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# Spatio-temporal evolution of heat waves severity and expansion across the Iberian Peninsula and Balearic islands

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ABSTRACT

In the current climate change scenario, heat waves have become one of the most concerning extreme climatic events, both because of their implications for human health and the economy, and because of their increase in intensity and frequency in recent decades. This work presents for the first time a climatological analysis of heat waves in the Iberian Peninsula and Balearic Archipelago (IPB) using the Excess Heat Factor index (EHF). This index considers the factor of intensity and the acclimatization process of human body in the study of heat waves. We focused on the intensity (also called severity), duration, frequency and spatial extension of heat waves in the IPB in the 1950–2020 period. The exceptional heat wave of August 2018 was approached in a similar way to further explore the usefulness of the EHF index. We found that the EHF index identified heat wave conditions 2 days earlier than indices that used only maximum temperatures. Results showed a significant increase in intensity, duration, frequency and spatial extension of heat waves for the whole IPB for 1950–2020 period. The average extent of heat waves increased by 4.0% per decade and the maximum extent by 4.1% per decade. This trend suggested a significant increase in human exposure, droughts, fire risk and energy demand in this region in the last decades.

## 1. Introduction

According to the IPCC et al. (2018), the global warming of 1 °C above pre-industrial levels that we are observing currently is accompanied by extreme weather events that provoke a significant impact on society and ecosystems. One of the most concerning extreme events are heat waves, periods of excessive heat that contribute negatively to human health, and to the agricultural and energy sectors (Chhetri et al., 2012; Wolf and McGregor, 2013; Zander et al., 2015; Guo et al., 2017; Liss et al., 2017; Royé et al., 2020).

Over the last decades, the average surface temperature has increased globally by 0.2 °C/decade (IPCC et al., 2018), which in the Iberian Peninsula (IP) translates to 0.5 °C/decade in the last 30 years (Brunet et al., 2006, 2007; Ramos et al., 2011). These increases provoke changes in the intensity and frequency of extreme weather events (Rodríguez-Puebla et al., 2010; Perkins et al., 2012; IPCC Intergovernamental Panel on Climate Change, 2014; Schleussner et al., 2017). Since the beginning of the century, 4 extreme heat waves (2003, 2010, 2015 and 2018) have occurred over Europe (Kuglitsch et al., 2010; Russo et al., 2015; Molina et al., 2020) and 2022 is on track to repeat this situation. Climate projections predict an increase in global average temperatures of 1.5 °C above pre-industrial levels by 2030–2052 (IPCC et al., 2018), which will cause more intense, prolonged and recurrent heat waves in the 21st century. This is predicted to have a higher impact on the IP and Mediterranean regions (Fischer and Schär, 2008; IPCC Intergovernamental Panel on Climate Change, 2014; Gasparrini et al., 2017; King and Karoly, 2017; Dosio et al., 2018; Guerreiro et al., 2018; Vicedo-Cabrera et al., 2018; Oliveira et al., 2022).

Heat waves lack a universal definition because of the complex interactions between atmospheric events and human impacts. This has given rise to numerous indices with a wide range of criteria, variables and temperature thresholds, making it difficult to determine universal measures of any climate (Alexander et al., 2006; Beniston et al., 2007; Brunet et al., 2007; Rodríguez-Puebla et al., 2010; Andrade et al., 2012; Perkins et al., 2012; Montero et al., 2013; Perkins and Alexander, 2013; Russo et al., 2014, 2015, 2017; Acero et al., 2017; Viceto et al., 2019).

Heat wave events can be characterized by four dimensions: duration, frequency, intensity (or severity), and spatial extent (Raei et al., 2018). The last two characteristics, have been less studied, especially in the IP (Lhotka and Kyselý, 2015; Molina et al., 2020; Sánchez-Benítez et al.,

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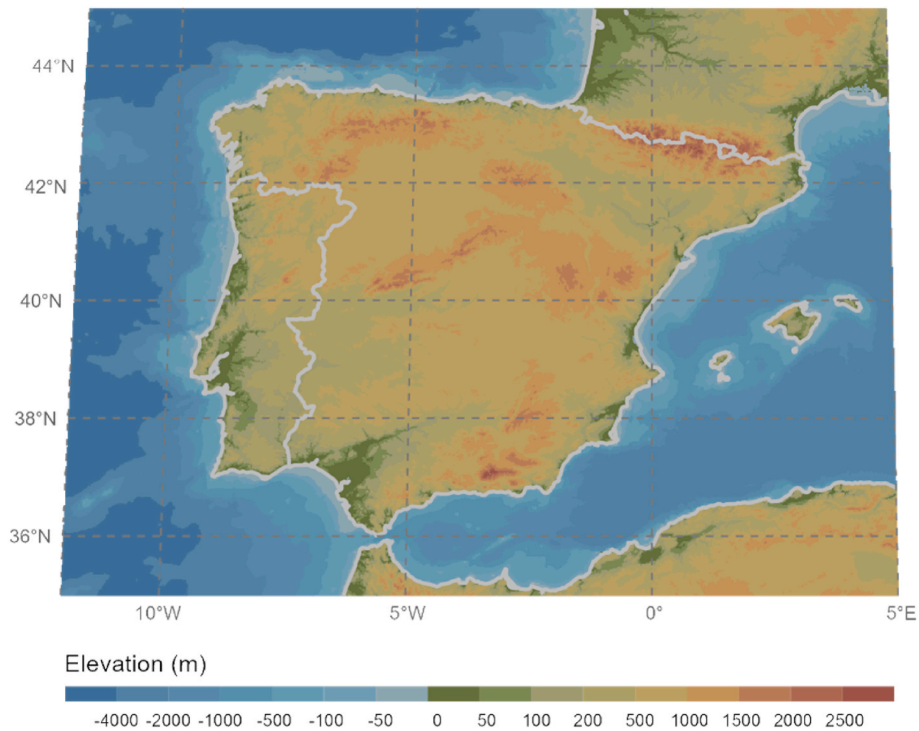


**Fig. 1.** Study area showing the limits of the IP and terrain elevation.

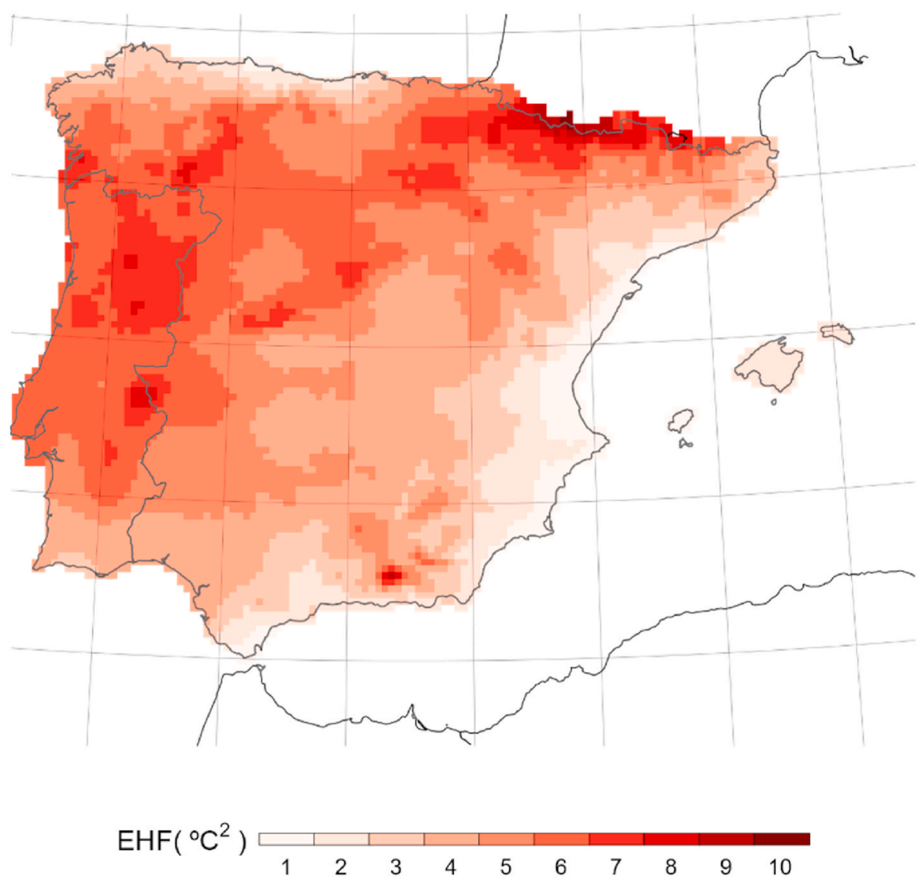


**Fig. 2.** Average positive EHF values for the period 1950–2020.

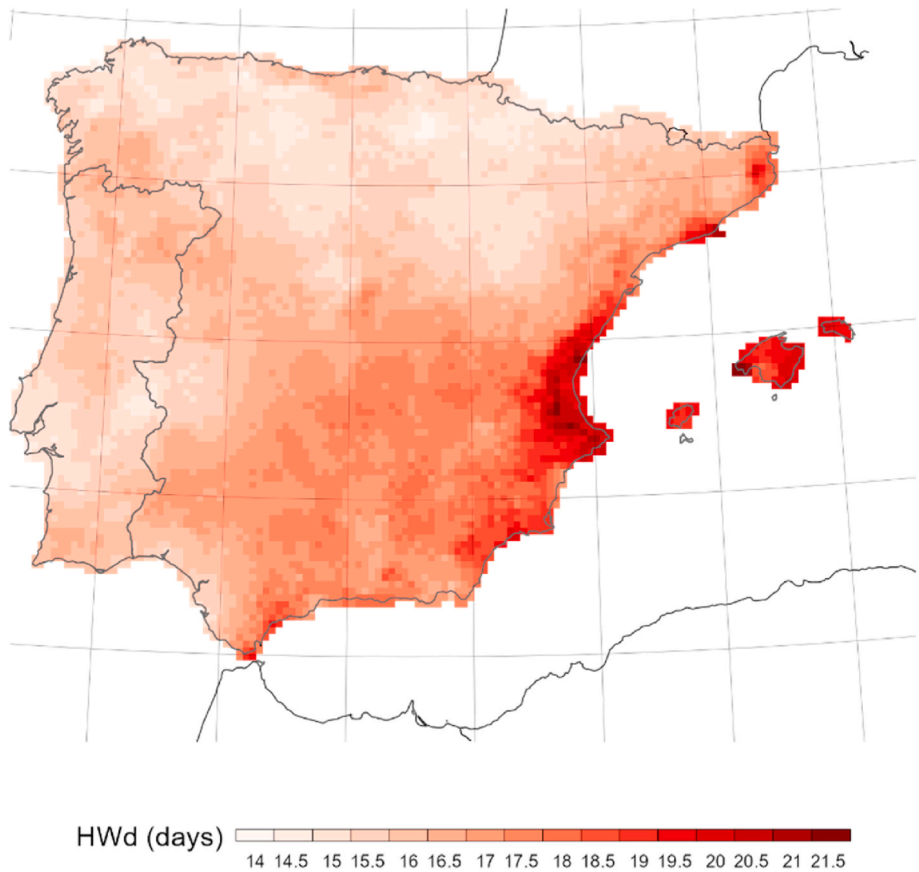


**Fig. 3.** Annual average heat wave days (HWd) for the period 1950–2020.

2020; Lorenzo et al., 2021).

Among the many heat wave indices available, the Excess Heat Factor (EHF) developed by Nairn and Fawcett (2015) stands out in recent years. This index, takes into account on the one hand the intensity of the heat wave and on the other hand the acclimatization process of the human body (Xu et al., 2016). Two important factors when analyzing the socio-health consequences of heat waves. Future climate projections for the IP using the EHF show for the near future 2021–2050 an increase of 60% in heat waves intensity and of 6%–8% per decade in its maximum spatial extent (Lorenzo et al., 2021).

Earlier studies suggested that the EHF could predict problems in the human health better than other heat wave indices (Scalley et al., 2015; Guo et al., 2017; Nairn et al., 2018; Williams et al., 2018; Royé et al., 2020; Sheridan et al., 2021; Wondmagegn et al., 2021). Knowledge and understanding of the effects of the different factors that describe a heat wave on health are indispensable for the public health system (Guo et al., 2011; Royé et al., 2020).

The aim of this study was to carry out a spatio-temporal analysis of the intensity and spatial extent of heat waves that affected the Iberian Peninsula and Balearic archipelago (IPB) during the period 1950–2020 using the EHF index. The duration and trends observed for the study period are estimated. To further explore the usefulness of the EHF, the intensity and spatial extent during the exceptional heat wave of August 2018 were also analyzed.

## 2. Study area

The IPB is located in south-western Europe, between 36° and 44° latitude and −10° and 5° longitude, with approximately 622,920 $km^2$ (Fig. 1). To the north it is bordered by the Cantabrian Sea, to the west by the Atlantic Ocean, and to the east by the Mediterranean Sea. The Pyrenees mountain range in the north-eastern corner connects it to the rest of Europe. Its location in mid-latitudes and its complex orography (Barry, 2008) cause great contrasts in the atmospheric conditions of the study region (Royé et al., 2019). The Azores anticyclone is the main center of atmospheric action of the IPB, conditioning through its inter-annual displacement the atmospheric circulation in the IPB, preventing summer rainfall and allowing the invasion of the IPB by tropical air masses from continental Africa. The latter factor is the cause of most heat wave episodes in the region. The rugged geography in combination with the Atlantic Ocean to the west and the Mediterranean Sea to the east gives the IPB an outstanding climatic diversity from oceanic and Mediterranean to continental climate.

## 3. Data and methods

### 3.1. Data

The gridded temperature data set was obtained from the E-OBS database within the EU-FP6 project UERRA (Cornes et al., 2018). This is a daily high spatial resolution 0.1° (~10 km) data set covering the European region based on station data collected by the ECA&D initiative (Klein Tank et al., 2002). The source data come from many European national meteorological services and other data suppliers throughout Europe and the Middle East. The data set covers the period from January 1, 1950 to the present, and is updated regularly. The gridded population data set used was the JCR – GEOSTAT 2018 (Batista e Silva et al., 2021), with a cell resolution of 1 km.

### 3.2. Excess Heat Factor

The EHF is a measure of heat wave intensity recently developed by Nairn and Fawcett (2013). This index is composed of two factors. The first one takes into account the three-day daily mean temperature and

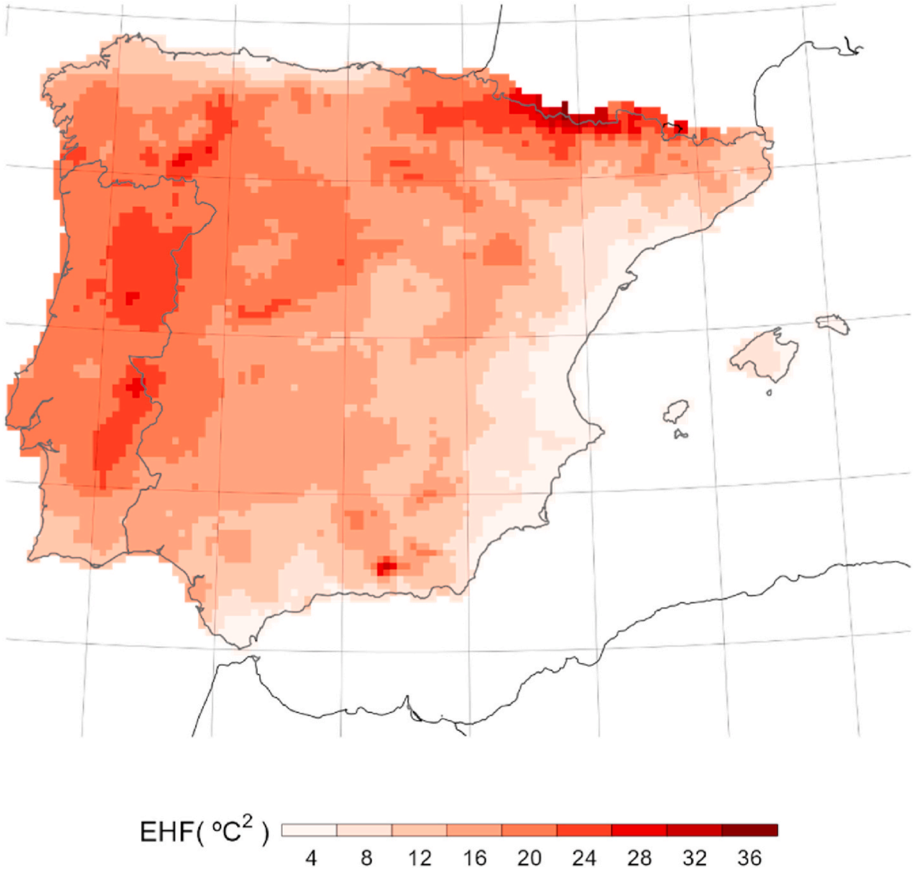


**Fig. 4.** The 95th percentile of positive EHF values for the period 1950–2020.

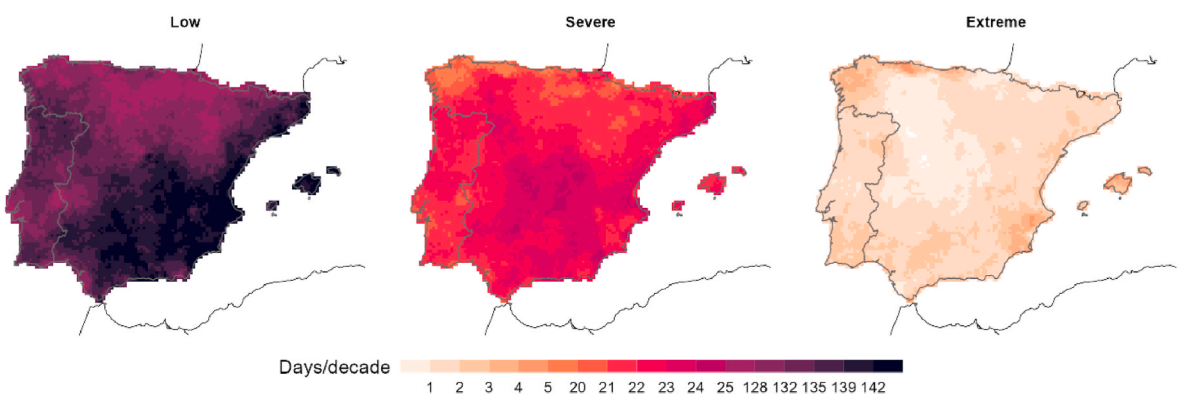


**Fig. 5.** Average duration of severity levels in days/decade for the period 1950–2020.

compares it to the 95th percentile of the daily mean temperature for the climatological study period, in this case, 1950–2020. This first factor is termed index of significance ($EHIsig_i$). If it is > 0, the period is considered to be abnormally warm compared to the climatology of the study area.

$$EHIsig_i = \frac{(T_i + T_{i+1} + T_{i+2})}{3} - T_{95}$$

where: T is the daily mean temperature, i represents each day of the study period and T95 is the 95th percentile of the daily mean temperature.

The second factor of the EHF index, called the acclimatization index ($EHIaccl_i$) (Nairn and Fawcett, 2015), compares the temperatures reached during the considered three-day period with the temperatures of the last 30 days.

$$EHIaccl_i = \frac{(T_i + T_{i+1} + T_{i+2})}{3} - \frac{(T_{i-1} + \cdots + T_{i-30})}{30}$$

With these two factors the index (EHF) is calculated where $EHIaccl_i$ acts as an amplifier of the factor $EHIsig_i$. $EHIsig_i$ is amplified when $EHIaccl_i$ is > 1, and only values of $EHF_i > 0$ can be considered heat wave days.

$$EHF_i = EHIsig_i \bullet \max\left(1, EHIaccl_i\right)$$

The severity of the heat wave will also be considered. According to Nairn and Fawcett (2013), the 85th percentile (P85) of all positive EHF values in the study period determines the severity threshold, separating normal from extreme events. As recently noted by Lorenzo et al. (2021), we consider three degrees of severity: low ($EHF/EHF_{P85} \leq 1$), severe (1

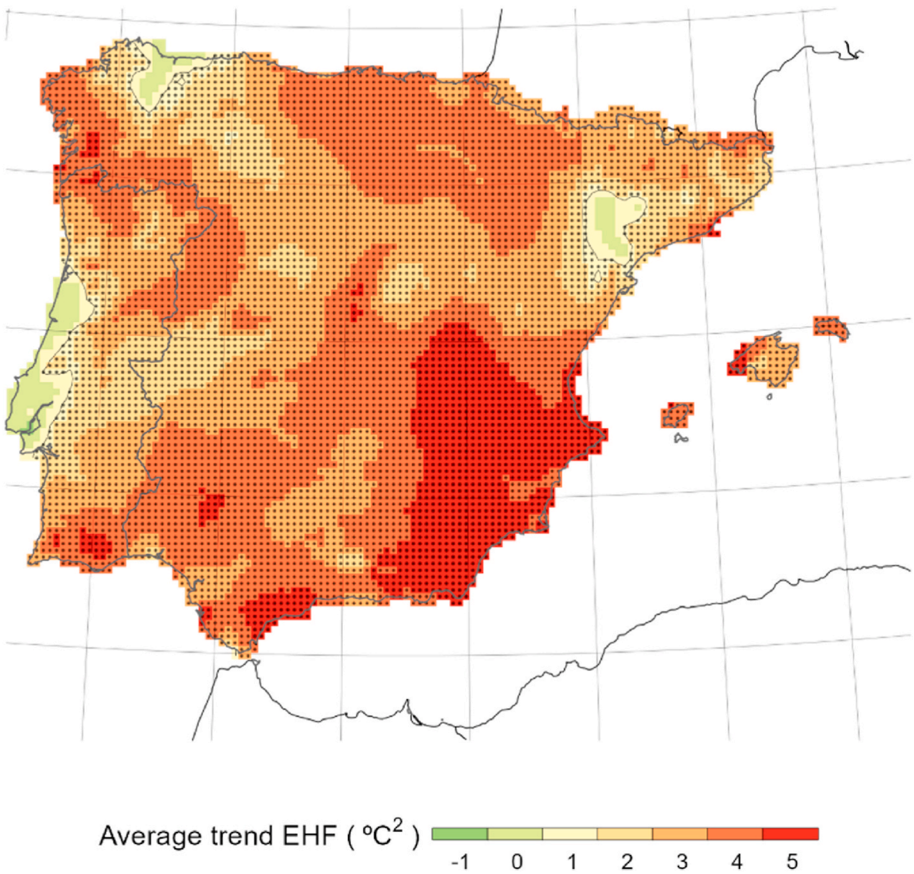


**Fig. 6.** Average trend in the intensity of events with positive EHF for the period 1950–2020. Values are expressed in °C2/decade.

$< EHF/EHF_{P85} < 3$), and extreme ($EHF/EHF_{P85} \geq 3$).

### 3.3. Analysis

To analyze the climatology of the four dimensions defining a heat wave with the EHF index, we calculated, using only positive values, the mean and maximum annual EHF value (intensity), the average number of heat wave days (EHF >0), the duration of the heat wave event (successive days with EHF >0), and the mean and maximum relative spatial extent (relative proportion of EHF >0 of all points) for the IPB over the period 1950–2020. For trend analysis, the nonparametric Mann-Kendall test (Mann, 1945; Kendall, 1975) was applied at a 95% confidence level. The illustrations of the results and statistical analysis are carried out with the R (4.0.4) statistical environment (R Core Team, 2021).

## 4. Results

### 4.1. Spatio-temporal trends of the EHF

The trends of the EHF during 1950–2020 show a large spatial variability. Fig. 2 shows the average positive EHF values for the study period. The maximum values (10°C$^2$) are recorded in the Pyrenees, and considerably high values (7-9°C$^2$) are also observed in the rest of the main mountainous areas of the IPB. The rest of the high values (6°C$^2$) are predominantly concentrated in the western peninsula and western fringe of the northern sub-plateau. The lowest values ($\leq$3°C$^2$) are found in the Balearic archipelago, in the Midwestern Cantabrian coast and, especially in the east, along the Mediterranean coast.

A latitudinal dependency of the average positive EHF is not observed, but a continental and, especially, altitudinal influence is discernible. The highest areas are more sensitive to warm tropical air masses coming from the Sahara, which materializes in a higher (lower) intensity of events in the Midwestern of the IPB (Cantabrian and Mediterranean coastal area).

The annual average of heat wave days (HWd) based on positive EHF values are presented in Fig. 3. The IPB has an annual mean value of 16.6 days. The eastern and south-eastern peninsula show a greater number of days with positive EHF throughout the year, while in the northern peninsula and in the main mountainous areas the number of days is reduced. A difference of 7 days a year can be found between one area and another.

The coefficient of variation HWd highlights high regional variability (Fig. S1, see supplement) in the areas of the Mediterranean coast, while the Cantabrian coast and the northern peninsula present a considerably lower variability.

The 95th percentile of the average positive EHF (Fig. 4) shows different spatial patterns, where the highest values are found in the north-central area of Portugal, and in areas of high elevations in the IPB. This means that the threshold temperature to give notice of heat wave must be higher in these regions than on the Mediterranean or Balearic coast, where the climate is milder and the $EHF_{95}$ value presents lower values. Hence, the intensity of heat waves decreases from west to east while the occurrence of heat waves increases from west to east.

The higher intensity values of $EHF_{95}$ in the western peninsula is related to the S-SE direction of the ridge from Africa, since this air mass practically does not dampen due to the short distance over the Mediterranean, as it does in its incursion to the eastern peninsula, as evidenced by the intensity values in the eastern peninsula and the Balearic archipelago. The $EHF_{95}$ on the eastern Cantabrian coast is higher than in the rest of the Cantabrian coast, because the dry and warm winds in their SN displacement do not overcome high orographic barriers in the Basque Mountains (<1600 m), contrary to what happens in the Cantabrian

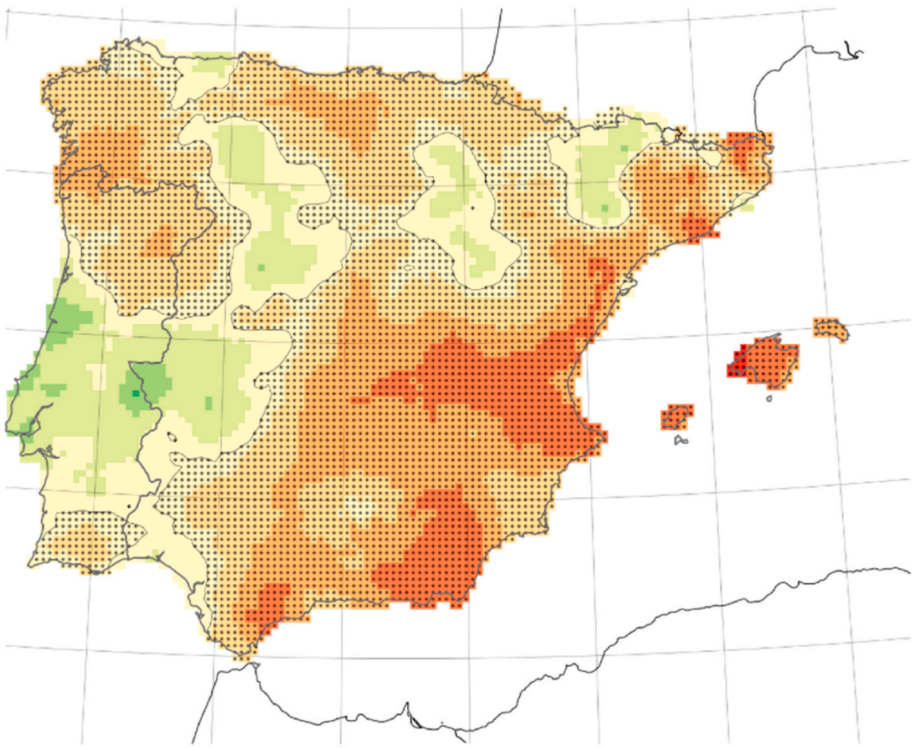


**Fig. 7.** Trend of the maximum of EHF for the period 1950–2020. Values are expressed in °C2/decade.

Mountains, with elevations higher than 2500 m (Fig. 1).

The duration of the heat waves, that is, the number of consecutive days in which the EHF is positive, shows that in most of the Mediterranean coast, heat wave events last more than 5 consecutive days while in half north-western they barely exceed 4 days (Fig. S2, see supplement). Fig. 5 shows the average number of days/decade by severity level. A large part of the northern and western peninsula register ≤132 days/decade of low severity conditions, while the south-eastern peninsula, Balearic archipelago and almost all the Mediterranean coast reach ≥142 days/decade. The number of days/decade under severe and extreme conditions is much higher in the Balearic archipelago and south-eastern Mediterranean, doubling the number of days of extreme severity (≥4 days/decade) compared to the rest of the IPB, with the exception of the north-western peninsular and southern Portugal. However, their local range of intensity and maximum intensity are lower (See Figs. 2 and 4).

The trends of intensity, occurrence and extension of the EHF are shown in Figures (6-9). The observed average trend in the intensity of the heat waves (Fig. 6) is significant and positive in 96.0% of the territory (Table S1, see supplement) with an increase of 5°C$^2$/decade, particularly in the east/southeast of the peninsula and Balearic archipelago, as well as in the south of Portugal. These trends are found in the regions where heat waves occur most frequently (see Fig. 3). Likewise, maximum EHF (Fig. 7) show a generalized significant increasing trend in the whole IPB, being positive in 71.9% of the territory. The greatest increases (≥4°C$^2$/decade) are once again recorded in the east/southeast of the peninsula, the Balearic Islands and small areas of the north-eastern peninsula. This means that the area not only experiences more intense heat waves but their extreme values are also higher. Both trends occur in regions where the range of intensity and maximum intensity is lower (see Figs. 2 and 4), making this increase especially significant.

In the 1950–2020 study period, the trend of heat wave duration is positive and significant in 74.5% of the territory (Fig. 8). In addition, this increase takes place in the eastern half of the IP and in the Balearic archipelago, which is also where the increase in the intensity is most noticeable.

Finally, the spatial extension of the heat waves is shown in Fig. 9. The spatial extension is defined as the area corresponding to the number of pixels that are in conditions of EHF >0. A significant trend in the average annual extension is seen, especially observable since the end of the 80s, with only 7 years since 1986 in which the extension of upper limit is less than 50%. In fact, until 1986, the upper limit reached values greater than 90% of the IPB extension for only one year, while since 1987 this extension has been exceeded for 16 years.

The 90th percentile, the threshold for large extension heat waves, is exceeded for an average of 3.9 days/year, reaching a maximum of 18 days in the heat wave of 2006. The positive trend observed in the extension of heat waves (Fig. 9) corresponds to an increase in the average extension of 4.0%/decade and in the maximum extension of 4.1%/decade. Large extension heat waves also increase by 1.5%/decade.

### 4.2. Heat wave event of August 2018

The heat wave that affected the IPB in August 2018, arose from a very intense high ridge above the IP, caused by the presence of a continental tropical air mass of North African origin (Sousa et al., 2019; Barriopedro et al., 2020). This air mass gave rise to a dry and warm environment that was especially intense in the west/northwest of the peninsula, due to the location of the ridge on the western peninsula. The south-eastern coast was not so affected in terms of intensity, since the advection of the warm air masses coming from Africa lose energy when

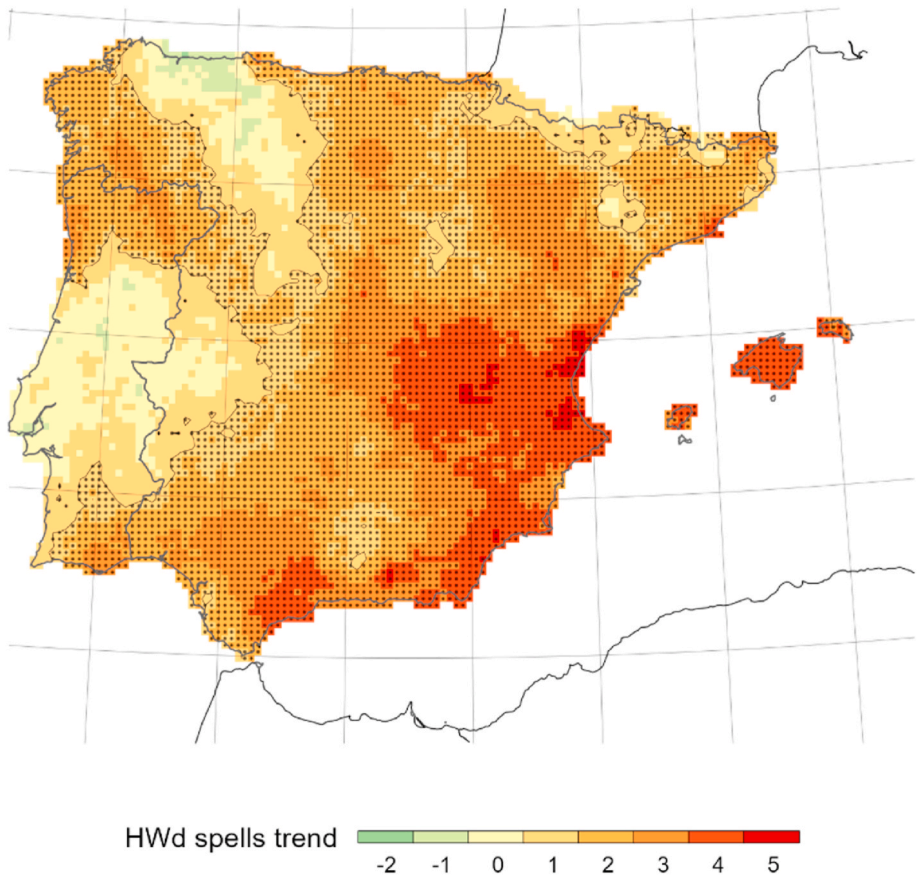


**Fig. 8.** Trend in heat wave spells in days (HWd) for the period 1950–2020. Values are expressed in days/decade.

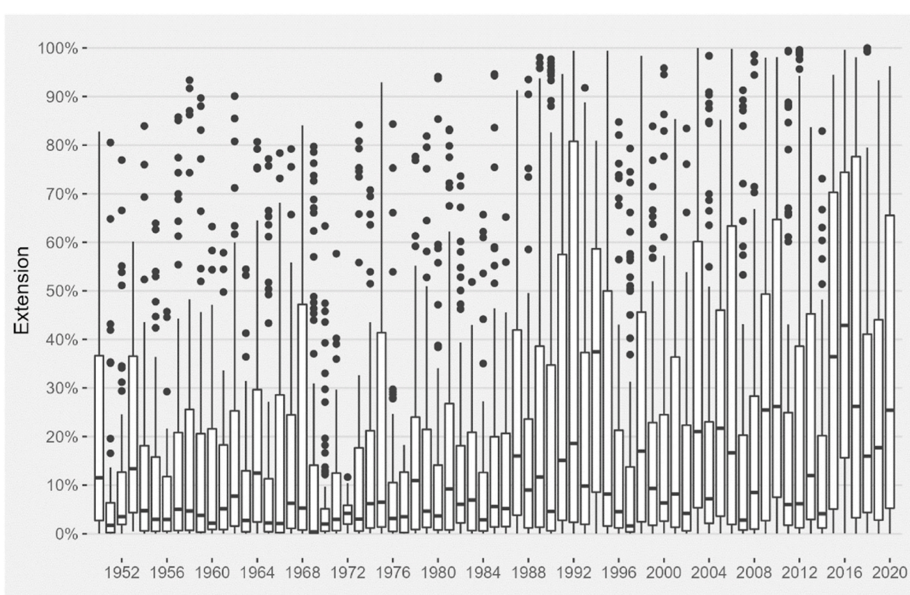


**Fig. 9.** Distribution of the spatial extensions of heat waves by year in the IPB (1950–2020).

crossing the Mediterranean Sea, but it did suffer the heat wave for a longer time.

Fig. 10 shows the days in which the EHF index was positive at some point in the study area, and therefore heat wave conditions occurred between July 29 and August 9. As can be seen, the greater intensity of the index occurs in the west of the peninsula, however the EHF index shows greater persistence in the eastern zone.

From $EHF_{mx}$ (Fig. 11) we could see that the maximum values are mainly concentrated in Portugal and its border area ($EHF_{mx} \geq 50^{\circ}C^2$). This is owing to the greater influence of the North African warm air ridge in these areas. The maximum intensity is higher in mountain areas such as Serra da Estrela ($EHF_{mx} = 86.6^{\circ}C^2$) and the adjacent region ($EHF_{mx} \geq$

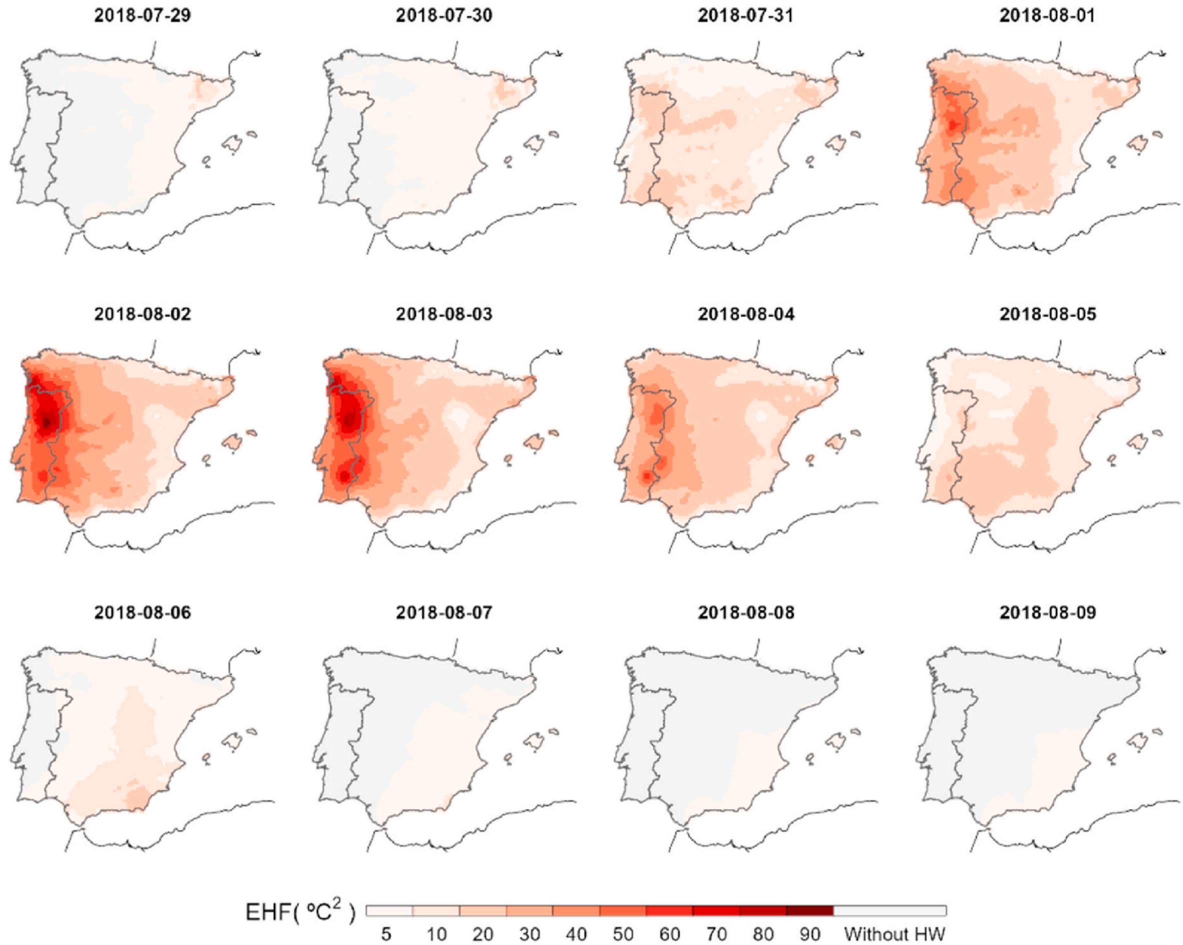


**Fig. 10.** EHF index values for the period 2018-07-29 to 2018-08-09 (in °C2).

80°C$^2$), where the $EHF_{95}$ 1950–2020 practically triples (see Fig. 4), possibly due to the circulation pattern in higher altitude.

In the southeast of the IPB, the Mediterranean Sea contributes humidity to the North African advection, considerably reducing its intensity in the Balearic Islands and practically throughout the Mediterranean coast, which translates into values of the $EHF_{mx} \leq 20°C^2$ index, except in the extreme northeast.

The sum of positive EHF values for the period from July 29 to August 9 (Fig. S3, see supplement) shows that the accumulated heat load, $EHF_{accum}$, is much higher in the west of the peninsula, coinciding with the $EHF_{mx}$ values. All the western peninsular strip except the north/northwest of Galicia and the coastal zone of the western sub-region and Grande Lisboa, has heat intensity accumulations $\geq 100°C^2$, particularly in the north and southeast of Portugal. These values confirm what was observed in the climatological study of the EHF index for the period 1950–2020. There is a great difference between the west and the east/southeast with a gradient of values that grows from east to west. The Balearic Islands, the central-western Cantabrian coast, and especially the southern half of the Mediterranean coast are the areas with the lowest values of the EHF index.

Fig. 12 shows the established levels of severity, taking into account the relationship between the $EHF_{P85}$ value for July 31 to August 5 with heat wave days where more than 99% of the territory reaches a positive EHF. On August 1, 78.3% of the IPB is under conditions of severe severity, and on August 2 and 3, more than 26.5% of the territory presents conditions of extreme severity. Although as of August 6 the heat wave withdraws from the western fringe of the IPB where heat wave conditions no longer exist, on the Mediterranean coast heat wave conditions of low severity persist until August 9. Thus, while in the western fringe the heat wave was active for 6 days, on the Mediterranean coast and the Balearic archipelago it was maintained for 12 days (Fig. S4, see supplement). This difference in the duration of the heat wave periods is in agreement with what was observed in the climatological study of the period 1950–2020 (see Fig. 7).

Another important characteristic of this heat wave event is its spatial extension, since it affected almost 100% of the territory days between July 31 and August 5, when only <0.8% of the territory was outside the heat wave conditions according to the EHF index. Fig. 13 shows the percentage of extension corresponding to each level of daily severity during this period. The most intense heat wave days are August 2 and 3, although from August 1 to 5, the EHF index reaches severe severity level ($1 < EHF/EHF_{P85} < 3$) in more than 41.4% of the territory.

Finally, the population affected by the heat wave, according to the different levels of severity established, is shown in Fig. 14. Between July 31 and August 5, a total of 50 million people were affected, while the extreme severity affected more than 14 million people between August 2 and 3.

## 5. Discussion

This study presents for the first time a climatological analysis of heat waves for the IPB using the EHF index. We analyze the intensity, duration, occurrence and extension of the heat waves for the period 1950–2020, as well as for the heat wave event in 2018. The results show that the intensity is greater in the west of the IPB and in mountainous zones. This is due to the existence in high altitudes of a ridge from North Africa, as several authors have already highlighted (Tullot, 2000; Gil Olcina and Gómez-Mendoza, 2001; Rodríguez-Puebla et al., 2010;

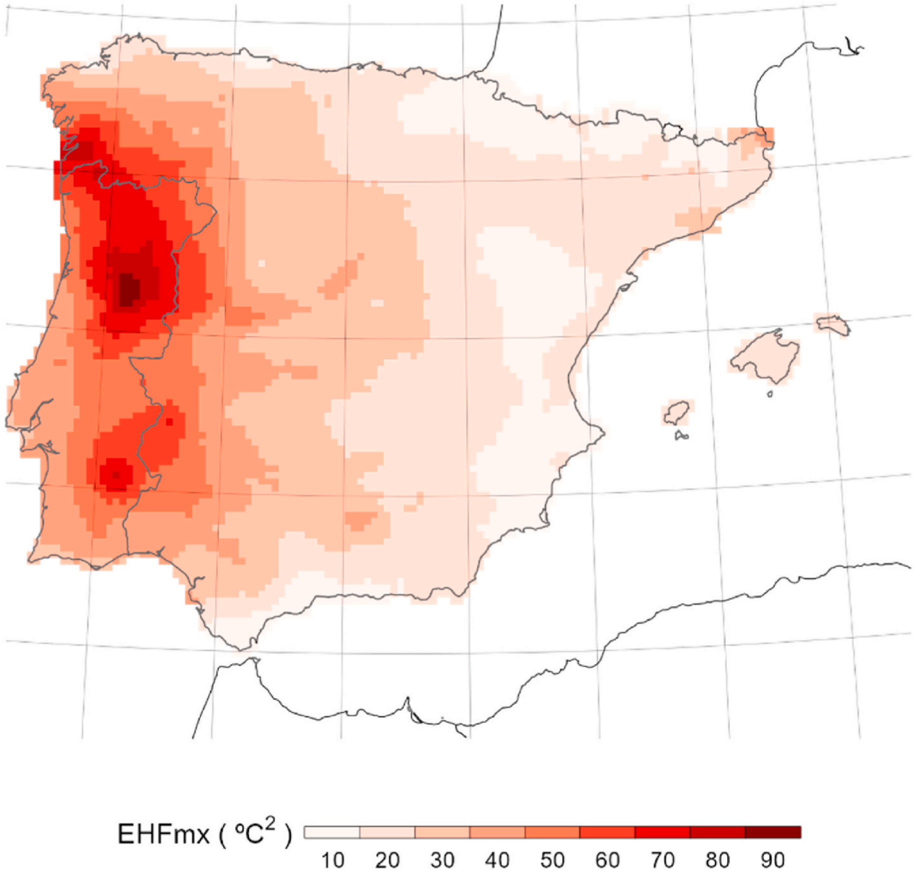


**Fig. 11.** Maximum EHF for the period 2018-07-29 to 2018-08-09 (in °C2).

Merino et al., 2018; Lorenzo et al., 2021). Although other authors (Mohammed et al., 2018) attribute to this ridge a residual role, in favour of the presence of a thermal drop generated in the IPB itself, the spatial location of much higher values of positive EHF and $EHF_{95}$ in the west and in the mountainous areas of the west, reveals that the role of this injection of warm air at high altitude is crucial in a large part of the heat waves that affected the IPB (Merino et al., 2018). This is observed in the spatial distribution of the $EHF_{mx}$ and $EHF_{accum}$ of the episode analyzed in 2018, according to Sousa et al. (2019) and Barriopedro et al. (2020).

Both in the period 1950–2020 and the 2018 episode analyzed, the EHF index reflects that heat waves occurring in the western area and mountainous zones present a higher value but shorter duration than heat waves in the south-eastern peninsula and on the Mediterranean littoral, due to the transport of air masses from the Atlantic Ocean to the west of the IPB. The intensity trends observed in positive EHF and in the $EHF_{mx}$ for the period 1950–2020 indicate that heat waves in the IPB are becoming more intense and extremes events are increasing in magnitude, as recently highlighted by Oliveira et al. (2022). Our results show a significant increase in both the duration of heat wave spells and their extension, with increases of 4.0% per decade for the average extent and 4.1% per decade for the maximum extent. In this context, large extension heat waves also follow this trend with an increase of 1.5% per decade. This significant increase in duration and extension is in agreement with previous studies (Rodríguez-Puebla et al., 2010; Ramos et al., 2011; Andrade et al., 2012; Russo et al., 2014; Pereira et al., 2017; Viceto et al., 2019; Barriopedro et al., 2020; Lorenzo et al., 2021; Lorenzo and Alvarez, 2022). These trends in the spatial extension suggest a substantial increase in human exposure, droughts, fire risk and energy demand.

When it comes to identifying a heat wave, the EHF index is more sensitive to local increases in temperature than other indices, allowing to warn the populations of a heat wave in advance. In the case of the 2018 heat wave event, the EHF index detects heat wave conditions two days earlier than indices that use only maximum temperatures. In comparison, the heat wave warning was established by the Agencia Estatal de Meteorología (AEMET) two days after than EHF index. In line with this, from a biometeorological perspective, Nairn et al. (2018) recently showed that regardless of the local climate, the EHF index also anticipates by 1–2 days the date when the greatest health impact of the heat wave occurs. Likewise, other indices do not allow us to see the variability of the duration of heat wave events, which is very important when it comes to knowing which regions should maintain the health alert, for example.

## 6. Conclusions

We carried out a spatio-temporal analysis of the intensity, duration, frequency and spatial extension of heat waves in the IPB for the period 1950–2020 using the EHF index. To explore the usefulness of the index, we also estimated the intensity, duration and special extent of the 2018 heat wave, with the following conclusions:

- The highest intensities are observed in the western peninsula and mountainous areas. The southeast of the IPB and, particularly, the Mediterranean coast, have milder intensities. The regions showing the maximum intensities do not correspond to the areas where heat waves have the longer duration.
- The trends for the period 1950–2020 show that the heat waves in the IPB are becoming more intense and extreme events are increasing in magnitude. The increase in the duration of heat wave periods is more pronounced in the east/southeast, where the increase in intensity is also greater.

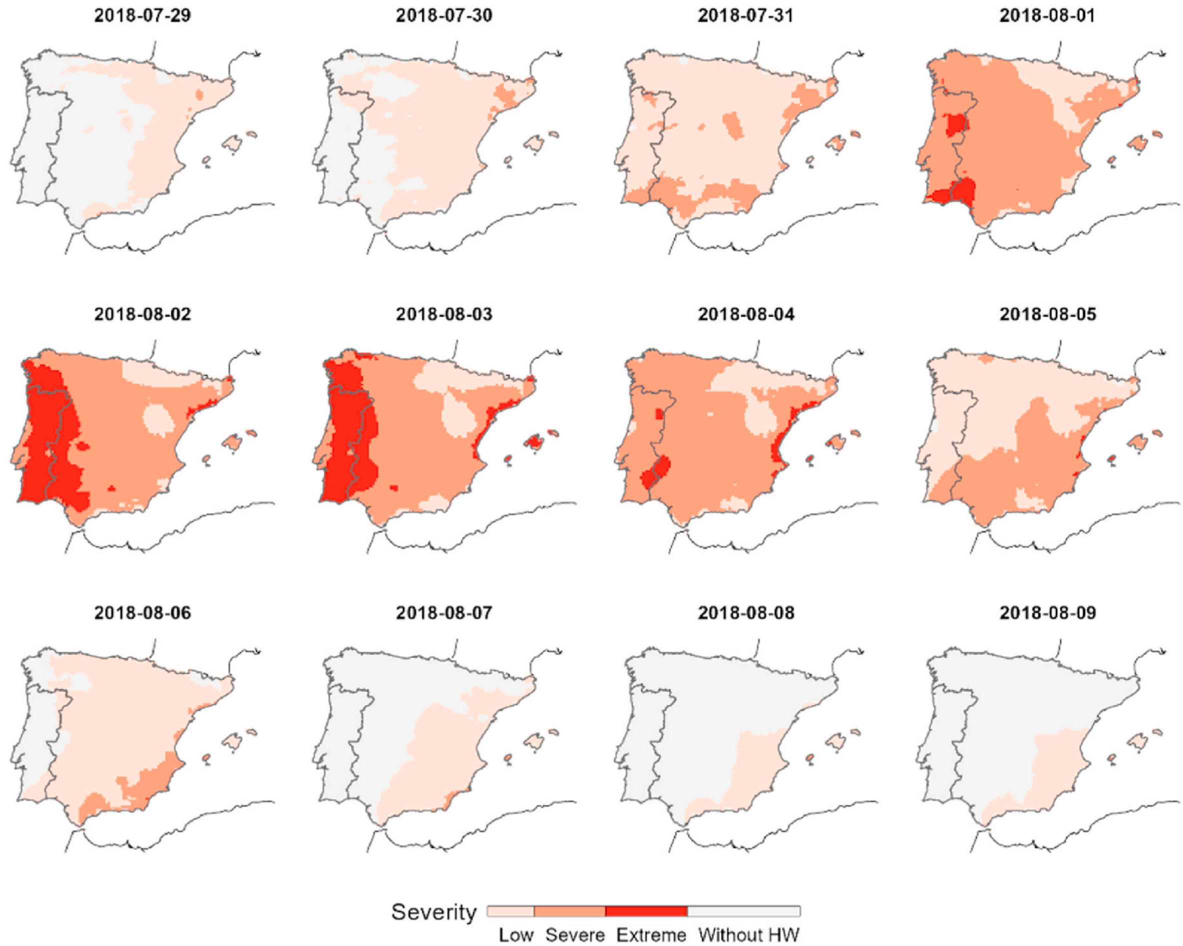


**Fig. 12.** Severity threshold for the period 2018-07-29 to 2018-08-09 (in °C2).

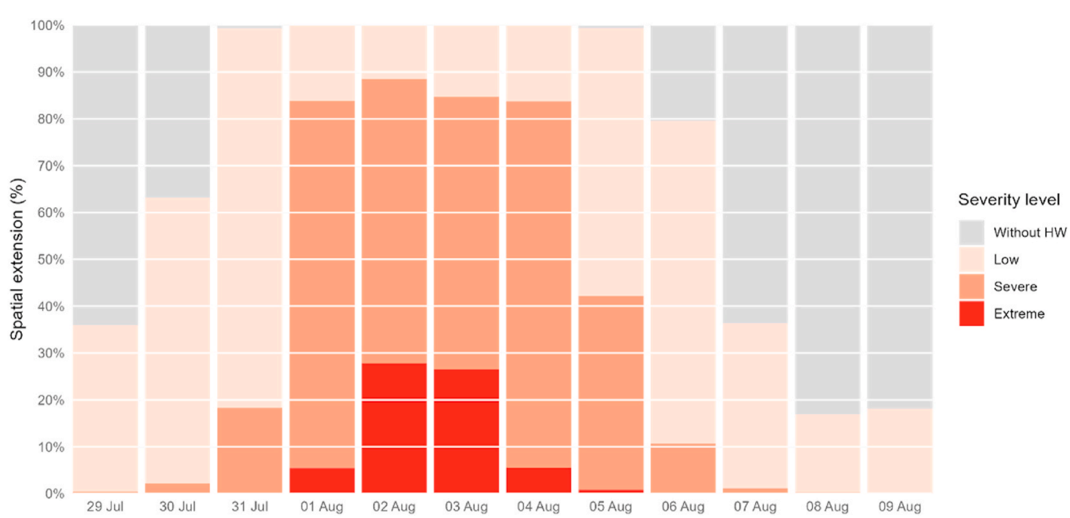


**Fig. 13.** Spatial extension of the heat wave for the period 2018-07-29 to 2018-08-09.

- The maximum extent of heat waves increases even more than the average extent, with increases of 4.1% and 4.0% per decade, respectively.

The results show the ability of the EHF index to detect heat wave conditions earlier than other indices, as well as its effectiveness in assessing their intensity, duration, frequency or extent, making it a useful index to contribute to decision making to minimize its effects on the health system or in vulnerable sectors such as energy or agriculture. This research will be continued in future studies by developing a spatio-temporal analysis of the intensity, frequency, duration and spatial extent of cold waves in the IPB, using the Excess Cold Factor Index.


**Fig. 14.** Population affected by the heat wave for the period 2018-07-29 to 2018-08-09.

## Credit author statement

**Alejandro Díaz-Poso:** Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Nieves Lorenzo:** Methodology, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Supervision. **Dominic Royé;:** Conceptualization, Methodology, Software, Validation, Writing – review & editing, Visualization, Supervision

## 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

Derived data may be requested from the authors.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.114864.

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