual and concurrent events (most prominently in September). Furthermore, regions with such increases also show a change in spatial extent, with a greater area simultaneously affected by the two extremes (particularly in June). Also, even though the incidence of large burned areas decreased in north-western Spain in July and August, these increased in June. Indeed, together with more extreme heat events observed in the region, an increase in burned area was also found in June. This work paves the way for future studies to delve into the causes and effects of extreme heat events over the IP, to raise awareness of the need by forest authorities of developing early warning systems.

Keywords: burned area, heatwaves, heat events, hot days, Iberian Peninsula, maximum temperature, summer, wildfires.

Introduction

The Iberian Peninsula (IP) is recurrently stricken by large wildfires (Trigo *et al.* 2006*a*; Sánchez-Benítez *et al.* 2018; Turco *et al.* 2019) that impact infrastructure and natural ecosystems, undermining the economy and threatening human lives and health (Liu *et al.* 2015, 2016, 2017; Augusto *et al.* 2020; Oliveira *et al.* 2020). The extreme wildfire season of 2017 in Portugal is a tragic example, with a record of more than 500 000 ha burned area (BA) and more than 100 fatalities (Departamento de Gestão de Áreas Públicas ede Proteção Florestal 2017). Extreme fire events are also likely to become more frequent in the near future, as climate change is expected to increase fire danger and the severity of fires (Moriondo *et al.* 2006; Sousa *et al.* 2015; Dupuy *et al.* 2020; Ruffault *et al.* 2020). In turn, the implementation of ignition control activities and fire suppression actions in the last decades has led to decreasing fire activity in some Mediterranean countries (Turco *et al.* 2016), namely in Spain (Urbieta *et al.* 2019; Jiménez-Ruano *et al.* 2020; Rodrigues *et al.* 2020).

Weather and climate at different timescales, combined with the presence of available biomass and human activities, are examples of mechanisms enabling wildfire occurrence and associated BA (Lavorel *et al.* 2007; Costa *et al.* 2011). Indeed, large summer wildfires in the IP may be enabled and driven by meteorological conditions ranging from synoptic weather patterns (Pereira *et al.* 2005; Hernandez *et al.* 2015*a*; Trigo *et al.* 2016; Ruffault *et al.* 2017) down to local-scale weather conditions that may produce a combination of high temperature, low humidity and strong winds (Vieira *et al.* 2020). Furthermore, long-term drought events followed by heat spells are known for providing a background conducive to large summer wildfires (Pereira *et al.* 2005; Trigo *et al.* 2006*b*; Gouveia *et al.* 2009, 2016; Hernandez *et al.* 2015*b*; Turco *et al.* 2017). The IP was recently affected by some of the most intense droughts (García-Herrera *et al.* 2007; Sousa *et al.* 2011; Gouveia *et al.* 2012) and heatwaves (Garcia-Herrera *et al.* 2010; Barriopedro *et al.* 2011, 2020; Sánchez-Benítez *et al.* 2018; Sousa *et al.* 2019) on record. This led national authorities to face new challenges to control and tackle extreme fires, assist the directly affected population and mitigate the destruction (e.g. wildfires of 2003, 2005 and 2017 in Portugal; and 2005, 2016 and 2019 in Spain).

In addition, wildfires increase public health problems and associated morbidity and mortality (Liu *et al.* 2015, 2016, 2017; Augusto *et al.* 2020; Oliveira *et al.* 2020), either owing to several diseases caused or aggravated by smoke inhalation (Richardson *et al.* 2012; Shaposhnikov *et al.* 2014) or because of psychological illnesses induced by grieving and material losses. Heatwave events also provide an environment conducive for a number of pathogens to prosper, increase the risk of temperature-related health conditions, and aggravate pre-existing diseases (Gasparrini *et al.* 2017; Rossiello and Szema 2019; Geirinhas *et al.* 2020).

Several recent studies have tackled the relationship between hot and dry extreme events and wildfires for different regions and using various approaches, mostly focusing on coupled hazards. Mazdiyasni and AghaKouchak (2015) showed that the number of concurrent summer droughts and heatwaves in the USA have experienced a considerable increase in the last decades, and Kong *et al.* (2020) reached similar conclusions for eastern China. Russo *et al.* (2019) took a step further and introduced different time lags, which allowed them to show that summer heatwaves in the Mediterranean are usually preceded by drought events in spring and early summer. Although focusing on compound dry and hot events, these works lack an analysis focused on their relationship to fires. This caveat is partially analysed by several other authors, who address the relationship between hot extremes and fires (the relationship between droughts and heatwaves being nevertheless implicit). For instance, Parente *et al.* (2018) performed a comprehensive study relating heatwaves and wildfire episodes over Portugal and concluded that more than 90% of large wildfires that occurred between 1981 and 2010 were concurrent with heatwaves. Some recent works tackle these tri-variate compound events by analysing the combined effect of drought, heatwaves and wildfires (e.g. Gouveia *et al.* 2016; Sutanto *et al.* 2020) but, to the best of our knowledge, there are no studies specifically focusing on the evolution of individual and concurrent heat spells and wildfires over the full IP (encompassing Portugal and Spain) during the last decades.

The assessment of the adverse impacts associated with multiple climatic factors is now the focus of a variety of studies (Leonard *et al.* 2014; Vitolo *et al.* 2019; Zscheischler *et al.* 2020). Vitolo *et al.* (2019) proposed a new methodology to identify areas prone to concurrent hazards, an added value in the context of a multi-hazard early warning system. This recently adopted perspective on hazards is guided by the fact that compound events often lead to larger impacts compared with hazards occurring separately (Zscheischler *et al.* 2018).

The present work aims to assess whether there has been an increase in BA associated with concurrent wildfire and heat spell events over the IP. The main objectives are as follows:

(1) To study the relationship between monthly BA and the number of days with maximum temperature above the 90th percentile in the same and previous months (number of hot days, NHDs), covering the period from June to September 1980–2015,
(2) To assess changes of monthly BA and monthly NHDs between the first half (1980–1997) and the second half (1998–2015) of the study period,
(3) To compare simultaneously large NHDs and BAs for these two periods over the IP with the objective of verifying if an increase in the number of concurrent events is observed.

Results from this work will contribute to a better understanding of how very high temperatures and heatwaves are related to BA over the IP, and whether this relationship has changed over time. They will also contribute to improving state-of-the-art knowledge about the characteristics of both individual and concurrent events of high temperatures and BA. By dividing the period into two halves, we intend to characterise the evolution of such events, and identify whether specific regions of the IP show a particular behaviour of increased or decreased events. We further aim to study whether regions affected by concurrent events of heatwaves and BA show a spatial increase or decrease of area affected. Such assessment is crucial for effective mitigation and adaptation planning in this region.

Data and methods

Burned area database for Iberia

Values of BA associated with fire events over the IP were derived from official information provided by the Portuguese (Instituto da Conservação da Natureza e das Florestas (ICNF)) and Spanish (Estadística General de Incendios Forestales (EGIF) from the Ministerio de Agricultura, Pesca y Alimentación (MAPA)) state agencies. BA data (burn scars larger than 1 ha) covering the period from January 1980 to December 2015 were then organised into monthly time-series of total BA for the 18 districts of Portugal and the 47 provinces of Spain, adding up to 65 Administrative Regions (ARs). Using information provided by the CORINE land cover database (https://land.copernicus.eu/pan-european/corine-land-cover), monthly normalised values of BA in each AR (hereafter referred to as NBA) were obtained by dividing by the respective area covered by fire-prone

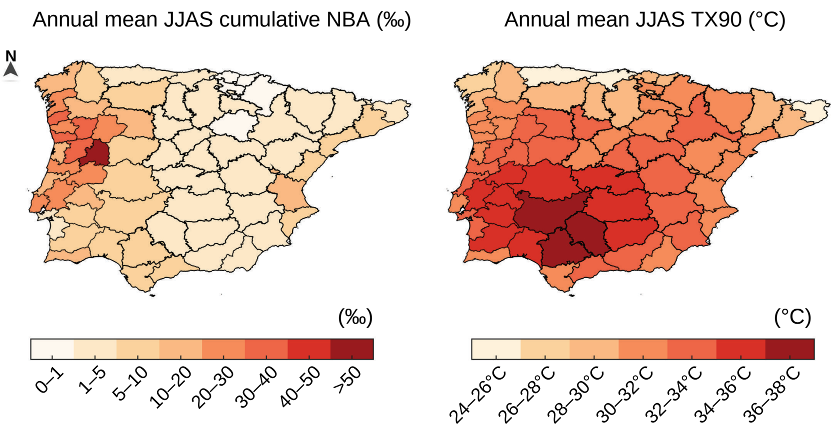

Fig. 1. Annual mean JJAS (left) cumulative Normalised Burned Area (NBA) in permillage (‰) and (right) 90th percentile of maximum temperature (TX90) in degrees Celsius (°C) for the Iberian Peninsula (IP) during the period 1980–2015. Values are represented for the Administrative Regions (ARs). The NBA is defined as the quotient between the burned area (BA) in each of the ARs and the fire-prone area of that AR.

vegetation, which includes agro-forestry areas, broad-leaved forest, coniferous forest, mixed forest, natural grasslands, moors and heathlands, sclerophyllous vegetation, transitional woodland shrub, sparsely vegetated areas, and burnt areas (which in time become revegetated). Owing to the low temporal resolution of CORINE updates and the shortage of datasets before 2000, two versions of CORINE were used, namely the 2000 and 2018 ones. The former was used to estimate fire-prone vegetation for the first half of the studied period (1980–1997) and the latter for the second half (1998–2015). The annual mean cumulative NBA in the period covering June, July, August, and September (JJAS) is shown in Fig. 1 (left panel).

Hot days and heatwaves

Hot days and heatwave events in the period 1980–2015 are defined based on daily values of maximum temperature as obtained from the European Climate Assessment & Dataset (ECA&D) E-OBS version 20.0e (Cornes *et al.* 2018). First, daily time-series of maximum temperature are spatially averaged over each AR and then, for each calendar day, the 90th percentile of maximum temperature is estimated using a 5-day window centred on the day being considered and covering the entire period (a climatology of this percentile for JJAS is shown in Fig. 1, right panel) (Zhang *et al.* 2005). A hot day is defined as a day with a maximum temperature greater than the 90th percentile of that day, and for each AR, the NHDs in a given month of a given year are obtained by adding up the recorded number of hot days. In turn, a heatwave event is defined as a period of 3 or more consecutive hot days above the 90th percentile.

Relationship between NHD and NBA

For each AR, the relationship between NBA and NHD is assessed using Pearson's linear correlation coefficient between the time series of the logarithm of NBA for a given month m and (1) NHD for the same month m; (2) cumulative NHD for months m and $m-1$; and (3) cumulative NHD for months m, $m-1$ and $m-2$. The log transformation is used to decrease the skewness of NBA distributions. The null hypothesis of correlation between the logarithms of NBA and NHD is assessed using a two-tailed Student's t-test at the 5% significance level.

Recent change in NHD, NBA and concurrent events

When the correlation between synchronous NHD and NBA is statistically significant in a given AR, temporal changes during 1980–2015 are assessed for both variables (first as independent and then as concurrent events). For this purpose, the entire period between 1980 and 2015 is split into two 18-year subperiods, the reference period 1980–1997 and the subsequent period 1998–2015. Then, a comparison is performed between the number of times a given month, in JJAS, presents 7 or more hot days in the reference and subsequent subperiods. Afterwards, the same procedure is used to assess the number of times NBA is larger than its median value in each AR. Finally, the method is repeated to test for concurrent occurrences of 7 or more hot days in a month and NBA larger than its median. For a given statistical measure X, changes between the reference and the subsequent periods are quantified by the normalised change coefficient Δ defined as:

$$\Delta(\%) = \frac{X_2 - X_1}{X_1 + X_2} \times 100 \tag{1}$$

where X_1 and X_2 are the values for the reference and subsequent periods, respectively. Negative (positive) Δ represents a(n) decrease (increase) in the statistical measure in 1998–2015 when compared with the reference period 1980–1997. The statistical significance of changes in X is assessed by using bootstrapping to generate 1000 samples of each subperiod, computing the means $\overline{X_1}$ and $\overline{X_2}$ of X for the reference and subsequent periods, and then using a two-sample Kolmogorov–Smirnov test verifying the null hypothesis that $\overline{X_1}$ and $\overline{X_2}$ are from the same continuous distribution at the 5% significance level.

Although this approach provides evidence about the change between two consecutive time periods of concurrent NBA and NHD monthly events, the use of the latter does not provide information on continuous extremely hot days, i.e. heatwaves. Accounting of NHD only allows the number of hot days in a certain month to be known and the information regarding whether the days are consecutive is disregarded. To account for the existence of continuous days, the methodology is repeated to assess the evolution of concurrent NBA but this time with monthly heatwaves. Here, a heatwave occurs if a group of 3 or more consecutive days have TX above the 90th percentile. It should be noted that the analysis of monthly NHD is different from that of heatwaves, as in the former analysis the 7 days may be scattered through the month, whereas in the latter analysis, a heatwave is defined as 3 or more consecutive days with TX above the 90th percentile. However, NBA percentiles are defined as previously. Finally, the Δ for each AR is again estimated following Eqn 1.

This analysis shows the increase or decrease in concurrent events of NBA and NHD/heatwaves focusing on the behaviour of each AR individually. However, it is also relevant to understanding the spatial behaviour of concurrent events over the IP. Thus, empirical cumulative distributions functions (ECDFs) are estimated taking each map (referring to a given month per year) of concurrent events for reference and subsequent periods, indicating the probability of having less than a given percentage of ARs area affected by concurrent events of NBA and NHD/heatwaves. Moreover, as more than one heatwave may occur in the same month, ECDFs are further divided into concurrent NBA and one, two, and three or more heatwaves.

Results

Correlation between NHD and NBA

Maps of correlation between synchronous NBA and NHD (Fig. 2, left panels) show that significant correlations are mainly clustered on the north-western IP in June, July and August, the month of July also presenting a cluster encompassing some ARs over the north-eastern IP. However, September shows different ARs with significant correlations, mainly centred over the southern quadrants of the IP. These results show the sensitivity of the north-western IP BA to synchronous very hot days. The month of July shows the largest number of ARs with significant correlations, while August shows a decrease in the number of Spanish ARs with significant correlation, leaving most of these correlations over Portuguese territory. Finally, there is a shift of significant correlations to southern regions in September.

When the correlations are performed with cumulative NHDs from previous months (Fig. 2, middle and right panels), different spatial patterns are obtained. For instance, in the months of June and September, NBA and NHD in most of the ARs do not present statistically significant correlations. In the case of June, this result indicates that NHDs in

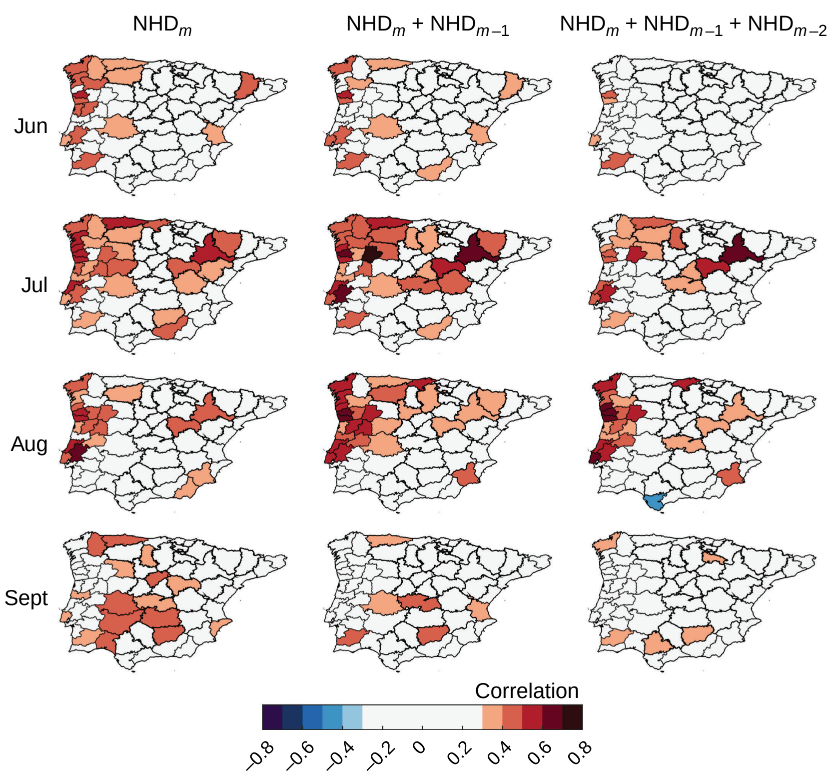

Fig. 2. Pearson's correlation coefficient between fire season monthly (June, July, August, September) log-transformed Normalised Burned Area (NBA) and the number of hot days (NHDs) for the same month (left), combined with the previous month (centre), and combined with the 2 previous months (right). Administrative Regions (ARs) with correlations that are not statistically significant at the 5% significance level are coloured white.

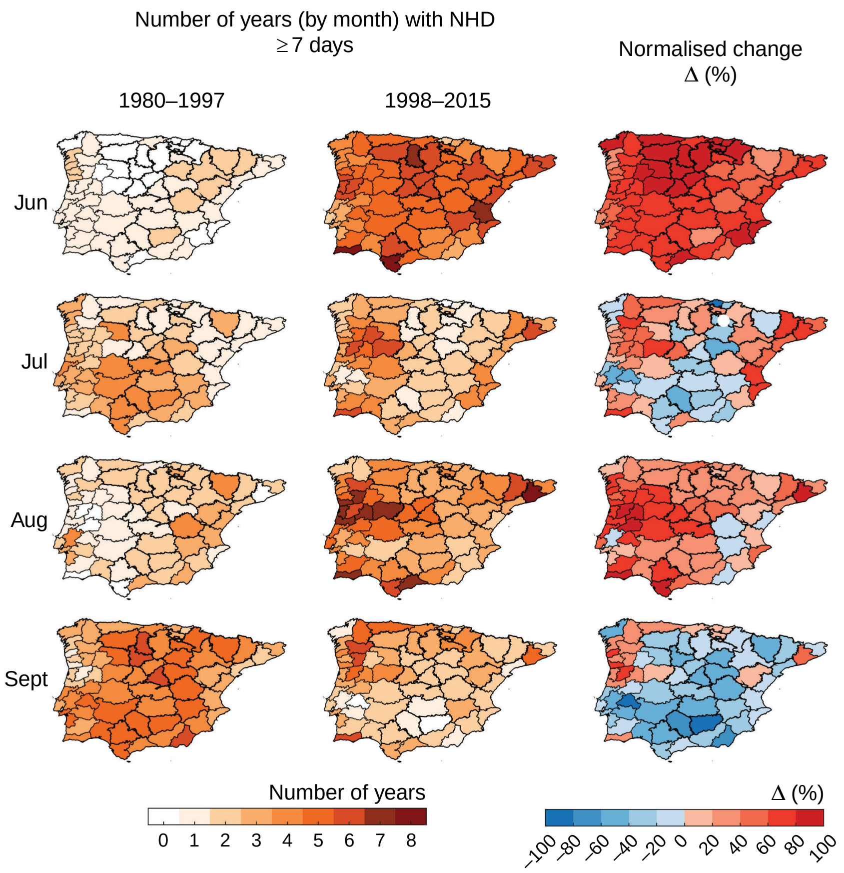

Fig. 3. Number of years (by month) with 7 or more hot days (NHDs) in the reference (left) and subsequent (centre) periods, and respective normalised change coefficient (right).

spring – i.e. April and May – have virtually no impact on the occurrence of wildfires in June. However, the months of July and August present larger correlations in some ARs when NHDs are combined with previous months. Furthermore, there is a larger number of ARs that have significant correlations in both July and August when combining NHDs with the previous month.

Recent change of individual NHD and NBA

When compared with the reference period (1980–1997), normalised changes of individual NHDs (Fig. 3) in the recent period (1998–2015) show a substantial increase of the occurrence of 7 or more hot days in June and a decrease in September.

Fig. 4 shows the change between the number of times NBA is equal to or larger than the 50th percentile for the two considered periods, highlighting the fact that in June, there is an increase that affects most of the IP. Results for July, August and September indicate a decrease in NBA over most of the territory. Some exceptions may be found, mainly over Portugal and in some ARs located in Spain.

Recent change in concurrent NHD and NBA

Results also show a spatially monotonous increase of both variables in June, which is reflected in a similar increase of concurrent events (Fig. 5). During August, a dominance of increasing concurrent events is evident when compared with the reference period. However, the eastern IP shows a decrease in such events. During July, a decrease in concurrent events in most of the IP is present, but there is still an increase in regions like southern Portugal and the north-western IP. Finally, the month of September presents a decrease of concurrent events in most of the IP. It is also worth noting that the north-western IP represents the larger cluster of increasing concurrent events, independently of the month.

ECDFs (Fig. 6) show the differences in area affected by concurrent events between reference (dashed orange lines) and subsequent (solid red lines) periods for JJAS.

For June, there is a shift of the curve representing the recent period to the right. This shift is found for both very low percentages of area and extreme events, meaning that there has been an increase in area affected by these events. Differences at the lower end of the curves – smaller areas affected by concurrent events – are ~0.40, i.e. the probability of having concurrent events affecting fewer ARs has decreased in the recent period and, consequently, concurrent events taking place in the recent period tend to affect larger areas of the IP. Furthermore, extreme events (defined by the upper end of the curves) affected a maximum of ~40% of the area in the reference period, whereas these values increased to ~70% in recent years.

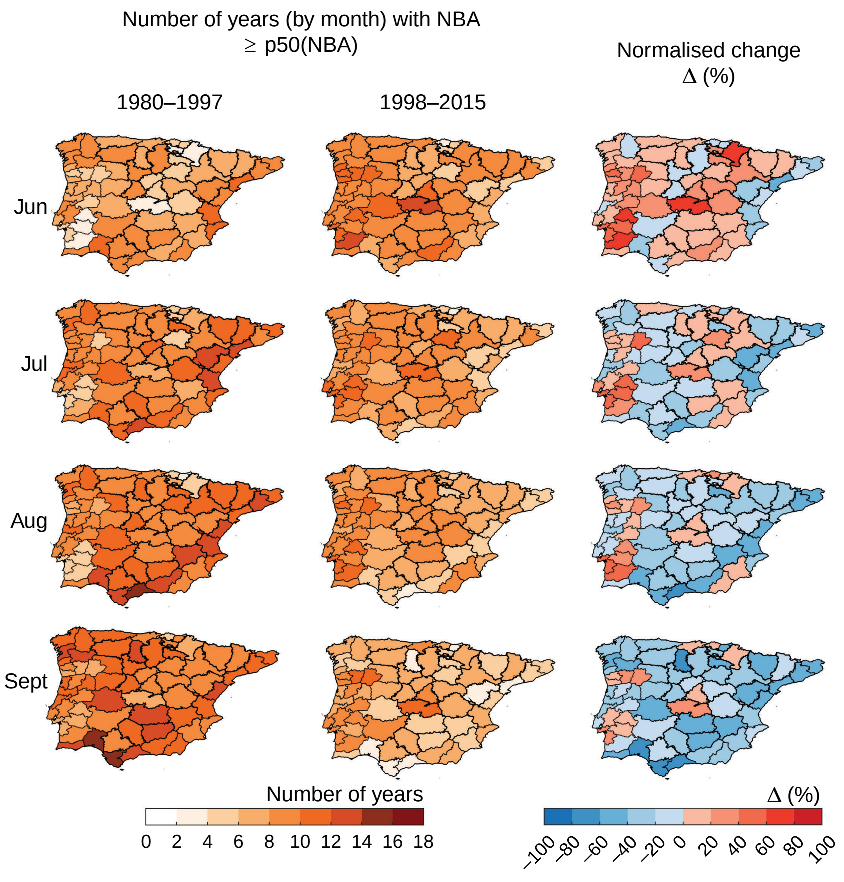

Fig. 4. As in Fig. 3, but for Normalised Burned Area (NBA) larger or equal than the median of NBA, i.e. p50(NBA).

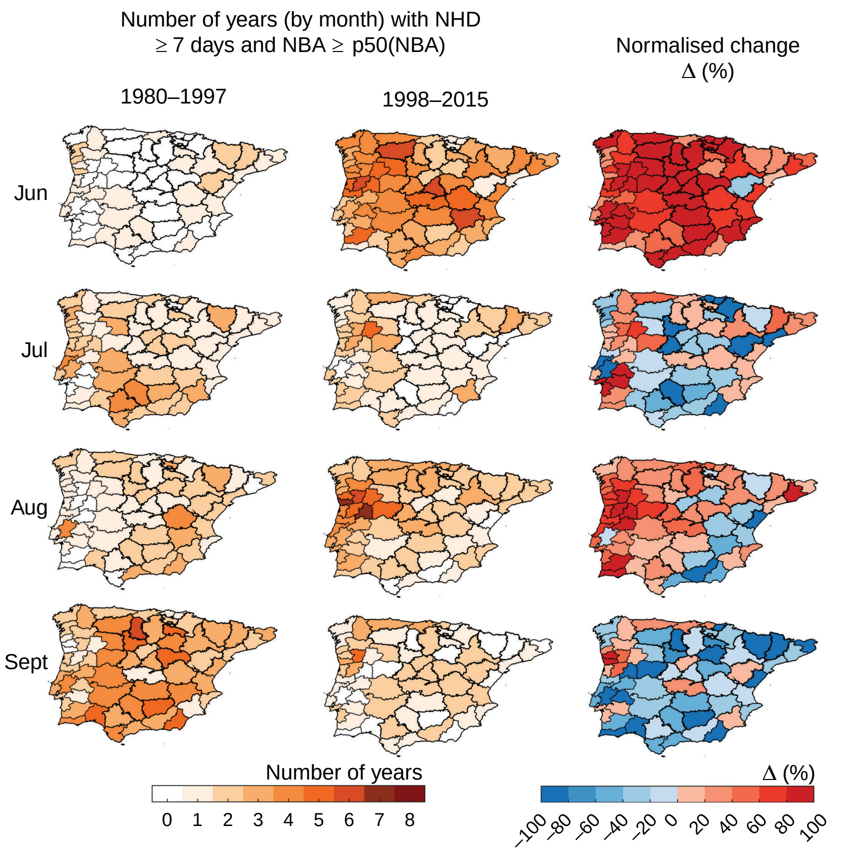

Fig. 5. As in Figs 3, 4 but for concurrent events (in the same month) of number of hot days (NHDs) larger or equal to 7 days and normalised burned area (NBA) larger or equal than p50(NBA).

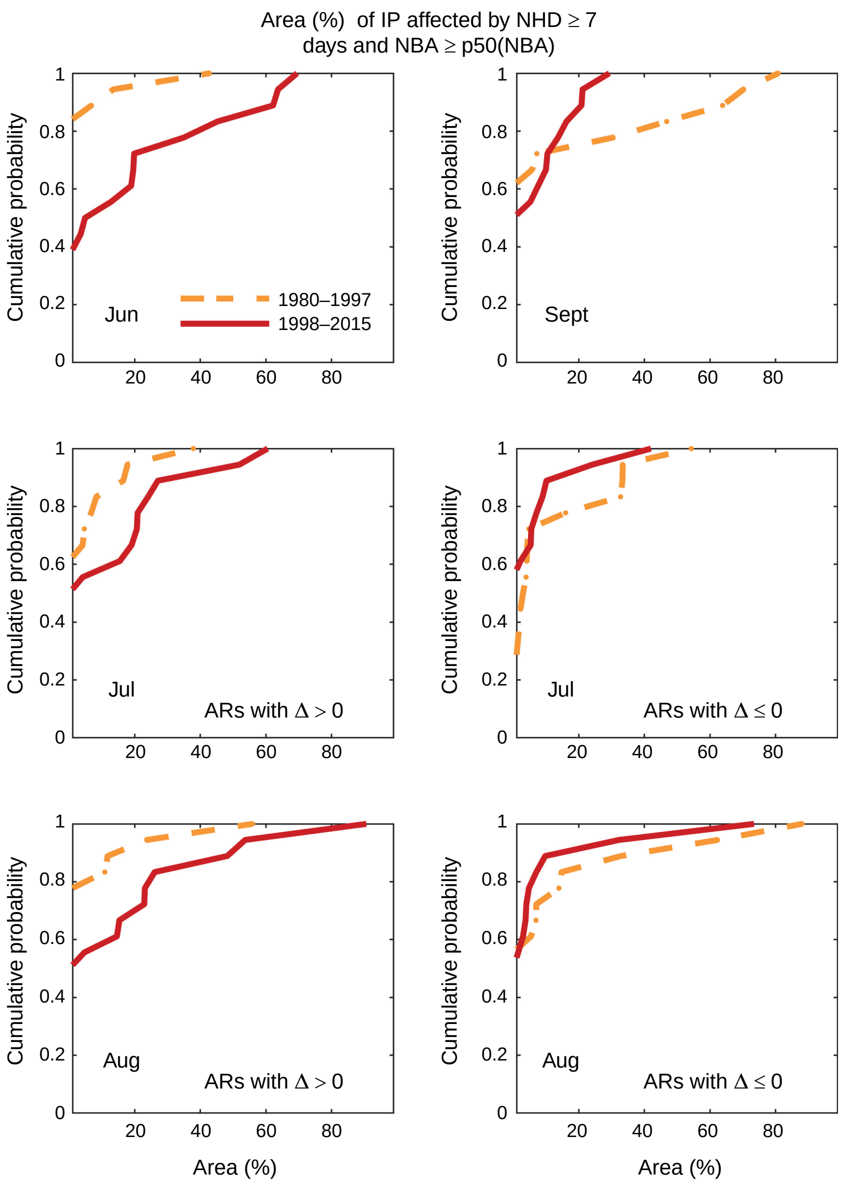

Fig. 6. Area (%) of Iberian Peninsula (IP) affected by concurrent hot days (NHDs) larger or equal than 7 days and normalised burned area (NBA) larger or equal than p50(NBA). Empirical Cumulative Distribution Functions (ECFDs) show the probability of having 1 month with some area (%) affected by concurrent events. Reference period (1980–1997) and the subsequent period (1998–2015) are marked as dashed orange lines and solid red lines, respectively.

Conversely, the month of September shows a large difference in area affected by extreme events (upper end of the curves; from 80% of area affected in the reference period to ~30% in recent years). In turn, the likelihood of having up to 10% of an area affected by concurrent events has increased in recent years. Finally, July and August show very similar results between the reference and recent ECDFs.

ECDFs representing the months of July and August are further divided into positive and negative changes in NHDs greater than 7 days and NBA higher than usual, i.e., ARs with $\Delta > 0$ (Fig. 6, left) and $\Delta \leq 0$ (Fig. 6, right), respectively, because there is a more pronounced dichotomic behaviour between ARs in these months when compared with June (mainly positive Δ) and September (mainly negative Δ). Indeed, results in July and August for positive change show a similar behaviour to June with an overall increase in area affected by these events. However, for negative changes, differences between the two periods are small, especially when compared with differences found in September.

Recent change in concurrent heatwaves and NBA

Similar results are observed when, instead of 7 or more hot days in 1 month, at least one heatwave is considered as concurrent with NBA (Supplementary Fig. S1). A composite of the concurrent events in the JJAS period is shown in Fig. 7, where the map (left) shows the values of Δ for these events (between the reference and subsequent periods). The ECDFs are divided into positive and negative changes in both number of heatwaves and higher than

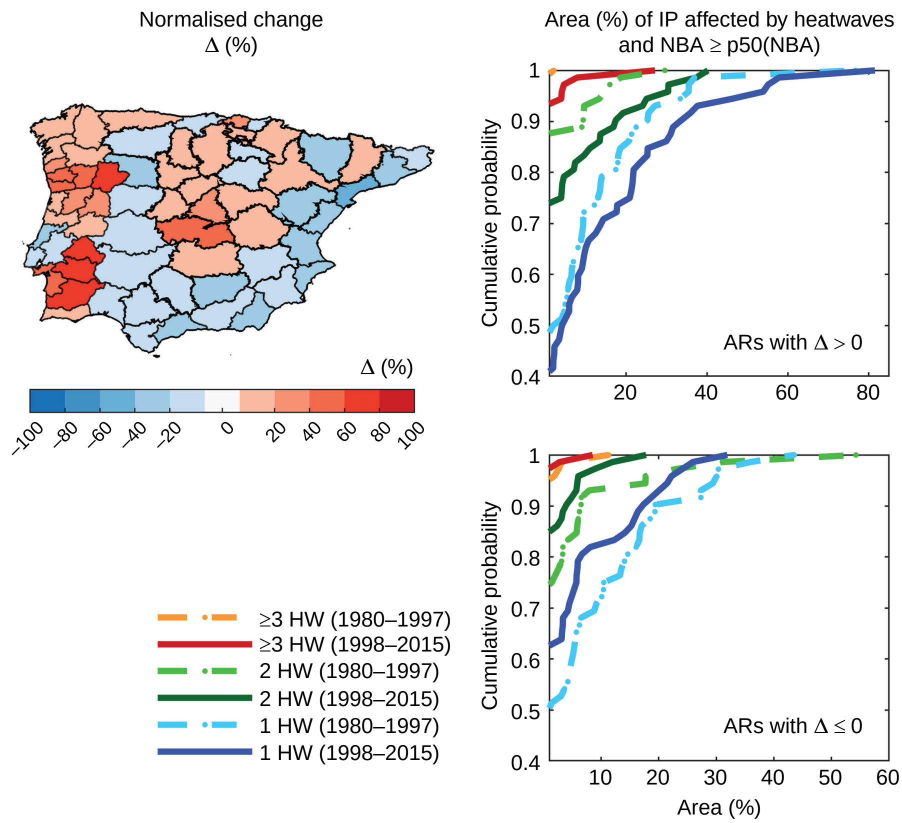

Fig. 7. Normalised change coefficient (map) of JJAS concurrent events (in the same month) of at least one heatwave (individual months in Supplementary Fig. S1) and NBA larger than or equal to p50(NBA). Empirical Cumulative Distribution Functions (ECDFs) show the area (%) of the Iberian Peninsula (IP) affected by concurrent heatwaves and normalised burned area (NBA) larger or equal than p50(NBA). These are divided into concurrent events with one heatwave (orange/red), two heatwaves (green), and three or more heatwaves (blue) in the same month. The reference period (1980–1997) and the subsequent period (1998–2015) are marked by dashed lines and solid lines, respectively.

usual NBA, respectively ARs with $\Delta > 0$ (right, top panel) and $\Delta \leq 0$ (right, bottom panel). Furthermore, ECDFs also characterise concurrent NBA larger than its 50th percentile and one, two, and three or more heatwaves in the same month (blue, green and red, respectively). As with NHDs, concurrent NBA and heatwaves increased mainly in June and August and decreased in July and September (Supplementary Fig. S1), with an overall summer increase of such events mainly over Portugal and regions of central and north-western Spain.

When comparing ECDFs representing positive values of Δ (Fig. 7, top panel), results show that changes in area affected by one heatwave and NBA larger than its 50th percentile (dashed blue line for reference period and solid blue line for subsequent period) are minor, with a shift of the subsequent period curve to the right that is followed by the reference period for the maximum values. This may be due to severe heatwaves that took place during the reference period, such as the one that affected Portugal in June 1981 (Garcia *et al.* 1999; Trigo *et al.* 2005) and the heatwave at the origin of the July–August extreme fire season of 1991 (Nunes *et al.* 2005, 2019; Carmo *et al.* 2011). Without these two extreme cases, the maximum percentage area affected by concurrent events in the reference period decreases from 80% (as shown in Fig. 7) to ~35%. Moreover, ECDFs representing area affected by concurrent NBA and more than one heatwave (dashed and solid green lines for two heatwaves for recent and subsequent periods, respectively; and dashed and solid red lines for ≥3 heatwaves, respectively) experience a larger shift to the right, meaning a lower probability of a smaller area affected by concurrent events and higher probability of a larger areas affected by these events. Indeed, the maximum area affected by concurrent NBA larger than its median and three or more heatwaves in the reference period was ~3% (orange dashed line), whereas in the subsequent period that maximum area increased tenfold to ~30% (solid red line).

Conversely, ARs with negative values of Δ (Fig. 7, bottom panel) show a shift to the left of the curves characterising the subsequent period, independently of the number of heatwaves, meaning these regions experience a decrease in probability of having large areas affected by these events.

Finally, and as expected, concurrent events of wildfires defined with an NBA larger than usual (median) for the JJAS period and 7 or more NHDs in the same month or heatwaves defined as 3 or more consecutive hot days in the same month, show very similar spatial patterns. However, the discretisation of heatwaves in number of heatwaves in a month may be viewed as an added value regarding the use of NHD (which may be scattered along the month). Indeed, the number of years with monthly concurrent heatwaves and NBA larger than its median is generally higher than the number of years with 7 or more hot days(Fig. 5, Supplementary Fig. S1).

Discussion

The relationship between NBA and NHD is stronger over the north-western IP in the months of June, July and August. These regions are extensively forested and are those with larger BA (Fig. 1, left panel), which mainly results from wildfire occurrences in July and August (Oliveira *et al.* 2012; Pereira *et al.* 2015; Trigo *et al.* 2016). The shift of significant correlations to southern regions observed in September may be related to the different fire regimes over the IP. Indeed, these regions are characterised by a drier climate, the vegetation being drier and sparser than in the northern parts. It should also be stressed that the ARs shown in September are generally characterised by lower values of BA (Fig. 1, left panel). Moreover, when NHDs are combined with those of the previous months, parts of the north-western IP (particularly those located over Portugal) present an increase in the correlations between NBA and NHDs in July and August.

When combining NHDs with previous months, an interesting case arises: the north-western region of Portugal in August. This region presents larger correlations when combined with the previous and the two previous months (Fig. 2, centre and right panels, respectively). This is an indication of the sensitivity of fire danger – which in turn is directly related to the high availability of biomass and fuel over the region (Gouveia *et al.* 2012) – to very hot days occurring in June (the month that precedes July) and in June and July (the 2 months preceding August).

It is worth noting that correlations between NBA and NHD indicate: (1) the existence of spatial consistency, i.e. larger significant correlations are clustered in specific regions, which are mainly found in the north-western IP; (2) the largest correlations are found in fire-prone regions; and (3) the existence of memory in the relationship between BAs and NHDs from previous months. Although this work reveals a strong relationship between these two variables, it is worth stressing that hot days are just one of the drivers of fire occurrence among other variables such as wind speed and direction, relative humidity and available biomass (Russo *et al.* 2017; Nunes *et al.* 2019; Vieira *et al.* 2020; Oliveira *et al.* 2021). Even so, these results reveal the importance of summer and early summer hot days for BA in specific regions of the IP.

The number of years with 7 or more hot days has substantially increased in June over the entire IP in the period 1998–2015 when compared with 1980–1997. Indeed, early hot events have been widely recorded in the last decade over the IP (Sánchez-Benítez *et al.* 2018; Sousa *et al.* 2019), namely in June 2017. Furthermore, according to the studies by Peña-Ortiz *et al.* (2015), as a result of the ongoing climate change, summers are becoming longer and with an earlier onset (i.e. June), and the linear trends of temperature over the IP agree with results presented here that show a positive trend in June, and a negative trend in September. Additionally, in September, several ARs (except northwest Portugal and some ARs over northwest Spain) experienced a decrease in NHDs over the same period. Regarding NBA, this seems to have decreased over time, especially over Spanish territory. This may be connected to mitigation policies such as the increase in fire suppression to protect urban settlements and increases in firefighting resources, particularly aerial ones (Seijo and Gray 2012; Urbieta *et al.* 2019; Jiménez-Ruano *et al.* 2020; Rodrigues et al. 2020). The substantial decrease in concurrent events in September may also be a result of the shift to early summers as well as of fire mitigation policies (Peña-Ortiz *et al.* 2015).

Concurrent NBA (larger than the 50th percentile) and NHD (larger or equal to 7 days) or heatwaves (three or more consecutive hot days) have substantially increased in June (entire IP) and August (except eastern Spain), and mainly decreased in September. In July, there is an increase in concurrent events in some ARs (e.g. southeast IP) while others show a decrease in events (e.g. southern Spain). Furthermore, the probability of having a larger area of the IP simultaneously affected by such events in June has substantially increased in the recent period, whereas in September it has decreased. Finally, the area affected by concurrent wildfires and three or more heatwaves in 1 month has increased tenfold over the IP (for ARs that show an increase in concurrent events between the reference and subsequent periods).

Conclusions

Wildfires are a recurrent phenomenon that entail serious social and economic consequences. Furthermore, wildfires are known to frequently occur in southern European countries such as Portugal and Spain. With climate change projections showing an increase in wildfire danger and indicating this region as a hotspot of global warming, the study and understanding of the mechanisms and responses of wildfires to meteorological events are increasingly relevant. The rationale of this work was to understand the relationship between wildfire-related NBA and summer heat extremes (defined based on the observed number of monthly NHDs or heatwaves) over the IP (at the ARs level). Correlations between the two variables indicated the existence of spatial consistency with higher values in the north-western region of the IP, which is also characterised by fire-prone vegetation, and the existence of a 'memory factor' in the relationship between BA and NHDs from previous months. Results showed that there were substantial changes in the behaviour of NBA and NHD and concordance between the two in different summer months over the IP. Furthermore, this study draws attention to changes in extremely hot events in June over the IP, such as the 2017 heatwave that resulted in the deadliest wildfire episode ever recorded in Portugal. Hence, this work may pave the way to further studies that tackle extreme hot and dry events early in June, which in turn may become a key element in the development of early warning systems and awareness of national authorities of such events.

Supplementary material

Supplementary material is available online.

References

Augusto S, Ratola N, Tarín-Carrasco P, Jiménez-Guerrero P, Turco M, Schuhmacher M, Costa S, Teixeira JP, Costa C (2020) Population exposure to particulate-matter and related mortality due to the Portuguese wildfires in October 2017 driven by storm Ophelia. *Environment International* **144**, 106056. doi:10.1016/j.envint.2020.106056

Barriopedro D, Fischer EM, Luterbacher J, Trigo RM, García-Herrera R (2011) The hot summer of 2010: Redrawing the temperature record map of Europe. *Science* **332**, 220–224. doi:10.1126/science.1201224

Barriopedro D, Sousa PM, Trigo RM, García-Herrera R, Ramos AM (2020) The exceptional Iberian heatwave of summer 2018. *Bulletin of the American Meteorological Society* **101**, S29–S34. doi:10.1175/BAMS-D-19-0159.1

Carmo M, Moreira F, Casimiro P, Vaz P (2011) Land use and topography influences on wildfire occurrence in northern Portugal. *Landscape and Urban Planning* **100**, 169–176. doi:10.1016/j.landurbplan.2010.11.017

Cornes RC, van der Schrier G, van den Besselaar EJM, Jones PD (2018) An ensemble version of the E-OBS temperature and precipitation data sets. *Journal of Geophysical Research: Atmospheres* **123**, 9391–9409. doi:10.1029/2017JD028200

Costa L, Thonicke K, Poulter B, Badeck F-W (2011) Sensitivity of Portuguese forest fires to climatic, human, and landscape variables: Subnational differences between fire drivers in extreme fire years and decadal averages. *Regional Environmental Change* **11**, 543–551. doi:10.1007/s10113-010-0169-6

Departamento de Gestão de Áreas Públicas ede Proteção Florestal (2017) Nono relatório provisório de incêndios florestais - 2017. Instituto da Conservação da Natureza e das Florestas (ICNF) (Lisboa). Available at https://www.icnf.pt/api/file/doc/7b89239f0e8506f2

Dupuy J-l, Fargeon H, Martin-StPaul N, Pimont F, Ruffault J, Guijarro M, Hernando C, Madrigal J, Fernandes P (2020) Climate change impact on future wildfire danger and activity in southern Europe: a review. *Annals of Forest Science* **77**, 35. doi:10.1007/s13595-020-00933-5

Garcia A, Nogueira P, Falcão J (1999) Onda de calor de junho de 1981 em Portugal: efeitos na mortalidade. *Revista Portuguesa de Saúde Pública* **1**, 67–77.

García-Herrera R, Hernández E, Barriopedro D, Paredes D, Trigo RM, Trigo IF, Mendes MA, García-Herrera R, Hernández E, Barriopedro D, Paredes D, Trigo RM, Trigo IF, Mendes MA (2007) The outstanding 2004/05 drought in the Iberian Peninsula: associated atmospheric circulation. *Journal of Hydrometeorology* **8**, 483–498. doi:10.1175/JHM578.1

Garcia-Herrera R, Díaz J, Trigo RM, Luterbacher J, Fischer EM (2010) A review of the European summer heat wave of 2003. *Critical Reviews in Environmental Science and Technology* **40**, 267–306. doi:10.1080/10643380802238137

Gasparrini A, Guo Y, Sera F, Vicedo-Cabrera AM, Huber V, Tong S, de Sousa Zanotti Stagliorio Coelho M, Nascimento Saldiva PH, Lavigne E, Matus Correa P, Valdes Ortega N, Kan H, Osorio S, Kyselý J, Urban A, Jaakkola JJK, Ryti NRI, Pascal M, Goodman PG, Zeka A, Michelozzi P, Scortichini M, Hashizume M, Honda Y, Hurtado-Diaz M, Cesar Cruz J, Seposo X, Kim H, Tobias A, Iñiguez C, Forsberg B, Åström DO, Ragettli MS, Guo YL, Wu C-f, Zanobetti A, Schwartz J, Bell ML, Dang TN, Van DD, Heaviside C, Vardoulakis S, Hajat S, Haines A, Armstrong B (2017) Projections of temperature-related excess mortality under climate change scenarios. *Lancet Planetary Health* **1**, e360–e367. doi:10.1016/S2542-5196(17)30156-0

Geirinhas JL, Russo A, Libonati R, Trigo RM, Castro LCO, Peres LF, Magalhães MdeAFM, Nunes B (2020) Heat-related mortality at the beginning of the twenty-first century in Rio de Janeiro, Brazil. *International Journal of Biometeorology* **64**, 1319–1332. doi:10.1007/s00484-020-01908-x

Gouveia CM, Trigo RM, DaCamara CC (2009) Drought and vegetation stress monitoring in Portugal using satellite data. *Natural Hazards and Earth System Sciences* **9**, 185–195. doi:10.5194/nhess-9-185-2009

Gouveia CM, Bastos A, Trigo RM, DaCamara CC (2012) Drought impacts on vegetation in the pre- and post-fire events over Iberian Peninsula. *Natural Hazards and Earth System Sciences* **12**, 3123–3137. doi:10.5194/nhess-12-3123-2012

Gouveia CM, Bistinas I, Liberato MLR, Bastos A, Koutsias N, Trigo R (2016) The outstanding synergy between drought, heatwaves and fuel on the 2007 Southern Greece exceptional fire season. *Agricultural and Forest Meteorology* **218–219**, 135–145. doi:10.1016/j.agrformet.2015.11.023

Hernandez C, Drobinski P, Turquety S (2015*a*) How much does weather control fire size and intensity in the Mediterranean region? *Annals of Geophysics* **33**, 931–939. doi:10.5194/angeo-33-931-2015

Hernandez C, Keribin C, Drobinski P, Turquety S (2015*b*) Statistical modelling of wildfire size and intensity: A step toward meteorological forecasting of summer extreme fire risk. *Annals of Geophysics* **33**, 1495–1506. doi:10.5194/angeo-33-1495-2015

Jiménez-Ruano A, de la Riva Fernández J, Rodrigues M (2020) Fire regime dynamics in mainland Spain. Part 2: A near-future prospective of fire activity. *Science of the Total Environment* **705**, 135842. doi:10.1016/j.scitotenv.2019.135842

Kong Q, Guerreiro SB, Blenkinsop S, Li XF, Fowler HJ (2020) Increases in summertime concurrent drought and heatwave in eastern China. *Weather and Climate Extremes* **28**, 100242. doi:10.1016/j.wace.2019.100242

Lavorel S, Flannigan MD, Lambin EF, Scholes MC (2007) Vulnerability of land systems to fire: Interactions among humans, climate, the atmosphere, and ecosystems. *Mitigation and Adaptation Strategies for Global Change* **12**, 33–53. doi:10.1007/s11027-006-9046-5

Leonard M, Westra S, Phatak A, Lambert M, van den Hurk B, McInnes K, Risbey J, Schuster S, Jakob D, Stafford-Smith M (2014) A compound event framework for understanding extreme impacts. *Wiley Interdisciplinary Reviews: Climate Change* **5**, 113–128. doi:10.1002/wcc.252

Liu JC, Pereira G, Uhl SA, Bravo MA, Bell ML (2015) A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke. *Environmental Research* **136**, 120–132. doi:10.1016/j.envres.2014.10.015

Liu JC, Mickley LJ, Sulprizio MP, Yue X, Peng RD, Dominici F, Bell ML (2016) Future respiratory hospital admissions from wildfire smoke under climate change in the Western US. *Environmental Research Letters* **11**, 124018. doi:10.1088/1748-9326/11/12/124018

Liu JC, Wilson A, Mickley LJ, Dominici F, Ebisu K, Wang Y, Sulprizio MP, Peng RD, Yue X, Son JY, Anderson GB, Bell ML (2017) Wildfire-specific fine particulate matter and risk of hospital admissions in urban and rural counties. *Epidemiology* **28**, 77–85. doi:10.1097/EDE.0000000000000556

Mazdiyasni O, AghaKouchak A (2015) Substantial increase in concurrent droughts and heatwaves in the United States. *Proceedings of the National Academy of Sciences of the United States of America* **112**, 11484–11489. doi:10.1073/pnas.1422945112

Moriondo M, Good P, Durao R, Bindi M, Giannakopoulos C, Corte-Real J (2006) Potential impact of climate change on fire risk in the Mediterranean area. *Climate Research* **31**, 85–95. doi:10.3354/cr031085

Nunes MCS, Vasconcelos MJ, Pereira JMC, Dasgupta N, Alldredge RJ, Rego FC (2005) Land cover type and fire in Portugal: Do fires burn land cover selectively? *Landscape Ecology* **20**, 661–673. doi:10.1007/s10980-005-0070-8

Nunes SA, Dacamara CC, Turkman KF, Calado TJ, Trigo RM, Turkman MAA (2019) Wildland fire potential outlooks for Portugal using meteorological indices of fire danger. *Natural Hazards and Earth System Sciences* **19**, 1459–1470. doi:10.5194/nhess-19-1459-2019

Oliveira SLJ, Pereira JMC, Carreiras JMB (2012) Fire frequency analysis in Portugal (1975–2005), using Landsat-based burnt area maps.

International Journal of Wildland Fire **21**, 48–60. doi:10.1071/WF10131

Oliveira M, Delerue-Matos C, Pereira MC, Morais S (2020) Environmental particulate matter levels during 2017 large forest fires and megafires in the center region of Portugal: A public health concern? *International Journal of Environmental Research and Public Health* **17**, 1032. doi:10.3390/ijerph17031032

Oliveira S, Gonçalves A, Zêzere JL (2021) Reassessing wildfire susceptibility and hazard for mainland Portugal. *Science of the Total Environment* **762**, 143121–143121. doi:10.1016/j.scitotenv.2020.143121

Parente J, Pereira MG, Amraoui M, Fischer EM (2018) Heat waves in Portugal: Current regime, changes in future climate and impacts on extreme wildfires. *Science of the Total Environment* **631–632**, 534–549. doi:10.1016/j.scitotenv.2018.03.044

Peña-Ortiz C, Barriopedro D, García-Herrera R (2015) Multidecadal variability of the summer length in Europe. *Journal of Climate* **28**, 5375–5388. doi:10.1175/JCLI-D-14-00429.1

Pereira MG, Trigo RM, Da Camara CC, Pereira JMC, Leite SM (2005) Synoptic patterns associated with large summer forest fires in Portugal. *Agricultural and Forest Meteorology* **129**, 11–25. doi:10.1016/j.agrformet.2004.12.007

Pereira MG, Caramelo L, Orozco CV, Costa R, Tonini M (2015) Space–time clustering analysis performance of an aggregated dataset: The case of wildfires in Portugal. *Environmental Modelling & Software* **72**, 239–249. doi:10.1016/j.envsoft.2015.05.016

Richardson LA, Champ PA, Loomis JB (2012) The hidden cost of wildfires: Economic valuation of health effects of wildfire smoke exposure in southern California. *Journal of Forest Economics* **18**, 14–35. doi:10.1016/j.jfe.2011.05.002

Rodrigues M, Jiménez-Ruano A, de la Riva J (2020) Fire regime dynamics in mainland Spain. Part 1: Drivers of change. *Science of the Total Environment* **721**, 135841. doi:10.1016/j.scitotenv.2019.135841

Rossiello MR, Szema A (2019) Health Effects of Climate Change-induced Wildfires and Heatwaves. *Cureus* **11**(5), e4771. doi:10.7759/cureus.4771

Ruffault J, Moron V, Trigo RM, Curt T (2017) Daily synoptic conditions associated with large fire occurrence in Mediterranean France: evidence for a wind-driven fire regime. *International Journal of Climatology* **37**, 524–533. doi:10.1002/joc.4680

Ruffault J, Curt T, Moron V, Trigo R, Mouillot F, Koutsias N, Pimont F, Martin-StPaul N, Barbero R, Dupuy J-L, Russo A, Belhadj-Kheder C (2020) Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. *bioRxiv* 2020.01.09.896878. doi:10.1101/2020.01.09.896878

Russo A, Gouveia CM, Páscoa P, DaCamara CC, Sousa PM, Trigo RM (2017) Assessing the role of drought events on wildfires in the Iberian Peninsula *Agricultural and Forest Meteorology* **237–238**, 50–59. doi:10.1016/j.agrformet.2017.01.021

Russo A, Gouveia CM, Dutra E, Soares PMM, Trigo RM (2019) The synergy between drought and extremely hot summers in the Mediterranean. *Environmental Research Letters* **14**, 014011. doi:10.1088/1748-9326/aaf09e

Sánchez-Benítez A, García-Herrera R, Barriopedro D, Sousa PM, Trigo RM (2018) June 2017: The earliest European summer megaheatwave of reanalysis period. *Geophysical Research Letters* **45**, 1955–1962. doi:10.1002/2018GL077253

Seijo F, Gray R (2012) Pre-industrial anthropogenic fire regimes in transition: The case of Spain and its implications for fire governance in Mediterranean-type biomes. *Human Ecology Review* **19**, 58–69.

Shaposhnikov D, Revich B, Bellander T, Bedada GB, Bottai M, Kharkova T, Kvasha E, Lezina E, Lind T, Semutnikova E, Pershagen G (2014) Mortality related to air pollution with the Moscow heat wave and wildfire of 2010. *Epidemiology* **25**, 359–364. doi:10.1097/EDE.0000000000000090

Sousa PM, Trigo RM, Aizpurua P, Nieto R, Gimeno L, Garcia-Herrera R (2011) Trends and extremes of drought indices throughout the 20th century in the Mediterranean. *Natural Hazards and Earth System Sciences* **11**, 33–51. doi:10.5194/nhess-11-33-2011

Sousa PM, Trigo RM, Pereira MG, Bedia J, Gutiérrez JM (2015) Different approaches to model future burnt area in the Iberian Peninsula. *Agricultural and Forest Meteorology* **202**, 11–25. doi:10.1016/j.agrformet.2014.11.018

Sousa PM, Barriopedro D, Ramos AM, García-Herrera R, Espírito-Santo F, Trigo RM (2019) Saharan air intrusions as a relevant mechanism for Iberian heatwaves: The record breaking events of August 2018 and June 2019. *Weather and Climate Extremes* **26**, 100224. doi:10.1016/j.wace.2019.100224

Sutanto SJ, Vitolo C, Di Napoli C, D'Andrea M, Van Lanen HAJ (2020) Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale. *Environment International* **134**, 105276. doi:10.1016/j.envint.2019.105276

Trigo RM, García-Herrera R, Díaz J, Trigo IF, Valente MA (2005) How exceptional was the early August 2003 heatwave in France? *Geophysical Research Letters* **32**, 1–4. doi:10.1029/2005GL022410

Trigo RM, Pereira JMC, Pereira MG, Mota B, Calado TJ, Dacamara CC, Santo FE (2006*a*) Atmospheric conditions associated with the exceptional fire season of 2003 in Portugal. *International Journal of Climatology* **26**, 1741–1757. doi:10.1002/joc.1333

Trigo RM, Pereira JMC, Pereira MG, Mota B, Calado TJ, Dacamara CC, Santo FE (2006*b*) Atmospheric conditions associated with the exceptional fire season of 2003 in Portugal. *International Journal of Climatology* **26**, 1741–1757. doi:10.1002/joc.1333

Trigo RM, Sousa PM, Pereira MG, Rasilla D, Gouveia CM (2016) Modelling wildfire activity in Iberia with different atmospheric circulation weather types. *International Journal of Climatology* **36**, 2761–2778. doi:10.1002/joc.3749

Turco M, Bedia J, Di Liberto F, Fiorucci P, Von Hardenberg J, Koutsias N, Llasat MC, Xystrakis F, Provenzale A (2016) Decreasing fires in Mediterranean Europe. *PLoS One* **11**, e0150663. doi:10.1371/journal.pone.0150663

Turco M, Von Hardenberg J, AghaKouchak A, Llasat MC, Provenzale A, Trigo RM (2017) On the key role of droughts in the dynamics of summer fires in Mediterranean Europe. *Scientific Reports* **7**, 81. doi:10.1038/s41598-017-00116-9

Turco M, Jerez S, Augusto S, Tarín-Carrasco P, Ratola N, Jiménez-Guerrero P, Trigo RM (2019) Climate drivers of the 2017 devastating fires in Portugal. *Scientific Reports* **9**, 13886. doi:10.1038/s41598-019-50281-2

Urbieta IR, Franquesa M, Viedma O, Moreno JM (2019) Fire activity and burned forest lands decreased during the last three decades in Spain. *Annals of Forest Science* **76**, 90. doi:10.1007/s13595-019-0874-3

Vieira I, Russo A, Trigo RM (2020) Identifying local-scale weather forcing conditions favorable to generating Iberia's largest fires. *Forests* **11**, 547. doi:10.3390/f11050547

Vitolo C, Di Napoli C, Di Giuseppe F, Cloke HL, Pappenberger F (2019) Mapping combined wildfire and heat stress hazards to improve evidence-based decision making. *Environment International* **127**, 21–34. doi:10.1016/j.envint.2019.03.008

Zhang X, Hegerl G, Zwiers FW, Kenyon J (2005) Avoiding Inhomogeneity in Percentile-Based Indices of Temperature Extremes. *Journal of Climate* **18**(11), 1641–1651. doi:10.1175/jcli3366.1

Zscheischler J, Westra S, Van Den Hurk BJJM, Seneviratne SI, Ward PJ, Pitman A, Aghakouchak A, Bresch DN, Leonard M, Wahl T, Zhang X (2018) Future climate risk from compound events. *Nature Climate Change* **8**, 469–477. doi:10.1038/s41558-018-0156-3

Zscheischler J, Martius O, Westra S, Bevacqua E, Raymond C, Horton RM, van den Hurk B, AghaKouchak A, Jézéquel A, Mahecha MD, Maraun D, Ramos AM, Ridder NN, Thiery W, Vignotto E (2020) A typology of compound weather and climate events. *Nature Reviews Earth & Environment* **1**, 333–347. doi:10.1038/s43017-020-0060-z

Data availability. Burned area data was obtained from ICNF (https://www.icnf.pt/) and EGIF from MAPA (https://www.mapa.gob.es/es/). Land cover is from https://land.copernicus.eu/pan-european/corine-land-cover. Daily values of maximum temperature are from the European Climate Assessment & Dataset (ECA&D) E-OBS version 20.0e (https://www.ecad.eu/download/ensembles/download.php).

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