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Lightning-induced fire regime in Portugal based on satellite-derived and in situ data

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ABSTRACT

Fire databases typically contain information regarding the location, timing, and duration of fire occurrences, as well as the cause (natural or human-induced). These databases allow for the analysis and understanding of the circumstances surrounding the ignition and propagation of wildfires, being highly relevant when addressing fire suppression and management plans, or for improvement of prevention policies. In Portugal, a large number of fires in the official database have unknown causes, which limits the understanding about the relevance of each fire cause, in particular the role of lightning on the ignition of fires over the country. The objective of this paper is twofold: first, we investigated the spatial-temporal variability of lightning-induced fires from 2003 to 2020. Then, we evaluate the feasibility of using remote sensing data as a surrogate for identifying fire causes, through validation with the fire database. Our results revealed that lightning-ignited fires represent an even smaller fraction of all fire events than mentioned in the latest official report about fire causes in the country, accounting for only 1 % of the fire occurrences and 4.6 % of the total burned area in the 18-year period under analysis. The months of June to September comprise 91 % of all lightning fires, which occur more frequently in the northern, remote regions of the country and at relatively high altitudes. Moreover, lightning ignitions originate fires larger than the global average and contributed significantly to the total area burned during the extreme 2003 and 2017 fire seasons. Its importance in these extreme years suggests that lightning can trigger large fires when in conjunction with compound events such as droughts and heatwaves. When compared with in-situ databases, the application of remote sensing data reproduced the seasonality of lightning-ignited fires, but failed to account for the contribution of smaller fires, which represent the majority of occurrences in the Portuguese fire database. Finally, we discuss the implications of our findings for the improved assessment of fire risks, causes, and impacts in Portugal.

1. Introduction

Fires in southern Europe cause extensive economic and ecological losses, and even human casualties (Bowman et al., 2017; Turco et al., 2019, 2018). According to the provisional reports on rural fires over Portugal (ICNF, 2024a), prepared by the Institute for Nature Conservation and Forests (ICNF, Portuguese acronym), the years of 2003 and 2017 registered the largest burned extent over the 2000–2022 period, followed by the year 2005. These two extreme years for Portugal registered total annual burned areas values of over 430 000 ha in 2003 and reaching 470 000 ha in 2017 (Neves et al., 2023). The exceptional fire seasons of 2017 and 2003 were triggered by the compounding of several mechanisms, including severe heatwaves (Bastos et al., 2014; Sánchez-Benítez et al., 2018), drought conditions (Ermitão et al., 2022;

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Fink et al., 2004; García-Herrera et al., 2007; Turco et al., 2019) and the influence of tropical cyclone Ophelia in 2017 (Ramos et al., 2023). In particular, the fire season in 2017 lasted from June until October and was extremely intense over a wide region of Southern Europe, with large fires also observed in southern France, Italy and Spain (Ramos et al., 2023; Turco et al., 2018). Considering the latest climate projections, which point to an increase in frequency and severity of summer heatwaves and droughts (Arias et al., 2021), an increase in fire season severity is likely to occur in the Mediterranean basin (Calheiros et al., 2021; Dupuy et al., 2020; Ruffault et al., 2020; Turco et al., 2018). Variations in fuel availability and lightning flash rates driven by climate changes can also lead to a greater relevance of lightning as an ignition source especially under severe fire weather conditions (Krause et al., 2014; Pérez-Invernón et al., 2023).

The most recent analysis regarding fire causes showed that the vast majority of fires in Europe have an anthropogenic cause, while lightning plays a significant role only in the remote northern regions of Scandinavia (Dijkstra et al., 2022). Nevertheless, although Mediterranean-type areas are dominated by human-ignited fires, lightning can also trigger large events (Castedo-Dorado et al., 2011; Couto et al., 2020; Fernandes et al., 2021; Ganteaume et al., 2013; Nieto et al., 2012; Rodrigues et al., 2023). Recently, several studies are focusing on the interaction between lightning activity and fires in Northern and Western Europe, namely Larjavaara et al. (2005a, 2005b), Müller et al. (2013), Nieto et al. (2012), Couto et al. (2020), Conedera et al. (2006) and Pérez-Invernón et al. (2021). For instance, in Spain, lightning-ignited fires accounted for 3.9 % of all reported fires between 1991 and 2004 and most recently were the main cause of extreme fire events, larger than 5 000 ha, over the country during the 2022 fire season (Rodrigues et al., 2023). Natural-ignited fires tend to burn relatively large areas compared to human-ignited ones since they usually occur in remote areas, entailing two factors that contribute for the fire to become large: (i) initial suppression attack may be slow; (ii) alerts may be delayed because they are mostly triggered by people, and population density is low in such areas (Fernandes et al., 2021). These fires often occur in association with extreme meteorological conditions that promote dry thunderstorms and strong winds (Nieto et al., 2012), along with fire weather and lower fuel moisture conditions that favors the survival and development of the lightning ignition (Pineda and Rigo, 2017). In addition, Long-Continuum-Current lightning flashes, that is, CG (Cloud-to-ground) flashes presenting a continuing current phase lasting from tens to hundreds of milliseconds, are proposed to be the main precursor on the ignition of lightning-fires (Pérez-Invernón et al., 2023, 2021). In Brazilian wetlands, natural-caused fires only account for 1 % of the annual number of fires and 3 % of the burned area (Menezes et al., 2022). These numbers are considerably different from those recorded for the boreal and subalpine forests of Canada and in the USA, and for Australian forests. In Canada and in southeastern Australia, fires caused by lightning are responsible for up to 90 % of the burned area (Coogan et al., 2020; Dowdy and Mills, 2012; Hanes et al., 2019). In the western USA, lightning-ignited fires accounted for 40 % of the reported fires, corresponding to approximately 69 % of the total area burned from 1992 to 2013 (Abatzoglou et al., 2016). Since lightning ignitions constitute a major driver of fire in the boreal regions and also in U.S. forests (Abatzoglou et al., 2016; Larjavaara et al., 2005a, 2005b; Veraverbeke et al., 2017), research on lightning activity related to forest fire has a long tradition in these regions, contrary to what happens in Europe, where lightning causes only a small number of fires and is responsible for a limited percentage of total burned area (Dijkstra et al., 2022; Ganteaume et al., 2013; Nieto et al., 2012). However, in Mediterranean countries some very large fires have been started by lightning, such as the fire that consumed 17 521 ha in Góis, Portugal in June 2017, ignited moments after the widely reported fire of Pedrogão Grande, responsible for 64 fatalities and triggered by an electrical discharge from a power transmission line (Couto et al., 2020; CTI, 2022; Fernandes et al., 2021). Both fires took place during the most intense heatwave for the month of June ever recorded over Iberia (Sánchez-Benítez et al., 2018).

Individual fires can be analyzed using different sources of information, namely with field data collected by various agencies or through remote sensors (air- and space-borne). Information on where and when fires have started and their duration is typically included in fire databases, enabling the characterization of the conditions under which the fire ignited and spread (Benali et al., 2023, 2016). Additionally, other relevant attributes like the cause and type of fire (urban, wildfire, etc.), are also often available in these databases. Nevertheless, these are known to have: (i) multiple error sources; (ii) limited spatial coverage and/or time span, and; (iii) often unknown accuracy and uncertainty (Pereira et al., 2011). During the last decades, satellite data acquisition capabilities have improved significantly, being able to provide consistent and continuous data that can complement existing information and partially overcome some of the traditional limitations when studying individual fires (Benali et al., 2023, 2016; Chuvieco et al., 2018; Gouveia et al., 2018). Satellite data have been widely used to understand how land, atmosphere and climate affect vegetation dynamics and fire activity (Bastos et al., 2011; Chuvieco et al., 2018; Gouveia et al., 2018; Libonati et al., 2021) as well as to assess fire risk (Silva et al., 2019) and fire spread (Sá et al., 2017). Nevertheless, satellite data have their own limitations and uncertainties that need to be considered. In particular, satellite data are strongly affected by atmospheric factors (e.g. clouds) and the tradeoff between spatial resolution and the temporal revisiting period affects its utility, depending on the target application (Fusco et al., 2019; Ying et al., 2019). Additionally, fire size, duration, intensity, thermal contrast with surrounding areas, burned vegetation type, and persistent cloud clover and/or dense smoke plumes can influence the ability of satellites to monitor fires (Hawbaker et al., 2008; Oliva and Schroeder, 2015; Sá et al., 2017). Finally, from a comprehensive fire characterization database perspective, the largest limitation is that satellites cannot identify fire causes (Pereira et al., 2022).

In Portugal, previous published studies analyzed the relation between lightning activity and fire ignition, by means of the existing fire reports (Fernandes et al., 2021) or mostly relying on modeling approaches (Couto et al., 2020; Dijkstra et al., 2022). In this paper, we propose to take advantage of the potential of the existing satellite and fire reports databases to improve our understanding about the role of lightning activity in the ignition of fires in Portugal, and we investigate its relative contribution to the national fire regime based on a statistical approach. Additionally, we will explore the potential of satellites to provide alternative data in order to identify lightning-ignited fires. Based on these questions, we propose the following rationale: (i) investigate the temporal-spatial pattern of cloud-to-ground lightning discharges and of active fires over the 2003–2020 period; (ii) estimate the probability of a fire to be caused by a lightning event; (iii) for the fires that likely were triggered by lightning, we estimate the associated burned area; (iv) compare satellite-derived lightning fires with in-situ database information. Finally, we discuss the implications of our findings for improving assessment of the fire regime, risks, causes, and impacts in Portugal.

2. Materials

2.1. Study area

Portugal, the southwesternmost country in Europe, is characterized by a strong population density asymmetry between interior and coastal regions, which influences land use and, consequently, fire ignition and spread (Moreira et al., 2010). Comparatively to other Mediterranean countries, Portugal presented the largest burnt area and number of fires per unit of land area over the last five decades (Bastos et al., 2011; Marques et al., 2011; Pereira et al., 2011), which occurred mainly during the summer season (Ermitão et al., 2022; Koutsias et al., 2012; Ruffault et al., 2020; Turco et al., 2017). The years 2003, 2005 and 2017 were particularly extreme in Portugal, registering total burned areas of c.a. 430 000 ha, 340 000 ha and 470 000 ha (Neves et al., 2023), respectively. For this study, we will concentrate on the forest fires during the period 2003–2020 in the mainland of Portugal.

2.2. Lightning data

The Portuguese Lightning Location System has been in service since June 2002, and it is operated by the Portuguese Institute for the Sea and Atmosphere (IPMA, Portuguese acronym). This lightning network is composed of four IMPACT 141T-ESP detectors and also receives data from the Spanish agency (AEMET, Spain) that are acquired by five sensors located near the border of Portugal and Spain, which use the Time of Arrival (TOA) and Magnetic Direction Finder (MDF) techniques to locate lightning discharges and estimate the peak current (Rodrigues et al., 2010). According to Rodrigues et al. (2008), the manufactured flash detection efficiency exceeds 90 % for cloud to ground discharges that have the first return stroke with peak current greater than 5 kA. Moreover, the stroke detection efficiency is above 84 % for a study that integrated all LLS of Europe and it is known as EUCLID (Schulz et al., 2016). For this study, we used only CG lightning strokes (with time, location, and peak current information) for the period 2003–2020 observed in Portugal's mainland territory that had a major ellipse error lower than 10 km. During this 18-year period, a total of 328 522 CG lightnings meeting these criteria were detected by the Portuguese Lightning Location System. It is worth noting that positive and negative CG strokes were not distinguished in our work since previous studies have demonstrated that CG lightnings responsible for fire ignition did not present any characteristics that could distinguish them from the rest of the lightning sample, regarding its polarity, multiplicity or peak current (Moris et al., 2020; Pérez-Invernón et al., 2021; Pineda et al., 2014).

2.3. Forest fires data

2.3.1. ICNF database

The ICNF provides a dataset of individual fire reports containing information regarding several attributes of each fire, namely burned area, ignition and suppression date, ignition location, attributable cause, among others (ICNF, 2024b). This dataset has several caveats, namely uncertainties on location of the ignition point and area burned (Pereira et al., 2011). The first is a consequence of the uncertainty associated with the identification of the starting location. The database contains two types of fire start coordinates. When the fire cause investigation brigades were able to locate the fire start, the coordinates represent the actual point of ignition. When they fail to identify the ignition point, the coordinates of the placename nearest to the burned area are assigned as a nominal ignition point. On the other hand, there are important uncertainties in the estimation of the burned area associated with each ignition point, often presenting relevant discrepancies when compared with the burned area estimate using post-fire season remote sensing data. This caveat can be particularly pronounced for large fires with multiple ignitions coalescing in a single fire perimeter. Besides the above-mentioned spatial uncertainties and errors, the ICNF database also has temporal uncertainties associated with the time lag between the actual ignition time, which is typically unknown, and the time of first alert.

Nevertheless, an important aspect of the ICNF database is that it includes an attributed cause of the fire, allowing it to be classified into natural causes by lightning, negligence resulting from accidents or careless handling of the fire, arson, rekindling and undetermined causes (ICNF, 2014). However, fire cause is often missing from the fire database. For example, 65 % of all 398 964 occurrences do not have an attributed cause (i.e. were not investigated or have an undetermined cause), corresponding to roughly 35 % of the fires larger than 20 ha (Table 1) and 33.8 % of the total burned area in the study period. Nevertheless, the proportion of investigated fires began to increase significantly from 2006 onwards, reaching a maximum of 92 % in recent years (Figure S1).

2.3.2. Satellite active fire data

This dataset consists of active fires from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the satellites Terra and Aqua (MCD14ML), with spatial resolution of approximately 1 km at nadir, from 2003 to 2020 (FIRMS, 2024). The Aqua and Terra satellites overpass the study region twice each, at local times of around 1:30pm and 2:30am, and 10:30am and 10:30pm, respectively (Figure S2).

Here, we considered only pixels with inferred active fire type 0 (i.e. presumed vegetation fire) and estimated detection confidence equal or greater than 30 %, corresponding to nominal- and high-confidence fire pixels (Giglio, 2015). Excluding low confidence pixels from the sample will lower the false alarm rate and has little to no effect on detection rates, as they tend to occur at the periphery of higher confidence pixels (Hawbaker et al., 2008). The commission error of MODIS active fire detection algorithm increases with canopy cover, however over Europe it is considered negligible (less than 1 %), while the detection rate corresponds to roughly 9 % for a typical fire size of 5 ha (Giglio et al., 2016).

3. Methods

3.1. Lightning-ignited fire probability framework

The relationship between fire events and lightning occurrences was analyzed in terms of space and time proximity of the events, as proposed by Larjavaara et al. (2005b). This method consists of first computing the proximity index (A) between the fire event and all lightning strokes in the vicinity, denoted by Eq. (1). Secondly, it retrieves the probability (B) of the fire event being caused by lightning, according to Eq. (2).

$$A = \left(1 - \frac{\Delta t}{\Delta t_{max}}\right)\left(1 - \frac{D}{D_{max}}\right) \tag{1}$$

Table 1
Number of fire occurrences from the ICNF database, categorized by attributed cause and burned area (2003 - 2020). In parenthesis is the fraction represented by a given fire cause in each burned area category.

Burned Area (ha)	Fire frequency					
	Natural	Arson	Negligence	Rekindling	Undetermined	Non-investigated
< 1	1206 (**0.37 %**)	27,689 (**8.48 %**)	49,882 (**15.29 %**)	21,228 (**6.5 %**)	58,610 (**17.96 %**)	167,723 (**51.4 %**)
[1 - 10]	217 (**0.36 %**)	8150 (**13.46 %**)	13,605 (**22.47 %**)	2589 (**4.28 %**)	9741 (**16.09 %**)	26,244 (**43.35 %**)
[10 - 20]	30 (**0.73 %**)	807 (**19.63 %**)	1283 (**31.21 %**)	253 (**6.15 %**)	835 (**20.31 %**)	903 (**21.97 %**)
[20 - 50]	27 (**0.75 %**)	809 (**22.50 %**)	1190 (**33.09 %**)	233 (**6.48 %**)	745 (**20.72 %**)	592 (**16.46 %**)
[50 - 100]	12 (**0.70 %**)	429 (**24.99 %**)	533 (**31.04 %**)	96 (**5.59 %**)	379 (**22.07 %**)	268 (**15.61 %**)
[100 - 500]	36 (**1.92 %**)	543 (**28.93 %**)	541 (**28.82 %**)	153 (**8.15 %**)	386 (**20.56 %**)	218 (**11.61 %**)
[500 - 1000]	7 (**1.78 %**)	121 (**30.71 %**)	107 (**27.16 %**)	32 (**8.12 %**)	63 (**15.99 %**)	64 (**16.24 %**)
> 1000	17 (**4.42 %**)	140 (**36.36 %**)	77 (**20 %**)	31 (**8.05 %**)	62 (**16.10 %**)	58 (**15.06 %**)
Total	1552	38,688	67,218	24,615	70,821	196,070

$$B = 1 - \Pi_{i=1}^{n}(1 - A_i) \quad (2)$$

Where D and Δt represent the distance and the time interval between a lightning event and the fire event, Δt_{max} and D_{max} represent the maximum considered time interval (holdover time) and maximum distance between the lightning strokes and the fire ignition, n is the number of lightning strokes surrounding the fire and A_i is the proximity index for each lightning. For a given fire event, we discarded every surrounding lightning strike as a potential ignition source (i.e., the proximity index is set to zero) if either the time interval or distance are greater than their respective maximum values, thus both A_i and B can only vary between 0 and 1 and the higher the value of B, the higher is the probability that the fire event has been ignited by a lightning stroke.

For this approach, it is essential to determine the most suitable combination of Δt_{max} and D_{max} to select the potential candidate fires to be ignited by lightning, and the B threshold that will be used to identify fires that were likely ignited by lightning in the database. The maximum distance threshold (D_{max}) has been set to 10 km in respect to the maximum expected location error from the lightning location system (major ellipse error of 10 km). The temporal threshold would also have to account for holdover fires, that is, ignitions that go through a smoldering phase and take days before being detected and reported, which are a common phenomenon in the Alps (Moris et al., 2020). However, across the world lightning-ignited fires with short holdover times occur more frequently and the shortest holdover times are found in Mediterranean forests, woodlands and scrubs (Moris et al., 2023). In order to determine Δt_{max} and D_{max}, we first grouped the fire occurrences from ICNF into two subsets: validation, composed of the fires with a known attributed cause (arson, negligence, reignition and natural caused) and another subset, composed of the fires that were not investigated or had undetermined causes, hereafter designated as the unknown-cause subset. Then, we conducted two independent analyses, varying the temporal threshold (Δt_{max}) between one and five days: a sensitivity analysis, as described in Menezes et al. (2022), using the unknown dataset, and a performance assessment using only the dataset with known causes.

The performance assessment was conducted by calculating the true positive rate, the false alarm rate and the precision metrics (Wilks, 2019). The true positive rate was calculated as the ratio between the number of fires correctly indicated as lightning-caused and the total number of lightning-caused fires; the false alarm rate is the ratio between the number of fires wrongly indicated as lightning-caused and the total number of human-caused fires; the precision is given by the ratio between the number of fires correctly indicated as lightning-caused and the total number of fires estimated as likely lightning-ignited.

The most suitable combination of D_{max}, Δt_{max} and B threshold, based on the sensitivity analysis and performance assessment (see Section 4.2), is applied to post-classify the fire cause in the ICNF unknown subset, using the time of alert as reference. Accordingly, hereafter we refer to the lightning-ignited fires already classified by the ICNF as ICNF-LIF, while those post-classified as lightning-caused using our methodology will be referred to as ICNF-PCLIF. Thus, the two datasets are disjoint, such that all fires included in the new ICNF-PCLIF dataset are not part of the original ICNF-LIF list.

3.2. Relating active fires with lightning-caused fire reports

To assess the capability of this methodology to correctly identify lightning fires when using remote sensing data, we also classified all MODIS active fires used in this study according to their ignition cause, and compared only those classified as originated by lightning, hereafter referred to as lightning-ignited active fires (MODIS-LIAF), with ICNF-LIF and ICNF-PCLIF. The ICNF database only contains fire point location data, providing information such as the marked ignition point coordinates and its burned area. However, it does not provide information on the direction of spread. Therefore, the spatial assimilation was conducted considering a buffer radius surrounding the ICNF database fire, with an area equivalent to its total burned area. In turn, the MODIS active fire product presents a 1 km spatial resolution at nadir, but the spatial uncertainty of each individual observation may be higher depending on the view zenith angle and geometric correction process, necessary to remove geometric distortions caused by the instrument viewing geometry and other perturbations in the motion of the instrument relative to the surface (Wolfe et al., 1998). According to Benali et al. (2016), the spatial agreement of reported and satellite-derived ignitions from MODIS is below 2 km for most of the fire records, thus, this value was added to the buffer radius in order to account for the spatial uncertainty of the MODIS active fire product.

As stated before, the MODIS instrument overpasses the study area once each 12 h for each satellite, Terra and Aqua, totaling 4 scans at different times of the day. As a consequence of its temporal resolution, short-lived fire events could be extinguished between two consecutive satellite overpasses and not be detected. Additionally, omission error from the MODIS active fire product depends on weather conditions such as relative humidity, wind speed and cloud cover, but decreases with fire size (Fusco et al., 2019; Hawbaker et al., 2008; Ying et al., 2019), therefore, a fire event missed in the first scans would have to last until the following revisit cycle to be detected, resulting in a larger temporal lag between the reported and satellite-derived ignition time. However the absolute time lag between reported fires and MODIS active fires is below 12 h for most records, despite increasing with the area burned and reaching up to 48 h for fires greater than 10^4 ha (Benali et al., 2016). To account for this temporal uncertainty, in addition to the spatial assimilation we considered that a MODIS-LIAF was associated with a ICNF-LIF or ICNF-PCLIF if it was detected between its reported time of alert minus two days, and the reported extinction time. The MODIS-LIAF and the ICNF-LIF or ICNF-PCLIF are considered a match if they meet these criteria.

Finally, other MODIS-LIAF in the neighborhood of an assimilated one were also indicated as matched based on the same spatial and temporal thresholds, that is, if they are up to 2 km apart and had a time lag smaller than two days, which corresponds to four satellite overpasses.

4. Results

4.1. General patterns of lightning and fire activity

Fire seasonality inferred from the ICNF database (Fig. 1a) shows that the fire season in Portugal occurs mainly from June to October, with a peak in August, when total burned area per year reaches values greater than 10^4 ha (Fig. 1b). A secondary peak in March can be noted in both burned area and fire occurrence, often presenting values greater than 10^3 ha per year, which may be associated exclusively with pastoral burns, which are performed under mild weather conditions to ensure that fire does not get out of control, and negligent fires as discussed in Ganteaume et al. (2013) for Mediterranean countries. On the other hand, a minimum number of fire occurrences and burnt area (below 1000 ha) is seen from November to January, corresponding to the winter. Lightning frequency is also low during these months (Fig. 1c). Although during summer months there is a significant frequency of cloud-to-ground lightning, higher activity is concentrated at the end of spring (April and May) and beginning of autumn, particularly in September.

Looking for the inter-annual variability of CG strokes between 2003 and 2020 (Fig. 2a), we found an annual average of 18 251 ± 8 551 CG strokes per year. The years 2006, 2007 and 2018 had lightning activity above the mean value +1 standard deviation, while the years 2012, 2013, 2015 and 2016 had below normal lightning activity. Despite presenting an apparent negative trend in the annual number of fires, we do not observe the same tendency in the annual CG time series. The years 2005 and 2017, which presented a large amount of burned area (BA), were succeeded by one or more years with low values of BA and positive anomaly of CG strokes (Fig. 2b, c).

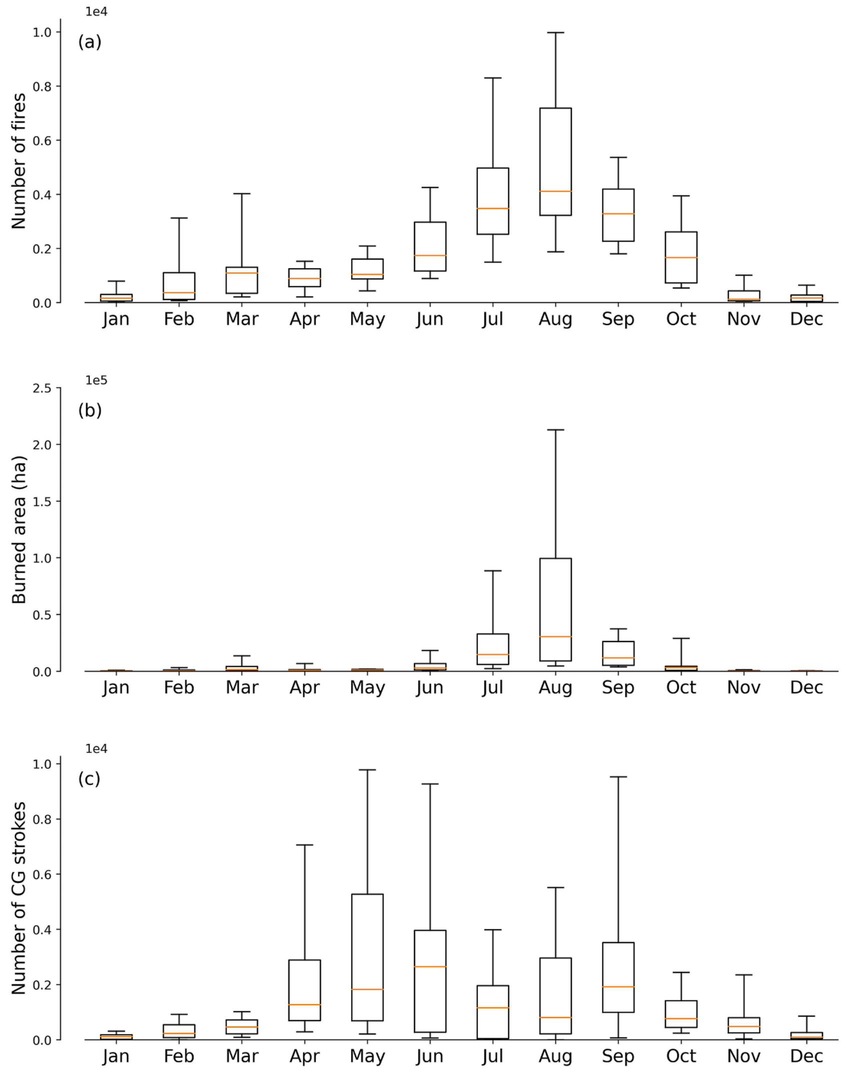

Fig. 1. Annual cycle of the (a) number of fires from the entire ICNF database, (b) corresponding total burned area and (c) number of CG strokes in Portugal, between 2003 and 2020. Orange lines inside each boxplot represent the median values, while the upper and lower whiskers denote the 5th and 95th percentiles, respectively.

The annual cloud-to-ground lightning density (CG strokes km^{-2} year^{-1}) values ranged from 0.4 in the central and northern regions and along 38°N (Fig. 3a), which characterizes two lightning density maxima over Portugal's mainland territory associated with mountain regions (Rodrigues et al., 2010), to almost no lightning activity in the southern and western shores of Portugal. Regarding the number of fires, independently of their cause, most of them were reported in the northwest region, while a second peak can also be seen along the western shore of Portugal, mainly over 39°N and 9°W (Fig. 3b), areas with low altitude and high population density (Moreira et al., 2010). This distribution mostly addresses smaller fires, which composes the majority of the ICNF database. On the other hand, Fig. 3c only depicts the spatial distribution of fires larger than 100 ha, many of which were reported in the northwest region as well as in the previous panel, but also in the northern and central regions of Portugal, towards the remote areas in the interior of the country.

4.2. Calibration of spatial and temporal thresholds

Given the need to determine the most suitable combination of Δt_{max}, D_{max}, and the B threshold, following the methodology described in Section 3.1, sensitivity analysis and performance assessments were conducted considering only the months in which the fire season takes place and CG lightnings are more relevant, that is, from June to September. The results were gathered for combinations varying the maximum holdover time between one to five days and the B threshold between 0.1 and 0.9, while keeping the maximum distance fixed at 10 km.

For the sensitivity analysis, the pattern of the results remained almost the same for different months. However, the number of fire occurrences from the unknown-cause subset selected as potential candidates tends to converge towards a common value when considering B values greater than 0.7 for different holdover times (Figure S3a to S3d). The total burned area from the potential candidates (Figures S3e to S3h) was more sensitive to changes in the thresholds during August, ranging from 30,000 ha for $B > 0.6$, to roughly 18,000 ha for $B > 0.9$. The use of three to five days as holdover time has negligible effects on the identification of lightning-related burned areas, in contrast with holdover times of one to two days.

In the performance assessment (Figure S4), up to 85 % of the true lightning fires were accounted for (i.e. presented at least one nearby lightning strike), given a minimum holdover time of three days. However, increasing the temporal threshold would slightly increase the true positive rate at the cost of precision, resulting in a considerable number of anthropogenic fires potentially being classified as lightning caused. The false alarm rate varies between 0.5 % and 3 % when considering B thresholds greater than 0.6 and are higher in June and September. Results applying either 0.7 or 0.8 as values for the B threshold did not vary,

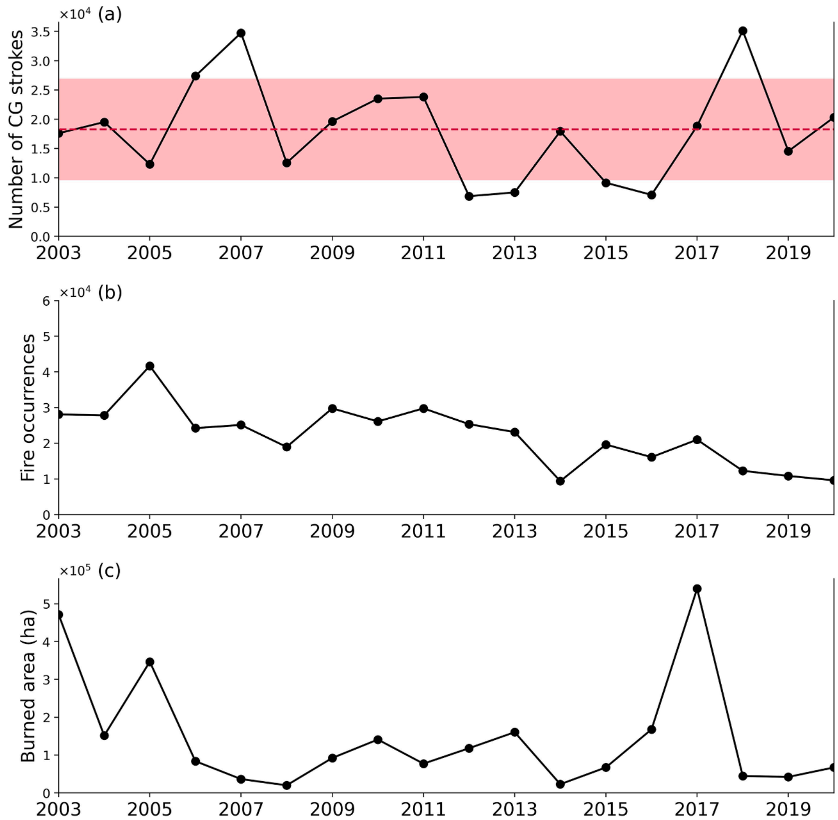

Fig. 2. Interannual variability of the (a) total number of CG strokes, (b) total number of fires from the entire ICNF database and (c) corresponding burned area. The red dashed lines and the red shaded areas in (a) correspond to the mean and +−1 standard deviation, respectively.

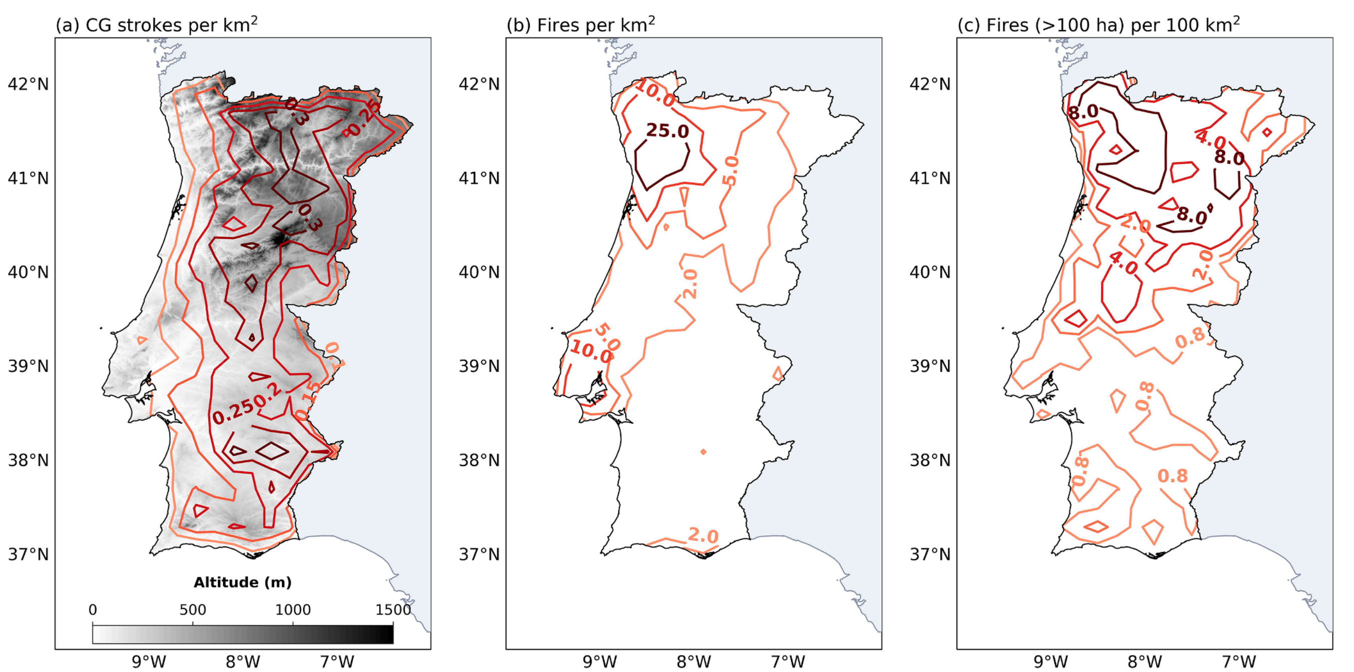

Fig. 3. Spatial distribution of (a) annual cloud-to-ground strokes, (b) total number of fires (counts / km^2) and (c) total number of fires larger than 100 ha (counts / 100 km^2) over a regular 0.2° × 0.2° grid, in Portugal from 2003 to 2020. Elevation data were obtained from the Digital Elevation - Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global, provided by USGS EROS Center (2017).

whereas increasing this threshold to 0.9 provides roughly 3 % of increase in precision and reduces the false alarm rate by 0.4 % but decreases the true positive rate by around 5 % in July and by 3 % in other months.

Therefore, we have opted to use for the subsequent analysis a combination of $D_{max} = 10$ km and $\Delta t_{max} = 3$ days. Accordingly, every fire event from the unknown-cause subset and MODIS active fire that presents a B threshold greater than 0.9 is considered to be lightning caused, denoted from here onwards as ICNF-PCLIF and MODIS-LIAF, respectively.

4.3. Climatology of lightning-ignited fires

In total, 1 552 fire occurrences were identified as lightning-caused over the study period by ICNF on their official database corresponding to ICNF-LIF, while those that we indicated as lightning fires (ICNF-PCLIF) total 1 917 occurrences. As stated before, most fire occurrences from the earlier years of the ICNF database were not investigated or do not have an attributed cause. Therefore, prior to 2009 there was a higher number of ICNF-PCLIF in comparison with ICNF-LIF, mainly in the years 2003, 2005 and 2006 (Fig. 4a). This was also addressed by Fernandes et al. (2021), who claimed that the true area burned by lightning-induced fires in the 2003 fire season may be substantially higher than the reported, due to the large number of fire records without an attributed cause. Moreover, the original ICNF-LIF dataset presents an increasing number of lightning fires over the years, while no significant trend was found when considering the joint ICNF-LIF and ICNF-PCLIF datasets, suggesting that the positive trend may be due to the increasing number of fires investigated (Fig. S1).

The total burned area aggregated from the fire reports in the ICNF-LIF is closely related to the total burned area by lightning in each year (Fig. 4b), meaning that the additional ICNF database fires here classified as likely ignited by lightning (ICNF-PCLIF) were, for the most part, small fires. Fig. 4c shows the spatial distribution of lightning fires over a regular 0.2° x 0.2° grid, according to the joint ICNF-PCLIF and ICNF-LIF datasets. Lightning-ignited fires occurred more frequently in the northern, more mountainous regions of the country, but the larger fires were reported in northeastern and central Portugal, while those recorded in the southwest occurred exclusively during the 2003 fire season. It is also possible to note that the region around 39°N and 9°W features a second peak in the distribution of lightning fires.

Even when the two datasets (ICNF-PCLIF and ICNF-LIF) are considered jointly, they only represent approximately 1 % of all fire occurrences in the 18-year period (Table 2), which is about half of the percentage presented in the fire cause report published by ICNF (2014). Regarding the burned area due to lightning fires, we also observed a lower percentage, corresponding to 4.6 % of the total burned area in the study period, in comparison with 5.6 % as gathered from the fire cause report. Since the published report only considers fires with known causes up to 2013, our results, despite being a relatively small percentage, may reflect the true proportion of lightning-ignited fires in the country. Nevertheless, lightning played a significant role as an ignition source in 2015, which presented a negative anomaly of CG strokes and below average burned area, in 2017 and especially in 2003, accounting for approximately 8.3 %, 4.2 % and 18.1 % of the total burnt area in these years, respectively. In addition, among the fraction of fires with known causes, lightning appears to have an increasing relevance as the fire size category increases (Table 1), which is in agreement with the statement that lightning fires are associated with more extensive burnt areas, on average (ICNF, 2014).

In Portugal, lightning-caused fires occur mainly between June and September, August being the most crucial month as it alone accounts for 75 % of the total burned extent (Fig. 5a). This pattern is also preserved when disregarding the 2003 and 2017 fire seasons, but rather than the second peak in June, we note an increasing value of burned area by natural causes from May to August (Fig. S5), followed by a significant decrease in September, even though lighting activity was found to be higher during May. MODIS-LIAF could reproduce well the intra-annual

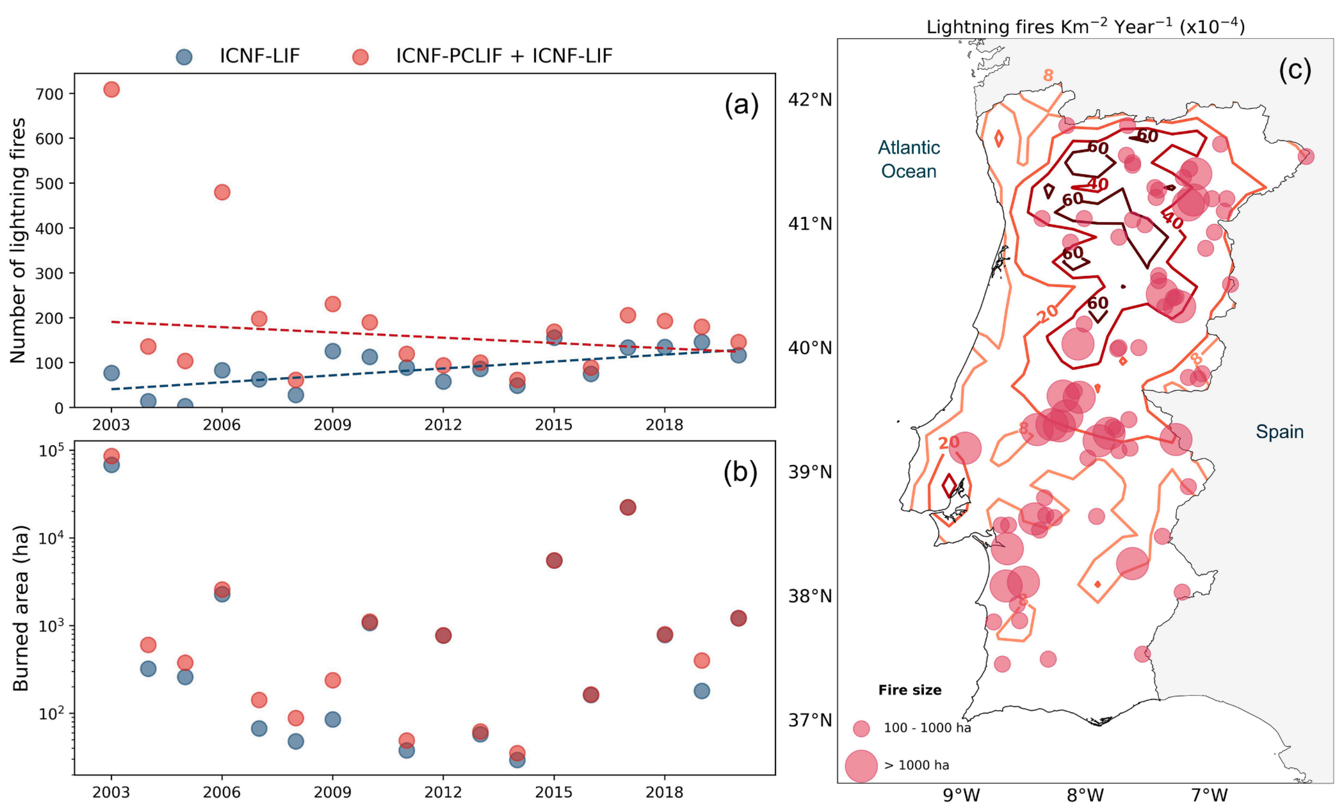

Fig. 4. Interannual variability of (a) number of lightning fires according to the original (ICNF-LIF) and the joint (ICNF-PCLIF and ICNF-LIF) datasets, (b) corresponding burned area and (c) spatial distribution of lightning fire counts over a regular 0.2° × 0.2° grid, in Portugal from 2003 to 2020. The location of lightning fires larger than 100 ha (according to the joint ICNF-LIF and ICNF-PCLIF datasets) is highlighted in the map. The trend for the number of lightning fires (ICNF-LIF) is denoted by the blue dashed line (p-value = 0.012), while the joint datasets is presented by the red dashed line (p-value = 0.343), which didn't present a sufficient statistical significance, according to the Mann-Kendall test.

Table 2
Annual contribution of lightning-ignited fires to the total number of occurrences and burned area, from the ICNF database.

Year	Relative frequency by year (%)					
	Occurrences			Burned area		
	ICNF-LIF	ICNF-PCLIF	ICNF-LIF + ICNF-PCLIF	ICNF-LIF	ICNF-PCLIF	ICNF-LIF + ICNF-PCLIF
2003	0.27	2.25	**2.52**	14.48	3.64	**18.12**
2004	0.05	0.44	**0.49**	0.21	0.19	**0.40**
2005	0.01	0.24	**0.25**	0.07	0.03	**0.10**
2006	0.34	1.64	**1.98**	2.73	0.35	**3.08**
2007	0.25	0.54	**0.79**	0.19	0.21	**0.40**
2008	0.15	0.18	**0.33**	0.24	0.20	**0.44**
2009	0.42	0.35	**0.77**	0.09	0.17	**0.26**
2010	0.43	0.29	**0.72**	0.76	0.03	**0.79**
2011	0.30	0.10	**0.40**	0.05	0.01	**0.06**
2012	0.23	0.14	**0.37**	0.65	*	**0.65**
2013	0.37	0.06	**0.43**	0.04	*	**0.04**
2014	0.52	0.14	**0.66**	0.13	0.03	**0.16**
2015	0.79	0.07	**0.86**	8.22	0.03	**8.25**
2016	0.47	0.09	**0.56**	0.10	*	**0.10**
2017	0.64	0.34	**0.98**	4.14	0.01	**4.15**
2018	1.10	0.47	**1.57**	1.75	0.03	**1.78**
2019	1.35	0.31	**1.66**	0.43	0.52	**0.95**
2020	1.22	0.30	**1.52**	1.81	0.01	**1.82**
Total	0.39	0.48	**0.87**	3.91	0.70	**4.61**

*<0.01 % of the total amount of occurrences / burned area in the year.

variability of burned area due to natural fires, despite the underestimation in June (Fig. 5b). The latter identifies a challenge for detection of active fires, particularly in Portugal where, regardless of its cause, most fires burn less than 10 ha (Table 1). To account for these limitations, Figs. 6, S6, S7 and S8 present a comparison between the location of MODIS-LIAF and natural fires from ICNF (ICNF-PCLIF and ICNF-LIF) that reached a burned area larger than 10 ha.

In August, we see a relatively high number of lightning fires in the southwest, northeast and central regions of Portugal. Most of these occurred during the exceptional fire season of 2003, which was characterized by large anomalies of surface meteorological variables that favored the ignition and spreading of fires, resulting in occurrences with large area burned (Trigo et al., 2006). According to Fig. 5a, 34 out of the 94 lightning fires (36.2 %) had matches with MODIS-LIAF, while 76 % of these active fires were correctly classified as caused by lightning. This percentage can be interpreted as the precision of the methodology in classifying fire causes when using MODIS remote sensing data. Excluding the 2003 fire season results in an even weaker performance, since only 5 of the 17 remaining lightning fires were matched, highlighting the impact of fire size on the detection rate of MODIS, and later in the classification of active fires likely ignited by lightning strikes.

During the months of June, there were 55 MODIS-LIAF concentrated around the latitude 40°N and in northeastern Portugal (Fig. S6). Most of them were matched with lightning fires, thus resulting in around 89 % of precision in this month. Nevertheless, a significant number of lightning fires have no matches, especially to the south of 40°N (see Section 4.4.2). The estimated precision decreased to 69 % and 59 % in July and September, respectively, months in which low values of burned area due to lightning fires were found (Fig. S7, S8). Most lightning fires larger than 10 ha reported in the months analyzed had no matches with any MODIS-LIAF.

4.4. *Case studies*

Besides the fire size, meteorological conditions may also affect the detection of a fire pixel. Once detected, the time lag between the reported fire and the remote sensing data, as well as the implications regarding the estimated location of individual occurrences from the forest fire database are examples of factors to be considered when assimilating these two events. Furthermore, the detected fire pixel must meet the B threshold criterion to be associated with a single natural fire occurrence. In this context, we've conducted two case study cases to understand the circumstances regarding the results shown so far, concerning the assimilation of a MODIS-LIAF and a lightning-ignited fire.

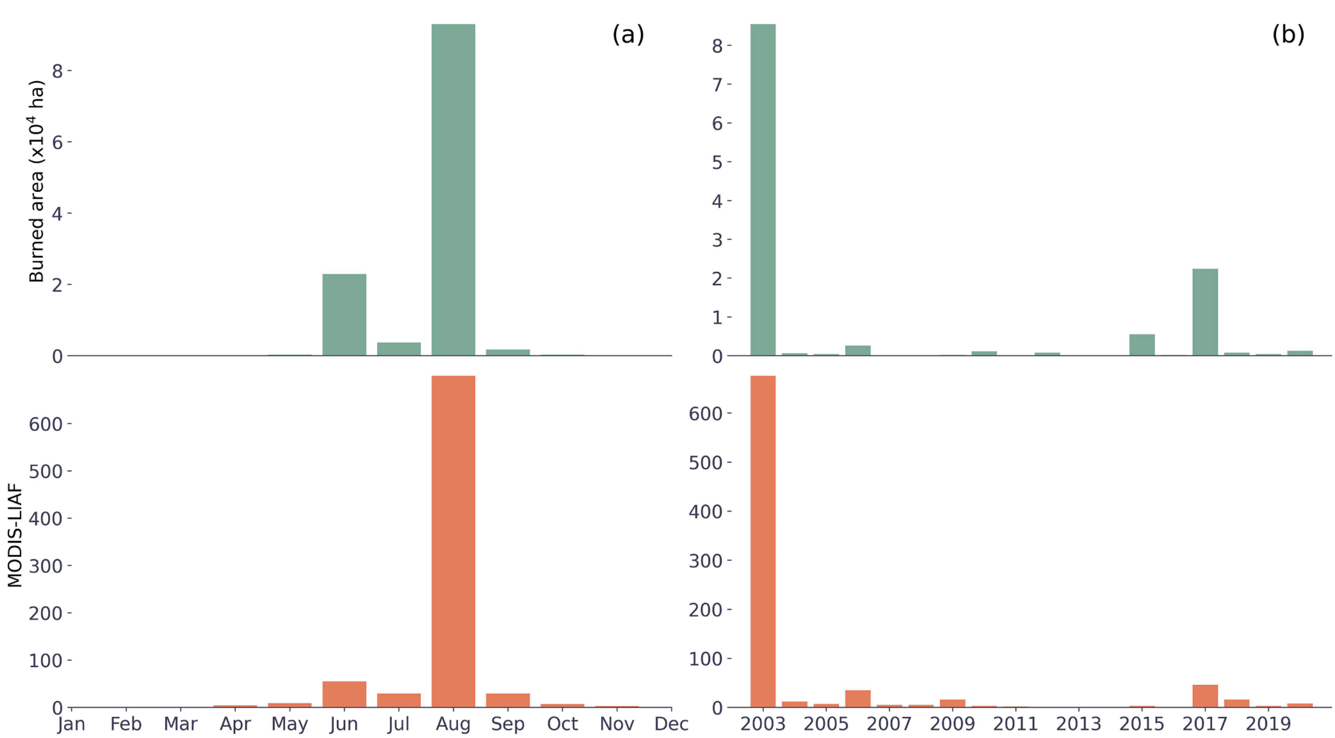

Fig. 5. (a) Intra-annual and (b) inter-annual variability of the burned area from lightning fires (ICNF-PCLIF and ICNF-LIF) and the MODIS-LIAF fire counts (bottom panel).

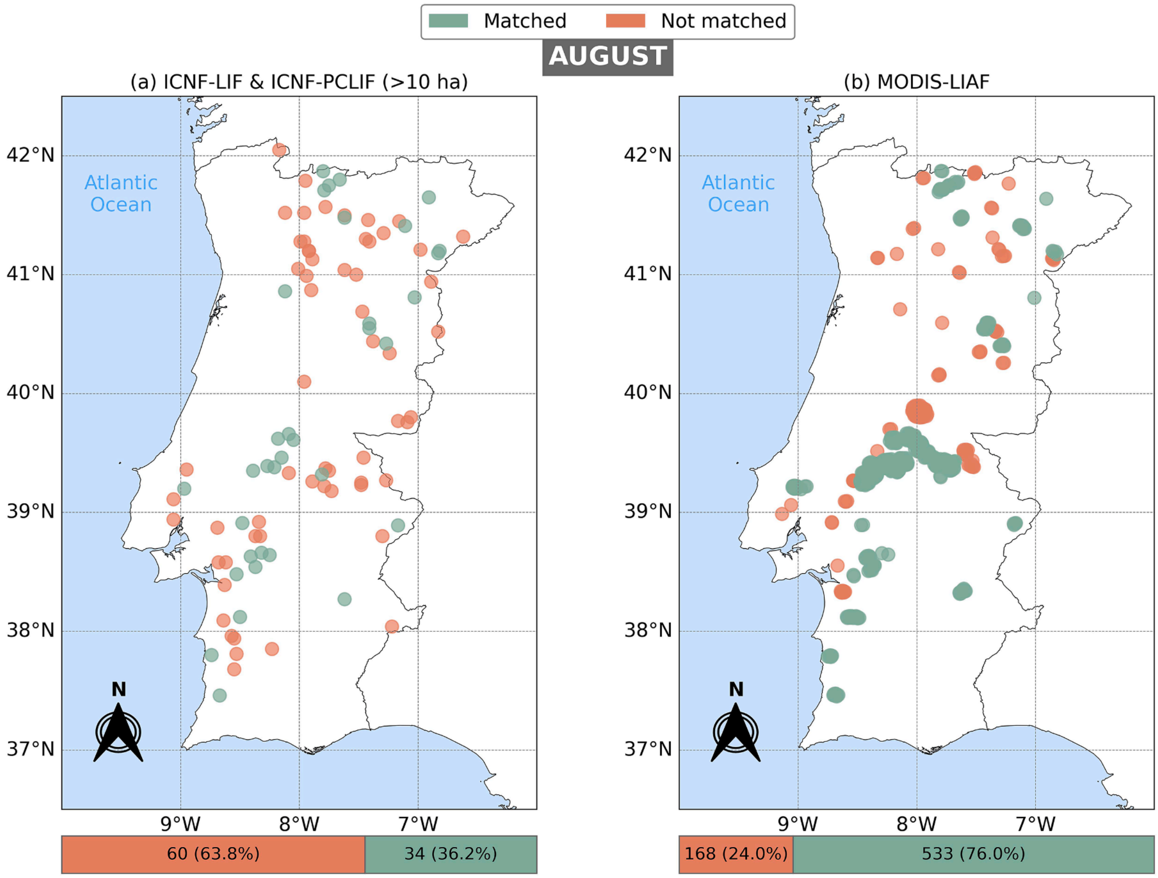

Fig. 6. Comparison between the spatial distribution of (a) lightning fires (ICNF-LIF and ICNF-PCLIF) larger than 10 ha and (b) MODIS-LIAF, for August. Lightning-fires matched with one or more MODIS-LIAF, or vice-versa, are colored green, while those not matched are orange. MODIS-LIAF not matched with an ICNF lightning fire can be denoted as false positives, thus the percentage inside the green bottom bar in (b) denotes the precision, while the green bottom bar in (a) denotes the true positive rate of the methodology when using MODIS remote sensing data.

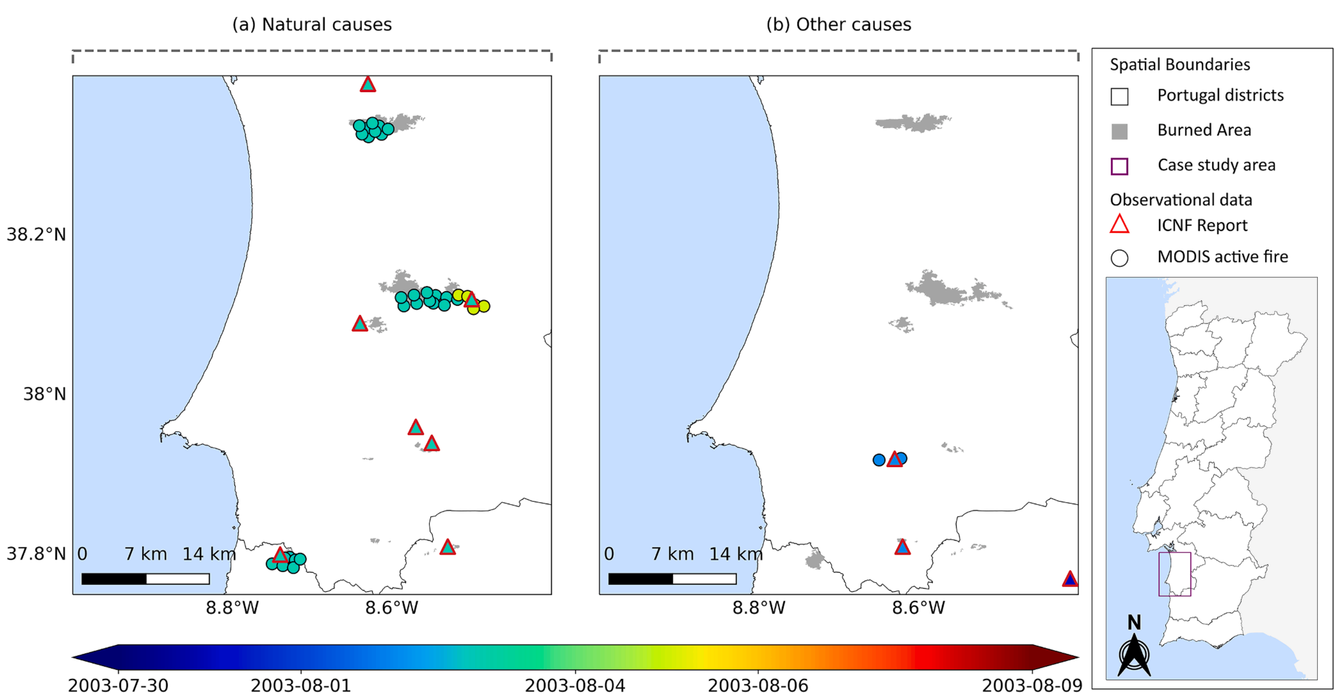

Fig. 7. Burned area and occurrences from the ICNF database (including both ICNF-LIF and ICNF-PCNIF), along with MODIS active fires (MODIS-LIAF) gathered between July 30th and August 9th of 2003. The figure was split in (a) natural causes, consisting of MODIS-LIAF and the joint ICNF-PCLIF and ICNF-LIF databases, and (b) other causes from both ICNF and MODIS. The mapped burned area was provided by (Neves et al., 2023).

4.4.1. First case study - 02 August 2003

The first case study took place during the main fire outbreak in the summer of 2003. Fig. 7 showcases several burnt areas mapped between July 30th and August 9th, along with MODIS active fires and fires recorded by ICNF during the same period. Of the 10 reported fire occurrences displayed, only five presented at least one nearby MODIS active fire, most likely due to cloud cover. Many of the occurrences not detected by MODIS are located southeast of the case study area and have burned areas ranging from 70 to 500 ha. When considering only lightning fires, four out of a total of seven presented at least one MODIS-LIAF.

In this case, two fires draw attention by their extent and distribution of observational data. The first one, located north of 38.2°N consumed an area of 1 394 ha between the 2nd and 3rd of august 2003, the reported location was about 5 km away from the mapped burned area, which prevented the active fires detected here from being assimilated to any ICNF-LIF, despite the correct classification. The second fire event was reported between 38.2°N and 38°N, east of 8.6°W and burned 2 735 ha over four days, in which the fire pixels presented here were correctly classified as caused by lightning. However, the occurrence located west of this fire was also assimilated with the same MODIS-LIAF due to its proximity, despite not presenting any fire pixel within its boundaries.

4.4.2. Second case study - 17 June 2017

The second case study displays three ICNF-LIF reported on the same day, June 17th, 2017, with sizes ranging from 11 ha to 17 500 ha (Fig. 8a). These lightning fires were correctly assimilated to one or more MODIS-LIAF, detected one to four days after the report. There were two fire reports with other causes in the same area (Fig. 8b), one of which was recorded as having unknown cause at south of 39.8°N, and the other one is listed as caused by negligence due to an accident related to a power transmission line, reaching up to 30 000 ha of burned area. Due to its spatial proximity, both the natural and negligence caused fires, reported on the same day, can be considered as a unique long lasting fire event with multiple ignition sources, in which care must be taken when attempting to distinguish the burned area resulting either from the lightning or the anthropogenic ignition. For instance, four active fires located southwest were classified as MODIS-LIAF despite being within the perimeter of the negligence caused fire.

There were other nine natural ignitions reported by the ICNF southward of the case study area in the same time period, with burned area ranging from 11 ha to 190 ha, and thus are not highlighted in this figure due to its smaller spatial extent, but are presented in **Figure S6a** as not being assimilated with any active fire (southward of 39.5°N), denoting an omission error from MODIS product. The intense heat produced by the fires of June 17th in Pedrógão Grande along with the existing meteorological conditions led to the development of a pyrocumulonimbus cloud, which in turn supported the spread of the existing fires and ignition by dry lightning. It is possible that some of the observed omission errors were caused by the presence of clouds and smoke plumes originated by those fires and later transported to other regions of Europe over the next few days (CTI, 2022; Solomos et al., 2019)

5. Discussion and conclusions

Despite the fire season in Portugal mainly occurring from June to October and reaching its peak in August, summer thunderstorms are not frequent, and develop as a result of daytime heating associated with thermal lows and generation of uphill currents by orographic systems in northeast Portugal, while during spring and autumn, in addition to these factors, other synoptic systems can contribute to greater lightning activity (Ramos et al., 2011). The last official report published by ICNF (2014) states that, amongst the reported fires investigated between 2003 and 2013, around 1.5 % were identified as being ignited by 'natural' causes, whilst 38 % had 'unknown' causes. Thus, and although only a small percentage of fires are lightning ignited, the large number of fires with unknown causes at the beginning of the 21st century suggests that further investigation is required to understand to what extent the lightning ignitions are a relevant fire cause in Portugal, as well as for other causes.

Based on the approach introduced by Larjavaara et al. (2005b), it was possible to estimate the ignition cause from the fire records indicated as unknown causes and non-investigated, into natural or other causes. From the performance assessment, we estimate that up to 85 % of the true lightning-ignited fires are accounted for when applying this approach with three days as the maximum holdover period and 10 km as the spatial window. Besides, there is a tradeoff related to increasing the temporal threshold, which in our study area causes a slight increase of

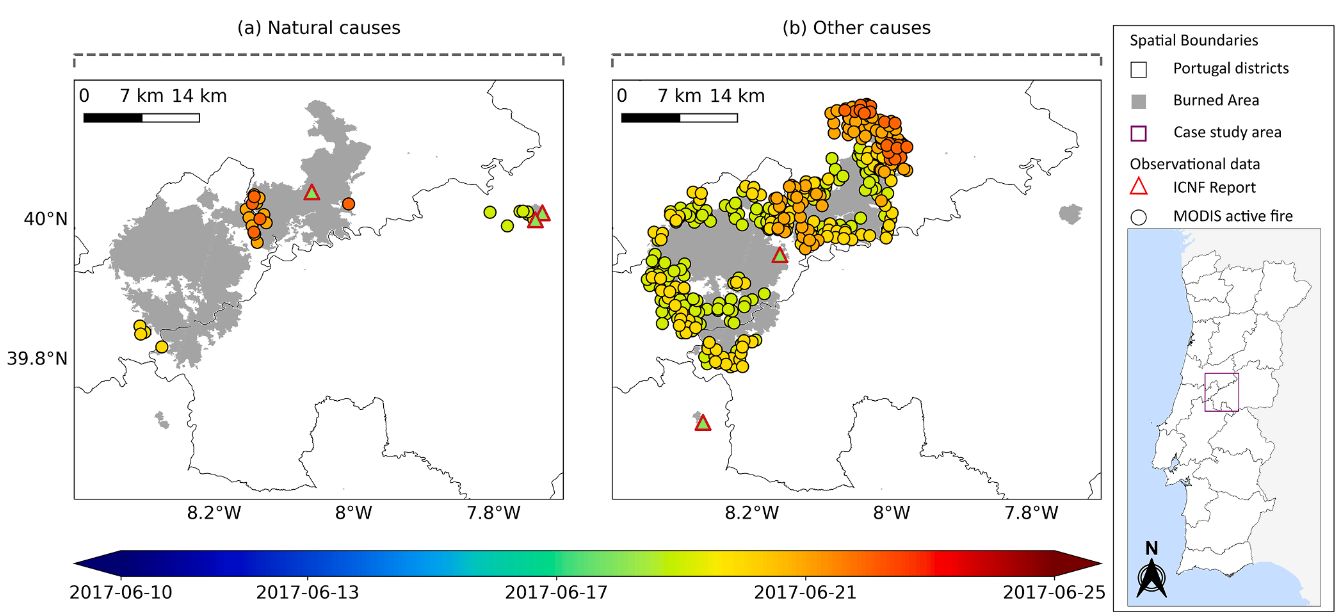

Fig. 8. Burned area and occurrences from the ICNF database (including both ICNF-LIF and ICNF-PCNIF), along with MODIS active fires gathered between June 10th and June 25th of 2017. The figure was split in (a) natural causes, consisting of MODIS-LIAF and the joint ICNF-PCLIF and ICNF-LIF databases, and (b) other causes from both ICNF and MODIS. The mapped burned area was provided by (Neves et al., 2023).

the true positive rate at the cost of precision, resulting in a considerable number of anthropogenic fires potentially being classified as caused by lightning.

The results presented here agree with the values identified for other Mediterranean areas (Castedo-Dorado et al., 2011; Ganteaume et al., 2013; Vazquez and Moreno, 1998), but are substantially lower than those identified in other European areas (Larjavaara et al., 2005b; Müller et al., 2013) and North-America (Abatzoglou et al., 2016). We estimate that, overall, lightning ignitions are responsible for about 1 % of all fires in Portugal, corresponding to 4.6 % of the total burned area by fires between 2003 and 2020. Although being lower than the values found in the latest ICNF publication regarding fire causes (ICNF, 2014) and the ones cited in Fernandes et al. (2021) it is worth noting that between 2003 and 2013 around 50 % of the fires were not attributed a cause (indicated as 'unknown' causes or non-investigated). Thus, our results ought to provide an updated and quite accurate view on the actual relevance of natural fires in the country. Based on a similar method, Pérez-Invernón et al. (2021) estimated that between 2009 and 2015 at least 359 fire events were lightning ignited in Portugal, corresponding to 0.22 % of all fires, while for the same time period we found 966 cases (677 ICNF-LIF and 289 ICNF-PCLIF). Despite the different spatiotemporal windows and thresholds applied in order to minimize the influence of anthropogenic fires in the sample, the authors also highlight the importance of the stroke detection efficiency of the lightning location systems employed for the selection of fires that were ignited by lightning (8- 13 % for the WWLLN and ~57 % for the ENTLN), which are significantly lower in comparison with the Portuguese lightning location system (see Section 2.2). Furthermore, we highlight the significant contribution of lightning fires to the 2015 fire season, and especially in 2003 and 2017 (Fernandes et al., 2021), which suggests that, when in conjunction with other compound events, such as drought conditions and heatwaves, lightning can trigger large fire events.

Most of the lightning fires occurred in the higher range of altitudes available in Portugal, in the northern regions of the country, similar to what was found by Müller and Vacik (2017) and Conedera et al. (2006) in other regions of Europe, which is related to the development of convective clouds due to orographic processes (Dijkstra et al., 2022; Rodrigues et al., 2010). Among the fires with known causes, the proportion of lightning-ignited fires increases with fire size, and the largest natural fires were reported in northeast and central Portugal. As a consequence of presenting a higher frequency in remote areas, the initial suppression attack may be slower, thus contributing to the larger fire size (Fernandes et al., 2021).

Under the scope of climate change, recents studies focused in the western and southeastern regions of the United States have shown an increase in the potential and severity of lightning ignitions under a warmer and drier climate (Fill et al., 2019; Li et al., 2021). In southeast Australia, Canadell et al. (2021) found an increasing trend of fire weather conditions and other factors that beneficiate pyroconvective processes, along with an increased frequency of dry lightning. Over Portugal, when considering only the annual number of lightning fires classified by the Portuguese Fire Database (ICNF-LIF) we were able to identify an increasing number over the years, similar to the positive trend found in Fernandes et al. (2021) in regard to lightning fire density. However, when accounting also for the fires that we classified as caused by lightning (ICNF-PCLIF), this trend disappears, suggesting that it may have resulted from the increasing rate of investigated fires (See Figure S1). Nevertheless, it is still necessary to better understand the local mechanisms driving lightning ignitions over Portugal and around the globe in order to understand the impact of climate change on the frequency of lightning fires (Pérez-Invernón et al., 2023).

Regarding seasonal variability of lighting-ignited fires in Portugal, 91 % of the natural fires occurred between the months of June to September, the most crucial months being August and July, which comprises 76 % and 18 % of the burned area by natural causes, respectively. Despite the higher frequency of CG strokes in May, in general, fuel moisture content, which possesses important implications on fire ignition and spreading, is relatively high during this month in Central Portugal, thus contributing to lower flammability. However it decreases in August and September when the fire season in Portugal reaches its peak (Viegas et al., 2001, 1992). Remote sensing data were able to reproduce this seasonality quite well, regarding the monthly and yearly burned area from natural causes, and we were able to confirm that most of the active fires here classified as likely ignited by lightning were, in fact, correctly classified. However, they only represent around 20 % to 35 % of the lightning fires larger than 10 hectares. Thus, a spatial characterization of this phenomenon considering only the MODIS active fire product would not be representative of the actual spatial distribution of lightning fires, especially in regions where individual fires often fail to reach a larger burned area, which is the case of Portugal. To overcome this limitation, one should resort to products with higher spatial resolution in order to account for the impact of smaller fires, as long as it is in line with the aim of the work. For example, the VIIRS active fire data is a good alternative that provides higher accuracy in fire monitoring in comparison with MODIS (Coskuner, 2022; Schroeder et al., 2014), however for this study we were also concerned in addressing the fire seasons that took place before 2012, when the VIIRS S-NPP instrument started its operation.

We are confident that the approach we presented can be useful to support the assessment of fire risk, to plan and coordinate efforts to identify areas at greatest risk and to design long-term fire management strategies. We also believe that this method will benefit in the future from the inclusion of new variables on the computation of the probability, namely through the inclusion of information regarding precipitation, fuel accumulation and fuel moisture, which can be accomplished by the use of weather radars in rainfall detection on a sufficiently fine spatial and temporal scale to permit the estimation of precipitation before and after an ignition (Dowdy et al., 2017; Soler et al., 2021) and the assessment of fuel moisture through the calculation of vapor pressure deficit (Nolan et al., 2016).

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CRediT authorship contribution statement

Lucas S. Menezes: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ana Russo:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Renata Libonati:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Ricardo M. Trigo:** Writing – review & editing, Conceptualization. **José M.C. Pereira:** Writing – review & editing, Conceptualization. **Akli Benali:** Writing – review & editing. **Alexandre M. Ramos:** Writing – review & editing. **Célia M. Gouveia:** Writing – review & editing. **Carlos A. Morales Rodriguez:** Writing – review & editing. **Ricardo Deus:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2024.110108.

References

Abatzoglou, J.T., Kolden, C.A., Balch, J.K., Bradley, B.A., 2016. Controls on interannual variability in lightning-caused fire activity in the western US. Environ. Res. Lett. 11, 045005 https://doi.org/10.1088/1748-9326/11/4/045005.

Arias, P.A., Bellouin, N., Coppola, E., Jones, R.G., Krinner, G., Marotzke, J., Naik, V., Palmer, M.D., Plattner, G.-K., Rogelj, J., Rojas, M., Sillmann, J., Storevelmo, T., Thorne, P.W., Trewin, B., Achuta Rao, K., Adhikary, B., Allan, R.P., Armour, K., Bala, G., Barimalala, R., Berger, S., Canadell, J.G., Cassou, C., Cherchi, A., Collins, W., Collins, W.D., Connors, S.L., Corti, S., Cruz, F., Dentener, F.J., Dereczynski, C., Di Luca, A., Diongue Niang, A., Doblas-Reyes, F.J., Dosio, A., Douville, H., Engelbrecht, F., Eyring, V., Fischer, E.A., Forster, P., Fox-Kemper, B., Fuglestvedt, J.S., Fyfe, J.C., Gillett, N.P., Goldfarb, L., Gorodetskaya, I., Gutierrez, J.M., Hamdi, R., Hawkins, E., Hewitt, H.T., Hope, P., Islam, A.S., Jones, C., Kaufman, D.S., Kopp, R.E., Kosaka, Y., Kossin, J., Krakovska, S., Lee, J.-Y., Li, J., Mauritsen, T., Maycock, T.K., Meinshausen, M., Min, S.-K., Monteiro, P.M.S., Ngo-Duc, T., Otto, F., Pinto, I., Pirani, A., Raghavan, K., Ranasinghe, R., Ruane, A.C., Ruiz, L., Sallée, J.-B., Samset, B.H., Sathyendranath, S., Seneviratne, S.I., Sörensson, A.A., Szopa, S., Takayabu, I., Tréguier, A.-M., van den Hurk, B., Vautard, R., von Schuckmann, K., Zaehle, S., Zhang, X., Zickfeld, K., 2021. Technical Summary, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel On Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33–144. https://doi.org/10.1017/9781009157896.

Bastos, A., Gouveia, C.M., DaCamara, C.C., Trigo, R.M., 2011. Modelling post-fire vegetation recovery in Portugal. Biogeosciences 8, 3593–3607. https://doi.org/10.5194/bg-8-3593-2011.

Bastos, A., Gouveia, C.M., Trigo, R.M., Running, S.W., 2014. Analysing the spatio-temporal impacts of the 2003 and 2010 extreme heatwaves on plant productivity in Europe. Biogeosciences 11, 3421–3435. https://doi.org/10.5194/bg-11-3421-2014.

Benali, A., Guiomar, N., Gonçalves, H., Mota, B., Silva, F., Fernandes, P.M., Mota, C., Penha, A., Santos, J., Pereira, J.M.C., Sá, A.C.L., 2023. The Portuguese Large Wildfire Spread database (PT-FireSprd). Earth Syst. Sci. Data 15, 3791–3818. https://doi.org/10.5194/essd-15-3791-2023.

Benali, A., Russo, A., Sá, A., Pinto, R., Price, O., Koutsias, N., Pereira, J., 2016. Determining fire dates and locating ignition points with satellite data. Remote Sens. 8, 326. https://doi.org/10.3390/rs8040326.

Bowman, D.M.J.S., Williamson, G.J., Abatzoglou, J.T., Kolden, C.A., Cochrane, M.A., Smith, A.M.S., 2017. Human exposure and sensitivity to globally extreme wildfire events. Nat. Ecol. Evol. 1, 1–6. https://doi.org/10.1038/s41559-016-0058.

Calheiros, T., Pereira, M.G., Nunes, J.P., 2021. Assessing impacts of future climate change on extreme fire weather and pyro-regions in Iberian Peninsula. Sci. Total Environ. 754, 142233 https://doi.org/10.1016/j.scitotenv.2020.142233.

Canadell, J.G., Meyer, C.P.(M), Cook, G.D., Dowdy, A., Briggs, P.R., Knauer, J., Pepler, A., Haverd, V., 2021. Multi-decadal increase of forest burned area in Australia is linked to climate change. Nat. Commun. 12, 6921. https://doi.org/10.1038/s41467-021-27225-4.

Castedo-Dorado, F., Rodríguez-Pérez, J.R., Marcos-Menéndez, J.L., Álvarez-Taboada, M.F., 2011. Modelling the probability of lightning-induced forest fire occurrence in the province of León (NW Spain). For. Syst. 20, 95. https://doi.org/10.5424/fs/2011201-9409.

Chuvieco, E., Lizundia-Loiola, J., Pettinari, M.L., Ramo, R., Padilla, M., Tansey, K., Mouillot, F., Laurent, P., Storm, T., Heil, A., Plummer, S., 2018. Generation and analysis of a new global burned area product based on MODIS 250 m reflectance bands and thermal anomalies. Earth Syst. Sci. Data 10, 2015–2031. https://doi.org/10.5194/essd-10-2015-2018.

Conedera, M., Cesti, G., Pezzatti, G.B., Zumbrunnen, T., Spinedi, F., 2006. Lightning-induced fires in the Alpine region: an increasing problem. For. Ecol. Manag. 234, S68. https://doi.org/10.1016/j.foreco.2006.08.096.

Coogan, S.C.P., Cai, X., Jain, P., Flannigan, M.D., 2020. Seasonality and trends in human- and lightning-caused wildfires $\geq$ 2 ha in Canada, 1959–2018. Int. J. Wildland Fire 29, 473. https://doi.org/10.1071/WF19129.

Coskuner, K.A., 2022. Assessing the performance of MODIS and VIIRS active fire products in the monitoring of wildfires: a case study in Turkey. IForest - Biogeosciences For. 15, 85. https://doi.org/10.3832/ifor3754-015.

Couto, F.T., Iakunin, M., Salgado, R., Pinto, P., Viegas, T., Pinty, J.-P., 2020. Lightning modelling for the research of forest fire ignition in Portugal. Atmos. Res. 242, 104993 https://doi.org/10.1016/j.atmosres.2020.104993.

CTI, 2022. Análise e Apuramento Dos Factos Relativos Aos Incêndios Que Ocorreram Em Pedrógão Grande, Castanheira de Pera, Ansião, Alvaiázere, Figueiró dos Vinhos, Arganil, Góis, Penela, Pampilhosa da Serra, Oleiros e Sertã, Entre 17 e 24 De Junho De 2017 – Relatório final. Comissão Técnica Independente, Lisboa, Portugal.

Dijkstra, J., Durrant, T., San-Miguel-Ayanz, J., Veraverbeke, S., 2022. Anthropogenic and lightning fire incidence and burned area in Europe. Land (Basel) 11, 651. https://doi.org/10.3390/land11050651.

Dowdy, A.J., Fromm, M.D., McCarthy, N., 2017. Pyrocumulonimbus lightning and fire ignition on Black Saturday in southeast Australia. J. Geophys. Res. Atmos. 122, 7342–7354. https://doi.org/10.1002/2017JD026577.

Dowdy, A.J., Mills, G.A., 2012. Characteristics of lightning-attributed wildland fires in south-east Australia. Int. J. Wildland Fire 21, 521. https://doi.org/10.1071/WF10145.

Dupuy, J., 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. Ann. For. Sci. 77, 1–24. https://doi.org/10.1007/s13595-020-00933-5.

Earth Resources Observation And Science (EROS) Center, 2017. Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global. https://doi.org/10.5066/F7PR7TFT. [Dataset].

Ermitão, T., Gouveia, C.M., Bastos, A., Russo, A.C., 2022. Interactions between hot and dry fuel conditions and vegetation dynamics in the 2017 fire season in Portugal. Environ. Res. Lett. 17, 095009 https://doi.org/10.1088/1748-9326/ac8be4.

Fernandes, P.M., Santos, J.A., Castedo-Dorado, F., Almeida, R., 2021. Fire from the sky in the anthropocene. Fire 4, 13. https://doi.org/10.3390/fire4010013.

Fill, J.M., Davis, C.N., Crandall, R.M., 2019. Climate change lengthens southeastern USA lightning-ignited fire seasons. Glob. Change Biol. 25, 3562–3569. https://doi.org/10.1111/gcb.14727.

Fink, A.H., Brücher, T., Krüger, A., Leckebusch, G.C., Pinto, J.G., Ulbrich, U., 2004. The 2003 European summer heatwaves and drought –synoptic diagnosis and impacts. Weather 59, 209–216. https://doi.org/10.1256/wea.73.04.

FIRMS, 2024. Fire information for resource management system. https://firms.modaps.eosdis.nasa.gov/download/(accessed 25 January 2024). [Dataset].

Fusco, E.J., Finn, J.T., Abatzoglou, J.T., Balch, J.K., Dadashi, S., Bradley, B.A., 2019. Detection rates and biases of fire observations from MODIS and agency reports in the conterminous United States. Remote Sens. Environ. 220, 30–40. https://doi.org/10.1016/j.rse.2018.10.028.

Ganteaume, A., Camia, A., Jappiot, M., San-Miguel-Ayanz, J., Long-Fournel, M., Lampin, C., 2013. A review of the main driving factors of forest fire ignition over Europe. Environ. Manage. 51, 651–662. https://doi.org/10.1007/s00267-012-9961-z.

García-Herrera, R., Hernández, E., Barriopedro, D., Paredes, D., Trigo, R.M., Trigo, I.F., Mendes, M.A., 2007. The outstanding 2004/05 drought in the Iberian Peninsula: associated atmospheric circulation. J. Hydrometeorol. 8, 483–498. https://doi.org/10.1175/JHM578.1.

Giglio, L., 2015. MODIS Collection 6 Active Fire Product User's Guide.

Giglio, L., Schroeder, W., Justice, C.O., 2016. The collection 6 MODIS active fire detection algorithm and fire products. Remote Sens. Environ. 178, 31–41. https://doi.org/10.1016/j.rse.2016.02.054.

in Gouveia, C., Páscoa, P., DaCamara, C., 2018. Post-fire vegetation recovery in Iberia based on remote- sensing information, Ed. In: Szmyt, J. (Ed.), Forest Fire. IntechOpen, London, pp. 114–130. pp.

Hanes, C.C., Wang, X., Jain, P., Parisien, M.-A., Little, J.M., Flannigan, M.D., 2019. Fire-regime changes in Canada over the last half century. Can. J. For. Res. 49, 256–269. https://doi.org/10.1139/cjfr-2018-0293.

Hawbaker, T.J., Radeloff, V.C., Syphard, A.D., Zhu, Z., Stewart, S.I., 2008. Detection rates of the MODIS active fire product in the United States. Remote Sens. Environ., Earth Observ. Terrestrial Biodivers. Ecosyst. Spec. Issue 112, 2656–2664. https://doi.org/10.1016/j.rse.2007.12.008.

ICNF, 2024a. Relatórios provisórios de incêndios rurais. https://www.icnf.pt/florestas/gfr/gfrgestaoinformacao/grfrelatorios/areasardidaseocorrencias (accessed 25 January 2024).

ICNF, 2024b. Gestão de Fogos Rurais | Estatísticas. https://www.icnf.pt/florestas/gfr/gfrgestaoinformacao/estatisticas (accessed 25 January 2024).

ICNF, 2014. ANÁLISE DAS CAUSAS DOS INCÊNDIOS FLORESTAIS - 2003 - 2013 (No. Causas03- 13/2014). Instituto da Conservação da Natureza e das Florestas, Departamento de Gestão de Áreas Classificadas. Públicas e de Proteção Florestal, Lisboa, Portugal.

Koutsias, N., Xanthopoulos, G., Founda, D., Xystrakis, F., Nioti, F., Pleniou, M., Mallinis, G., Arianoutsou, M., 2012. On the relationships between forest fires and weather conditions in Greece from long-term national observations (1894–2010). Int. J. Wildland Fire 22, 493–507. https://doi.org/10.1071/WF12003.

Krause, A., Kloster, S., Wilkenskjeld, S., Paeth, H., 2014. The sensitivity of global wildfires to simulated past, present, and future lightning frequency. J. Geophys. Res. Biogeosciences 119, 312–322. https://doi.org/10.1002/2013JG002502.

Larjavaara, M., Kuuluvainen, T., Rita, H., 2005a. Spatial distribution of lightning-ignited forest fires in Finland. For. Ecol. Manag. 208, 177–188. https://doi.org/10.1016/j.foreco.2004.12.005.

Larjavaara, M., Pennanen, J., Tuomi, T.J., 2005b. Lightning that ignites forest fires in Finland. Agric. For. Meteorol. 132, 171–180. https://doi.org/10.1016/j.agrformet.2005.07.005.

Li, Y., Mickley, L.J., Kaplan, J.O., 2021. Response of dust emissions in southwestern North America to 21st century trends in climate, CO_2 fertilization, and land use: implications for air quality. Atmos. Chem. Phys. 21, 57–68. https://doi.org/10.5194/acp-21-57-2021.

Libonati, R., Pereira, J.M.C., Da Camara, C.C., Peres, L.F., Oom, D., Rodrigues, J.A., Santos, F.L.M., Trigo, R.M., Gouveia, C.M.P., Machado-Silva, F., Enrich-Prast, A., Silva, J.M.N., 2021. Twenty-first century droughts have not increasingly exacerbated fire season severity in the Brazilian Amazon. Sci. Rep. 11, 4400. https://doi.org/10.1038/s41598-021-82158-8.

Marques, S., Borges, J.G., Garcia-Gonzalo, J., Moreira, F., Carreiras, J.M.B., Oliveira, M. M., Cantarinha, A., Botequim, B., Pereira, J.M.C., 2011. Characterization of wildfires in Portugal. Eur. J. For. Res. 130, 775–784. https://doi.org/10.1007/s10342-010-0470-4.

Menezes, L.S., De Oliveira, A.M., Santos, F.L.M., Russo, A., De Souza, R.A.F., Roque, F.O., Libonati, R., 2022. Lightning patterns in the Pantanal: untangling natural and anthropogenic-induced wildfires. Sci. Total Environ. 820, 153021 https://doi.org/10.1016/j.scitotenv.2022.153021.

Moreira, F., Catry, F.X., Rego, F., Bacao, F., 2010. Size-dependent pattern of wildfire ignitions in Portugal: when do ignitions turn into big fires? Landsc. Ecol. 25, 1405–1417. https://doi.org/10.1007/s10980-010-9491-0.

Moris, J.V., Álvarez-Álvarez, P., Conedera, M., Dorph, A., Hessilt, T.D., Hunt, H.G.P., Libonati, R., Menezes, L.S., Müller, M.M., Pérez-Invernón, F.J., Pezzatti, G.B., Pineda, N., Scholten, R.C., Veraverbeke, S., Wotton, B.M., Ascoli, D., 2023. A global database on holdover time of lightning-ignited wildfires. Earth Syst. Sci. Data 15, 1151–1163. https://doi.org/10.5194/essd-15-1151-2023.

Moris, J.V., Conedera, M., Nisi, L., Bernardi, M., Cesti, G., Pezzatti, G.B., 2020. Lightning-caused fires in the Alps: identifying the igniting strokes. Agric. For. Meteorol. 290, 107990 https://doi.org/10.1016/j.agrformet.2020.107990.

Müller, M.M., Vacik, H., 2017. Characteristics of lightnings igniting forest fires in Austria. Agric. For. Meteorol. 240–241, 26–34. https://doi.org/10.1016/j.agrformet.2017.03.020.

Müller, M.M., Vacik, H., Diendorfer, G., Arpaci, A., Formayer, H., Gossow, H., 2013. Analysis of lightning-induced forest fires in Austria. Theor. Appl. Climatol. 111, 183–193. https://doi.org/10.1007/s00704-012-0653-7.

Neves, A.K., Campagnolo, M.L., Silva, J.M.N., Pereira, J.M.C., 2023. A Landsat-based atlas of monthly burned area for Portugal, 1984–2021. Int. J. Appl. Earth Obs. Geoinformation 119, 103321. https://doi.org/10.1016/j.jag.2023.103321.

Nieto, H., Aguado, I., García, M., Chuvieco, E., 2012. Lightning-caused fires in Central Spain: development of a probability model of occurrence for two Spanish regions. Agric. For. Meteorol. 162–163, 35–43. https://doi.org/10.1016/j.agrformet.2012.04.002.

Nolan, R.H., Resco de Dios, V., Boer, M.M., Caccamo, G., Goulden, M.L., Bradstock, R.A., 2016. Predicting dead fine fuel moisture at regional scales using vapour pressure deficit from MODIS and gridded weather data. Remote Sens. Environ. 174, 100–108. https://doi.org/10.1016/j.rse.2015.12.010.

Oliva, P., Schroeder, W., 2015. Assessment of VIIRS 375m active fire detection product for direct burned area mapping. Remote Sens. Environ. 160, 144–155. https://doi.org/10.1016/j.rse.2015.01.010.

Pereira, J.M.C., Oom, D., Silva, P.C., Benali, A., 2022. Wild, tamed, and domesticated: three fire macroregimes for global pyrogeography in the Anthropocene. Ecol. Appl. 32, e2588. https://doi.org/10.1002/eap.2588.

Pereira, M.G., Malamud, B.D., Trigo, R.M., Alves, P.I., 2011. The history and characteristics of the 1980–2005 Portuguese rural fire database. Nat. Hazards Earth Syst. Sci. 11, 3343–3358. https://doi.org/10.5194/nhess-11-3343-2011.

Pérez-Invernón, F.J., Gordillo-Vázquez, F.J., Huntrieser, H., Jöckel, P., 2023. Variation of lightning-ignited wildfire patterns under climate change. Nat. Commun. 14, 739. https://doi.org/10.1038/s41467-023-36500-5.

Pérez-Invernón, F.J., Huntrieser, H., Soler, S., Gordillo-Vázquez, F.J., Pineda, N., Navarro-González, J., Reglero, V., Montanyà, J., Van Der Velde, O., Koutsias, N., 2021. Lightning-ignited wildfires and long continuing current lightning in the Mediterranean Basin: preferential meteorological conditions. Atmos. Chem. Phys. 21, 17529–17557. https://doi.org/10.5194/acp-21-17529-2021.

Pineda, N., Montanyà, J., van der Velde, O.A., 2014. Characteristics of lightning related to wildfire ignitions in Catalonia. Atmospheric Res 135–136, 380–387. https://doi.org/10.1016/j.atmosres.2012.07.011.

Pineda, N., Rigo, T., 2017. The rainfall factor in lightning-ignited wildfires in Catalonia. Agric. For. Meteorol. 239, 249–263. https://doi.org/10.1016/j.agrformet.2017.03.016.

Ramos, A.M., Ramos, R., Sousa, P., Trigo, R.M., Janeira, M., Prior, V., 2011. Cloud to ground lightning activity over Portugal and its association with circulation weather types. Atmos. Res. 101, 84–101. https://doi.org/10.1016/j.atmosres.2011.01.014.

Ramos, A.M., Russo, A., DaCamara, C.C., Nunes, S., Sousa, P., Soares, P.M.M., Lima, M. M., Hurduc, A., Trigo, R.M., 2023. The compound event that triggered the destructive fires of October 2017 in Portugal. iScience 26, 106141. https://doi.org/10.1016/j.isci.2023.106141.

Rodrigues, M., Cunill Camprubí, À., Balaguer-Romano, R., Coco Megía, C.J., Castañares, F., Ruffault, J., Fernandes, P.M., Resco De Dios, V., 2023. Drivers and implications of the extreme 2022 wildfire season in Southwest Europe. Sci. Total Environ. 859, 160320 https://doi.org/10.1016/j.scitotenv.2022.160320.

Rodrigues, R.B., Mendes, V.M.F., Catalao, J.P.S., 2010. Lightning data observed with lightning location system in Portugal. IEEE Trans. Power Deliv. 25, 870–875. https://doi.org/10.1109/TPWRD.2009.2037325.

Rodrigues, R.B., Mendes, V.M.F., Catalao, J.P.S., Correia, S., Prior, V., Aguado, M., 2008. An investigation over the lightning location system in Portugal for wind turbine protection development. in. In: 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century. Presented at the 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, pp. 1–8. https://doi.org/10.1109/PES.2008.4596513. pp.

Ruffault, J., Curt, T., Moron, V., Trigo, R.M., Mouillot, F., Koutsias, N., Pimont, F., Martin-StPaul, N., Barbero, R., Dupuy, J.-L., Russo, A., Belhadj-Khedher, C., 2020. Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. Sci. Rep. 10, 13790. https://doi.org/10.1038/s41598-020-70069-z.

Sá, A.C.L., Benali, A., Fernandes, P.M., Pinto, R.M.S., Trigo, R.M., Salis, M., Russo, A., Jerez, S., Soares, P.M.M., Schroeder, W., Pereira, J.M.C., 2017. Evaluating fire growth simulations using satellite active fire data. Remote Sens. Environ. 190, 302–317. https://doi.org/10.1016/j.rse.2016.12.023.

Sánchez-Benítez, A., García-Herrera, R., Barriopedro, D., Sousa, P.M., Trigo, R.M., 2018. The earliest European summer mega-heatwave of reanalysis period. Geophys. Res. Lett. 45, 1955–1962. https://doi.org/10.1002/2018GL077253.

Schroeder, W., Oliva, P., Giglio, L., Csiszar, I.A., 2014. The New VIIRS 375 m active fire detection data product: algorithm description and initial assessment. Remote Sens. Environ. 143, 85–96. https://doi.org/10.1016/j.rse.2013.12.008.

Schulz, W., Diendorfer, G., Pedeboy, S., Poelman, D.R., 2016. The European lightning location system EUCLID – part 1: performance analysis and validation. Nat. Hazards Earth Syst. Sci. 16, 595–605. https://doi.org/10.5194/nhess-16-595-2016.

Silva, P.S., Bastos, A., Libonati, R., Rodrigues, J.A., DaCamara, C.C., 2019. Impacts of the 1.5°C global warming target on future burned area in the Brazilian Cerrado. For. Ecol. Manag. 446, 193–203. https://doi.org/10.1016/j.foreco.2019.05.047.

Soler, A., Pineda, N., Segundo, H.S., Bech, J., Montanyà, J., 2021. Characterisation of thunderstorms that caused lightning-ignited wildfires. Int. J. Wildland Fire 30, 954–970. https://doi.org/10.1071/WF21076.

Solomos, S., Gialitaki, A., Marinou, E., Proestakis, E., Amiridis, V., Baars, H., Komppula, M., Ansmann, A., 2019. Modeling and remote sensing of an indirect Pyro-Cb formation and biomass transport from Portugal wildfires towards Europe. Atmos. Environ. 206, 303–315. https://doi.org/10.1016/j.atmosenv.2019.03.009.

Trigo, R.M., Pereira, J.M.C., Pereira, M.G., Mota, B., Calado, T.J., Dacamara, C.C., Santo, F.E., 2006. Atmospheric conditions associated with the exceptional fire season of 2003 in Portugal. Int. J. Climatol. 26, 1741–1757. https://doi.org/10.1002/joc.1333.

Turco, M., Jerez, S., Augusto, S., Tarín-Carrasco, P., Ratola, N., Jiménez-Guerrero, P., Trigo, R.M., 2019. Climate drivers of the 2017 devastating fires in Portugal. Sci. Rep. 9, 13886. https://doi.org/10.1038/s41598-019-50281-2.

Turco, M., Rosa-Cánovas, J.J., Bedia, J., Jerez, S., Montávez, J.P., Llasat, M.C., Provenzale, A., 2018. Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models. Nat. Commun. 9, 3821. https://doi.org/10.1038/s41467-018-06358-z.

Turco, M., Von Hardenberg, J., AghaKouchak, A., Llasat, M.C., Provenzale, A., Trigo, R. M., 2017. On the key role of droughts in the dynamics of summer fires in Mediterranean. Europe. Sci. Rep. 7, 81. https://doi.org/10.1038/s41598-017-00116-9.

Vazquez, A., Moreno, J., 1998. Patterns of lightning-, and people-caused fires in Peninsular Spain. Int. J. Wildland Fire 8, 103. https://doi.org/10.1071/WF9980103.

Veraverbeke, S., Rogers, B.M., Goulden, M.L., Jandt, R.R., Miller, C.E., Wiggins, E.B., Randerson, J.T., 2017. Lightning as a major driver of recent large fire years in North American boreal forests. Nat. Clim. Change 7, 529–534. https://doi.org/10.1038/nclimate3329.

Viegas, D.X., Piñol, J., Viegas, M.T., Ogaya, R., 2001. Estimating live fine fuels moisture content using meteorologically-based indices. Int. J. Wildland Fire 10, 223–240. https://doi.org/10.1071/wf01022.

Viegas, D.X., Viegas, M., Ferreira, A.D., 1992. Moisture content of fine forest fuels and fire occurrence in central Portugal. Int. J. Wildland Fire 2, 69–86. https://doi.org/10.1071/wf9920069.

Wilks, D.S., 2019. Forecast verification. in Statistical Methods in the Atmospheric Sciences. Elsevier, pp. 369–483. pp.

Wolfe, R.E., Roy, D.P., Vermote, E., 1998. MODIS land data storage, gridding, and compositing methodology: level 2 grid. IEEE Trans. Geosci. Remote Sens. 36, 1324–1338. https://doi.org/10.1109/36.701082.

Ying, L., Shen, Z., Yang, M., Piao, S., 2019. Wildfire detection probability of MODIS fire products under the constraint of environmental factors: a study based on confirmed ground wildfire records. Remote Sens. 11, 3031. https://doi.org/10.3390/rs11243031.