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Invited review article

Unprecedented warmth: A look at Spain's exceptional summer of 2022

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ABSTRACT

The warming of the global climate system is expected to result in significant socio-economic stress, primarily through the occurrence of extreme weather and climate events, with the potential for severe impacts on societies. This was evidenced by the vulnerability of European nations during the 2003 summer heatwave, which resulted in the death of tens of thousands of individuals due to heat-related complications. In this analysis, we examine the summer of 2022 in Spain, a Mediterranean country that is among the most impacted by the effects of climate change. A distinct pattern of the subtropical ridge in the 500 hPa geopotential height, which is typically linked to the occurrence of heatwaves in the Iberian Peninsula (IP), and the atmospheric blocking in the North Atlantic region facilitated the southerly flow of exceptionally warm air masses from Africa towards the IP, contributing to the sustained high temperatures throughout the summer season. Our results show that Spain experienced record-breaking temperatures in nearly half of the country that favored more frequent, intense, and longer-lasting heatwaves compared to previous historical records available from 1893. In general, despite normal rainfall conditions, the extremely high temperatures led to intense drought conditions in most areas. Finally, the paleoclimatic records suggest that the average summer temperature of 2022 was unprecedented within the last 700 years, and the driest within the last 279 in NE Spain. These findings highlight the need for measures to mitigate the effects of heat on at-risk populations, and to increase resilience and adaptation to climate change in the future.

1. Introduction

In the past two decades, Spain has experienced a significant increase in extreme heat waves and very intense droughts during the summer months (Serrano-Notivoli et al., 2022; Espín-Sánchez and Conesa-García, 2021). Warm summers of 2003 (García-Herrera et al., 2010), exemplified as the first major evidence of European vulnerability to extreme heat events (Robine et al., 2008), and 2015 (Russo et al., 2015) saw record-breaking high temperatures, albeit not very extraordinary within the context of the recent decades. In fact, the first 22 years of the 21st century witnessed 57% of the highest summer temperatures ever recorded in the country, resulting in notable impacts not only on temperature but also on hydroclimate conditions. Although dry situations are common in the Mediterranean climate summers, these warm conditions have caused unprecedented impacts on natural and socio-economic systems, with droughts like those in 2012 (Tejedor et al., 2016; Trigo et al., 2023) and 2017–2019 (Hoy et al., 2020; Ma et al., 2020; Kew et al., 2019; Sánchez-Benítez et al., 2018) altering the normal cycle of evapotranspiration rates (Mathbout et al., 2021; Rita et al., 2020). Over a longer-term period, summer droughts in Spain have increased in frequency since the mid-20th century (Domínguez-Castro et al., 2018), with many of them falling into the category of *flash-droughts*, characterized by rapid onset and intensification (Noguera et al., 2020). These conditions, characterized by high temperatures and low precipitations, are usually driven in summer in Spain by persistent anticyclonic conditions that lead to continued stability and enhanced by southern advections from the Sahara Desert (Serrano-Notivoli et al., 2022). During droughts, the North Atlantic Oscillation (NAO) and the

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Western Mediterranean Oscillation (WeMO) play a key role in determining the precipitation of the hydrological year. However, atmospheric blocking situations are primarily responsible for dry conditions at the synoptic scale (Vicente-Serrano, 2021; Vicente-Serrano and Cuadrat, 2007).

The impacts of extreme summers have already been witnessed in the region, including heat-related health issues, agricultural challenges, water resource management difficulties, and ecosystem disruptions. These effects highlight the vulnerability of the region to such extreme climatic events. While warm and dry summers are characteristic of the Western Mediterranean region, there are instances when exceptionally hot seasons occur, and they are characterized by persistent high temperatures that lead to a higher atmospheric evaporative demand and increased rates of evapotranspiration. At the same time, there is a reduction in humidity and precipitation, exacerbating the effects of the high temperatures. These conditions have been demonstrated to favor numerous impacts in the region, including the reduction of glacier extension to their minimum levels (Alonso-González et al., 2020), the creation of ideal conditions to forest fires (Resco de Dios et al., 2022), reduced vegetative activity due to hydric stress (Martinez del Castillo et al., 2022), affections to crops (Trnka et al., 2014), and an increase in heat-related deaths (Tobías et al., 2021), etc. Despite being potentially anomalous in Spain's climatic history, extreme summer conditions are expected to recur with increasing frequency in the future (Lorenzo et al., 2021; Markonis et al., 2021; Ionita and Nagavciuc, 2021; Hari et al., 2020).

Exploring the paleoclimatic context reveals that the substantial variability in Spanish summers is not a recent occurrence but rather a recurrent pattern throughout history. This perspective underscores the complexity of attributing the observed changes solely to climate change, as natural climate variability has played a significant role in shaping past summer conditions. Reconstructions of summer temperatures over the past 1000 years have shown significant temporal variability, although a clear positive trend has been observed since the mid-20th century (Esper et al., 2020; Sangüesa-Barreda et al., 2018; Büntgen et al., 2017; Tejedor et al., 2017a; Dorado-Liñán et al., 2012, 2015). Hydroclimatic variability is also a key feature of summers in Spain, with frequent droughts, occasional wet extremes, and no clear temporal trend (Tejedor et al., 2017a, 2017b, 2019; Lallana Llorente, 2018; Machado et al., 2011; Rodrigo and Barriendos, 2008). However, such studies are focused on a regional scale, thus it is difficult to assess the extent to which extreme changes in temperature and hydroclimate variability in the last centuries are regional or affect the entire country.

Nonetheless, the summer of 2022 in Spain has been marked by a unique combination of extreme weather events, including high occurrence and intensity of heatwaves (HW), and a long but not infrequent period of low precipitation amounts in most of the territory as a consequence of an unusual atmospheric pattern. While it is not straightforward to determine the extent to which these conditions can be attributed to the current climate change, past events in Europe, such as the 2018 HW, suggest that climate change may have played a role (Rousi et al., 2022). The available observational records showed that mainland Spain experienced in 2022 the hottest summer in the historical records, with an average temperature of 24.6 °C (0.5 °C higher than the previous highest record in 2003 and 2.1 °C higher than the average of 1981–2010 period). Several HW events were present throughout the summer, although their official definition could lead to diminish their magnitude. In order to classify a HW event, the Spanish Meteorological Agency (AEMET) requires at least 3 consecutive days with maximum temperatures above the 95th percentile for July and August, as measured between 1971 and 2000, occurring in at least 10% of the weather stations across the country. By these criteria, Spain experienced a total of 42 days under HW conditions, in different HW events, during the summer of 2022. The extreme temperatures during this period led to record-breaking heat in many cities across southern IP. For example, Morón de la Frontera saw a maximum temperature of 46.0 °C on July 24th, while Murcia recorded 45.1 °C on July 25th and Seville reached a high of 44.8 °C on July 13th (Aemet, 2022). In addition, the persistence of heat at night, favoring a high degree of thermal discomfort, was also present in the high records of nocturnal minimum temperature reached in numerous Spanish cities, near to 30 °C, which represented breaking records in the entire observation series: Palma de Mallorca, 29 °C; Menorca, 28.8 °C; Alicante, 28.6 °C; Cádiz, 28.2 °C Valencia, 27.5 °C; Segovia, 27.4 °C; and Murcia 27.2 °C.

This paper provides an overview of the weather patterns in Spain during the summer of 2022 and examines it within the context of longer-term climatic records. By considering multiple factors, including temperature, precipitation, drought indices, and other relevant variables, we aim to gain a holistic understanding of the complex interactions and feedbacks within the climate system. This multi-dimensional approach allows for a more comprehensive evaluation of the summer conditions and their implications. We analyze the data on two-time scales: 1) the historical period from 1893 to 2022, which provides a quantitative basis for comparison, and 2) the paleoclimatic perspective, which allows us to compare recent events with extreme climatic conditions from the past 1000 years using tree-ring proxies. Additionally, we identify the factors that led to the compound events that occurred in summer 2022 and discuss the potential environmental and socio-economic impacts.

2. Data and methods

The analysis of the climate in the summer of 2022 in mainland Spain involved the use of different sources and types of data, depending on the analyzed variables and the temporal range. In order to assess the uniqueness of the weather of the summer 2022 the temperature and precipitation values were contextualized in the instrumental period through extreme temperatures and drought indices using the available data records from the AEMET and satellite products. The paleoclimatic perspective was addressed by comparing recent instrumental data with the previously published proxy-based reconstructions of temperature and drought.

For the analysis of the instrumental data, we used daily observations of precipitation and temperature collected from 75 weather stations operated by AEMET. These stations were located throughout Spain, evenly distributed, and had at least 50 years of data records and were in operation in summer 2022 (JJA). The average missing records by station was 3.5% for precipitation and 7.6% for temperature. Since the quality of data series is controlled by AEMET, we did not apply any additional process to check the quality or the homogeneity of the data. The highest availability of observations was from the mid-1970s to 2022, as depicted in Fig. 1b, however, the longest data series extended over a period of 130 years.

HW events were identified following the procedure described in Serrano-Notivoli et al. (2022), which requires TMAX and TMIN simultaneously exceed in the same day and at least during 3 days in a row, their 90th percentile of a 7-day centered window within the warm season (in this case, from June to August). The intensity of all the HW events during the summer was computed as the sum of °C exceeding the 90th percentile threshold. In contrast to the AEMET definition, that only considers the exceedance of 95th percentile of TMAX of July and August, our approach provides a more robust consideration of a HW by incorporating minimum temperatures. This broader perspective avoids the limitation of the solely considering the potential impacts during the central hours of the day and takes into account the effects of night-time heat as well.

In order to assess the drought severity beyond the recorded rainfall, we used the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), which includes air temperature as an additional variable to compute the potential evapotranspiration when compared to the traditional SPI, which only considers precipitation. A lag of 3 months (SPEI3), ending in August, was considered to assess the hydroclimatic situation of the summer.

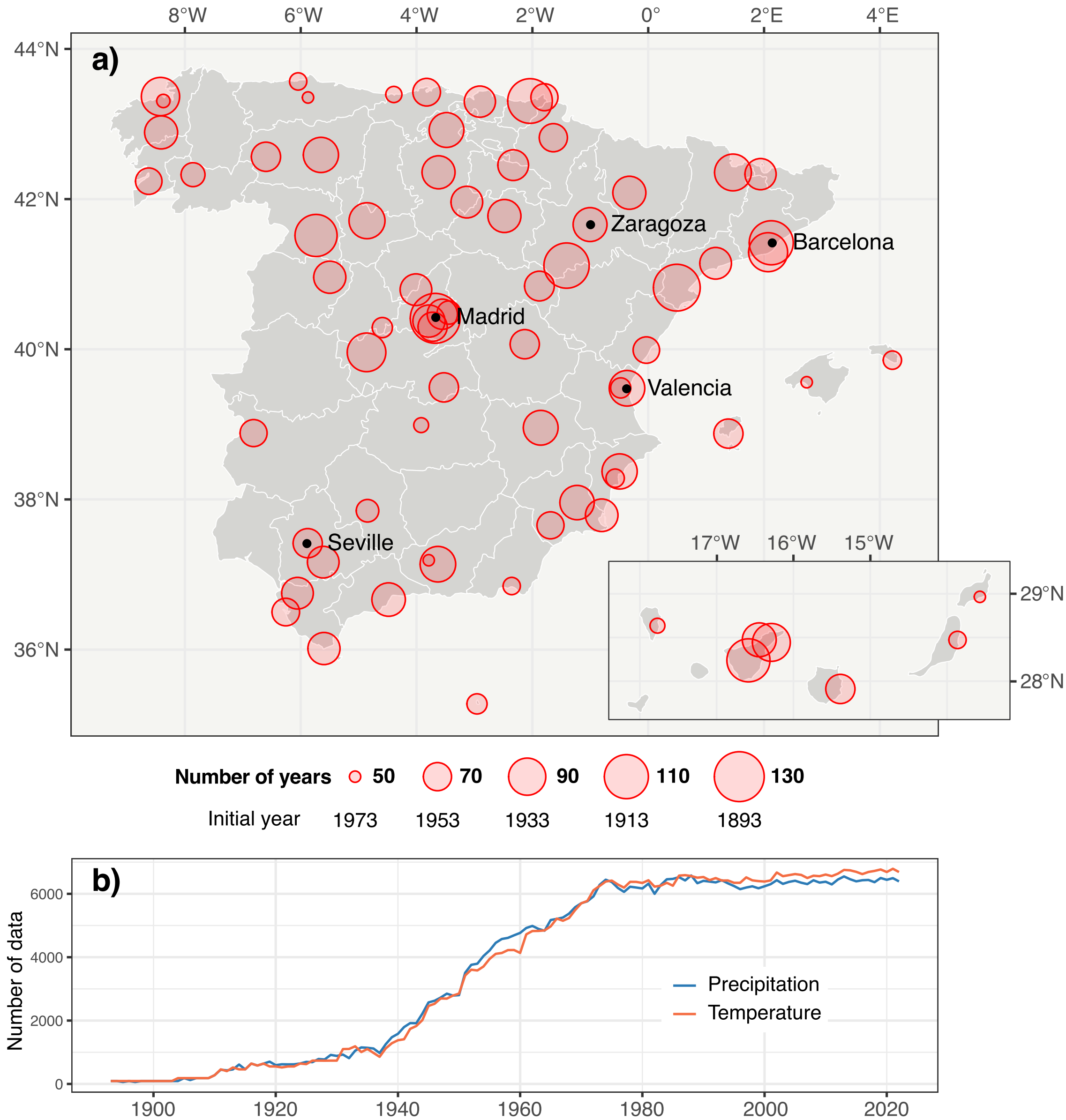

Fig. 1. a) Spatial and temporal distribution of the 75 weather stations used for the climatic analysis in the instrumental period (1893–2022). The stations contain at least 50 years of data records. b) Annual availability of data in summer season (JJA).

We conducted the analysis of land surface temperature (LST) by utilizing the MODIS product MOD11A1 at a spatial resolution of 1 km. The average summer values of day and night were calculated for the period 2002–2022, and annual anomalies were computed as the difference between these values and the average of the entire period. The complete methodological process is described in detail in Sarricolea et al. (2022). We finally extracted the data from the 52 province capitals and computed their average to depict the temporal evolution of urban LST.

The Institute of Atmospheric Sciences and Climate (CNR – Rome) (2016) provided the Sea Surface Temperature (SST) data for the Mediterranean basin. This dataset provides daily gap-free data (L4) at a 0.0625° spatial resolution over the Mediterranean Sea, and its data is obtained from satellite infra-red measurements and statistical interpolation. The available temporal period for this dataset ranged from 2008 to 2022.

Finally, to provide a long-term context for the 2022 summer, we updated the instrumental records that were previously used for calibration in a temperature reconstruction by Büntgen et al. (2017) and a hydroclimate reconstruction by Tejedor et al. (2017b). By employing this methodology, it became possible to extend the reconstructions of the estimated summer temperature in the Pyrenees and the estimated summer drought (SPEI2August) in Northeast Spain until the year 2022.

3. Results and discussion

3.1. A perspective from the historical observational records

3.1.1. Atmospheric dynamics

The average summer synoptic conditions in 2022 exhibited a spatial pattern similar to that of an average summer in terms of the 850 and 500 hPa geopotential height and SLP (Fig. 2). However, some distinct characteristics were present, which contributed to the unusually high temperatures observed in the IP. One example is the distinct more pronounced subtropical ridge pattern in the geopotential height during summer 2022, which is commonly associated with the occurrence of HWs in the IP (Serrano-Notivoli et al., 2022). Additionally, the blocking in the North Atlantic region facilitated the southerly flow of very warm

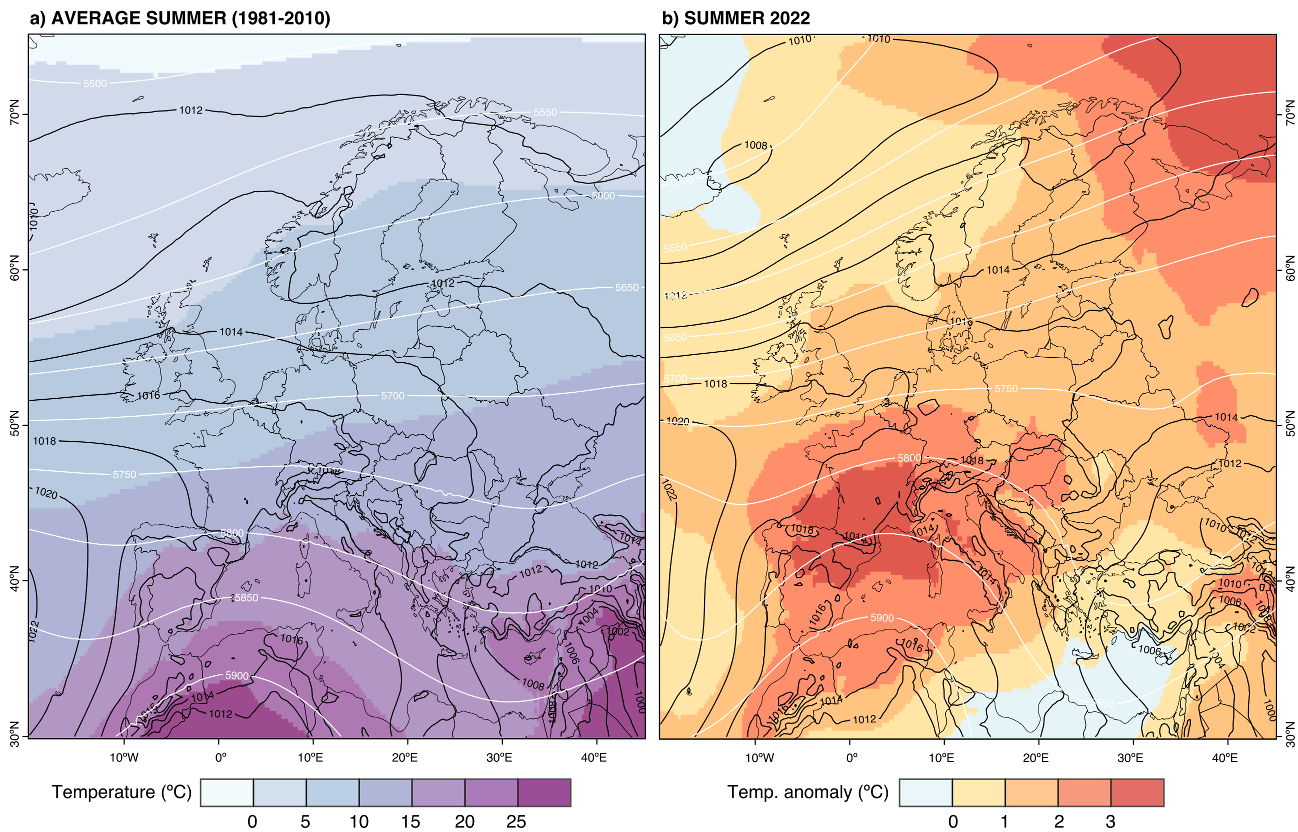

Fig. 2. Synoptic patterns of a) an average summer (1981–2010) and b) summer 2022. Summer (JJA) absolute temperatures (a) and anomalies (b) at 850 hPa (°C, shading), absolute geopotential height at 500 hPa (m, white contours), and mean sea level pressure (hPa, black contours).

air masses from African towards the IP, leading to the persistence of high temperatures during the entire summer season. On the other hand, the temperature anomalies at 850 hPa showed an exceptional +3 °C heat over northern Spain and southern France (Fig. 2b), which explains the numerous record-breaking temperatures observed in the northern region of the IP. A significant portion of these records were set during the extended HW in July. The cause of most the HW events in summer 2022 in the IP, and especially in July was different from the typical anticyclonic conditions. Instead, a cut-off low over the Atlantic that moved towards the western IP resulted in a flow of very warm air from northern Africa, contributing to an already present regular heat wave situation. The persistent blocking during several days (almost two weeks in July) led to a continued southerly flow that promoted an amplification of heating conditions. This combination of factors resulted in extreme summer temperatures and the warmest July in Spain's history (Aemet, 2022). While a comparison of atmospheric dynamics between the summer of 2022 and a regular summer (as depicted in Fig. 2) is useful to describe general patterns, it disguises some specific situations leading to isolated high-temperature events or long-lasting HWs.

For instance, the extended duration and intensity of the HW that affected mainland Spain throughout the summer of 2022 can be attributed to a persistent Azores high-pressure system over the Atlantic Ocean in July that, joined with the latent heat due to the dissipation of cloudiness and the high diurnal heating of the surface, promoted unprecedented conditions of extreme temperatures during several weeks. A low pressure in western north Atlantic Ocean in combination with the Azores anticyclone promoted the flow of a Saharan hot airmass over the IP, increasing the already warm conditions. Although there were some precipitation events, they were not enough to counteract the effects of below-average summer rainfall and high evapotranspiration rates due to continued extreme temperatures, resulting in worsening drought conditions.

This atmospheric configuration affected the whole European continent, contributing to breaking records in temperature and drought (Bonaldo et al., 2023; Toreti et al., 2022). In addition, other studies have linked this atmospheric anomaly to similar events occurred in the same season in eastern Asia, such as the anomalous anticyclone in the mid-upper troposphere over central-eastern China that caused intense HWs (Wang et al., 2023), and the anomalous zonal flow over subtropical Tibetan Plateau (Chao et al., 2023).

3.1.2. Mediterranean SST

The Western Mediterranean basin recorded a truly exceptional SST in summer 2022. These temperatures were linked to the development of very warm summer months in the whole western Europe, where new maximum records were set in land observatories (Copernicus., 2022). The SST anomalies exceeded 1 °C in the entire western basin (Fig. 3a), with the highest values observed in the Ligurian Sea, which typically has cooler waters during the year in this marine sector.

Three aspects stand out in the analysis of sea surface thermal records in this particular summer: 1) On the one hand, the persistence of high SST values throughout the season, with a clear delay in the cooling phase compared to the usual annual cycle. This phenomenon is known as a "marine heatwave" (MHW), which is defined as a prolonged period of anomalously high sea surface temperatures, typically lasting five or more days (Hobday et al., 2016). In the case of the western Mediterranean in summer 2022, the MHW lasted for 6 weeks, with SST values above the 90th percentile (anomaly > +2.5 °C) of the historical record (Fig. 3b). 2) Although the highest recorded SST in the area with slightly higher temperatures were recorded in some days during the summer of 2018, the high values reached in the entire western basin were particularly prevalent in the Balearic Sea, with maximum records reaching nearly 30 °C in August in the central part of the Mediterranean coast. Notably, these high temperatures were constant during the whole

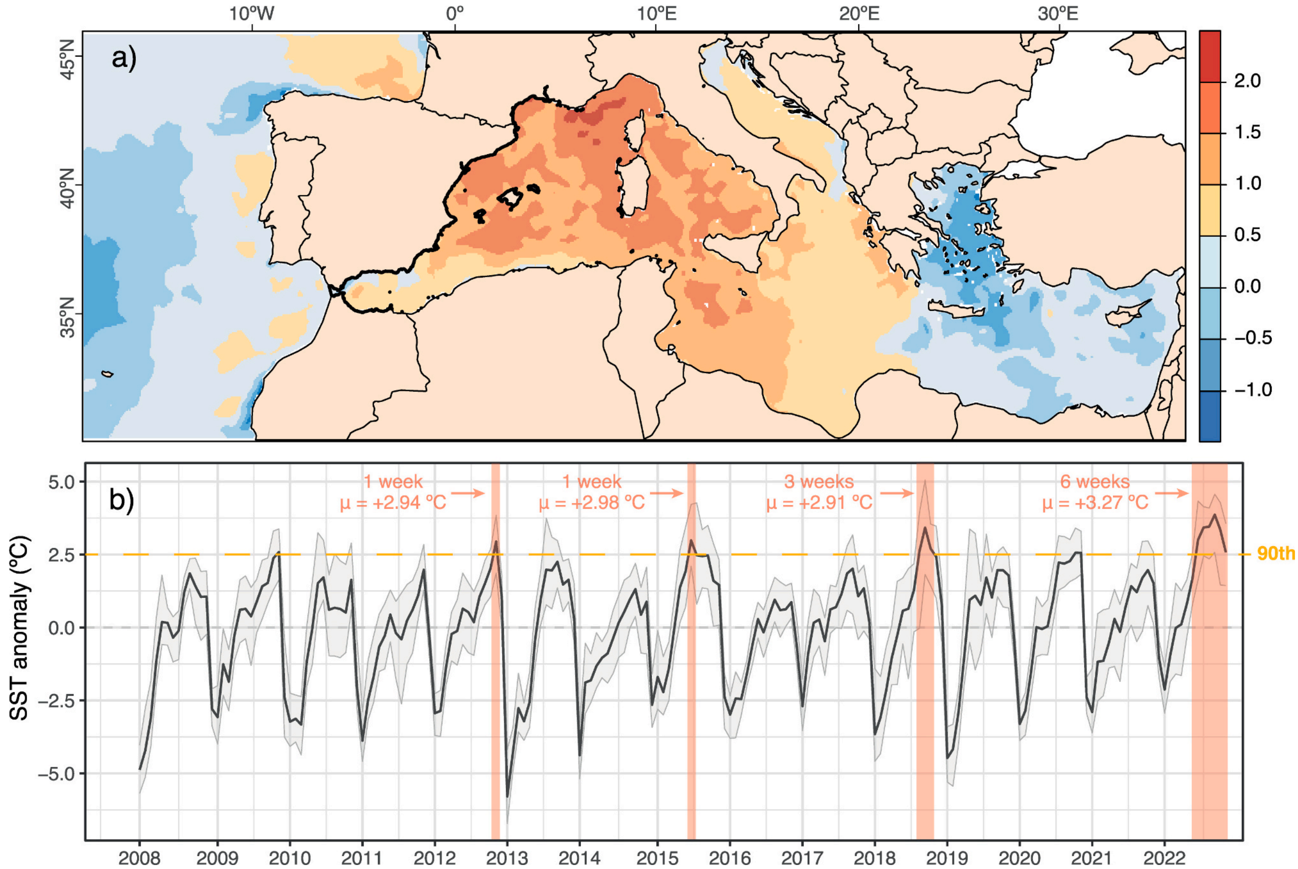

Fig. 3. a) SST summer (JJA) 2022 anomaly in relation to 2008–2022 summers. Black bold line encloses the Western Mediterranean (WM) basin (IHO, 1953). b) Weekly evolution of summer SST anomalies (2008–2022) in WM. Black line is the average values of pixels in each week and grey shading spans 5th and 95th percentile. Red bars highlight episodes of +2.5 °C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

summer; 3) Additionally, the prolonged hot air temperatures during the season led to a prolonged period of hot SSTs, with the longest continuous period with mean SST above 27 °C, including 43 consecutive days from mid-June to the end of September.

Starting in 2010, the entire western Mediterranean basin has been experiencing a warming trend (CEAM, 2022). Although the period of available data is too short to infer conclusions as significant changes, previous research with data spanning since late 20th century (Pastor and Khodayar, 2023) confirmed the significant positive trend of days within MHW conditions. Between 2008 and 2022 period, there were only four instances where the SST anomalies were higher than +2.5 °C (2012, 2015, 2018 and 2022), and the summer of 2022 had the longest (6 weeks), and warmest (average + 3.27 °C) episode of all (Fig. 3b). This trend is associated with a more frequent occurrence of MHWs in western Mediterranean, which is linked to the expansion of tropical continental air in this region of atmospheric circulation (Khodayar and Paredes-Fortuny, 2022).

The persistence of the positive SST anomalies in summer months as well as the preservation of the heat in sea surface in previous and subsequent summer months (June, September, October) have direct links with air temperatures and precipitation events during the season and several weeks after. These conditions are manifested in several aspects that have been already experienced in the past: a) Loss of thermal comfort registered in the observatories of Mediterranean shore, with a prominent expression through the increase (+65%) of tropical nights in Spain since 1980, becoming four times more frequent in the Mediterranean area (Olcina Cantos et al., 2019), reaching an average of 70 nights in 2022; b) Higher intensity of precipitations due to the higher mobilization of energy in instability processes (Tamayo and Núñez, 2020); c) Extension of risks calendars against extreme events such as intense rains, HWs or tornadoes, which forces to reformulate emergency management (Meseguer-Ruiz et al., 2021; López-Martínez, 2022); and d) Biological effects on marine ecosystems with an important increase in benthic communities (Garrabou et al., 2022) and the expansion of invasive species (MedECC, 2020).

3.1.3. *Temperature variability*

Summer 2022 set historical records for temperature in 45% and 32% of stations, based on maximum and minimum temperature, respectively (Fig. 4). The spatial pattern revealed that most of the breaking records occurred in the northeastern half of the IP, where the median elevation of the stations round 500 m a.s.l. (Fig. S1). Only 15% and 20% of locations recorded a normal summer for TMAX and TMIN records (below 10 highest values), respectively. In addition, the Canary Islands showed the highest number of these normal records, suggesting that extreme temperatures were confined to the IP. While this can be considered an exceptional summer because of the generalized breaking records, a wider analysis revealed that after the year 2000, 56% and 59% of all registered data had a positive anomaly for TMAX and TMIN, respectively. The summer of 2022 was characterized not only by the reaching of records but by the persistence of extreme temperatures throughout the season.

These anomalies are a continuation of a warming trend in Spain that has been ongoing since the mid-19th century (Brunet et al., 2007), with a stronger prevalence since the mid-20th century (Peña-Angulo et al., 2021; Perkins-Kirkpatrick and Lewis, 2020; Fernández-Montes et al., 2013; del Río et al., 2012) with a diverse spatial incidence (González-Hidalgo et al., 2022). The 21st century has already seen the highest

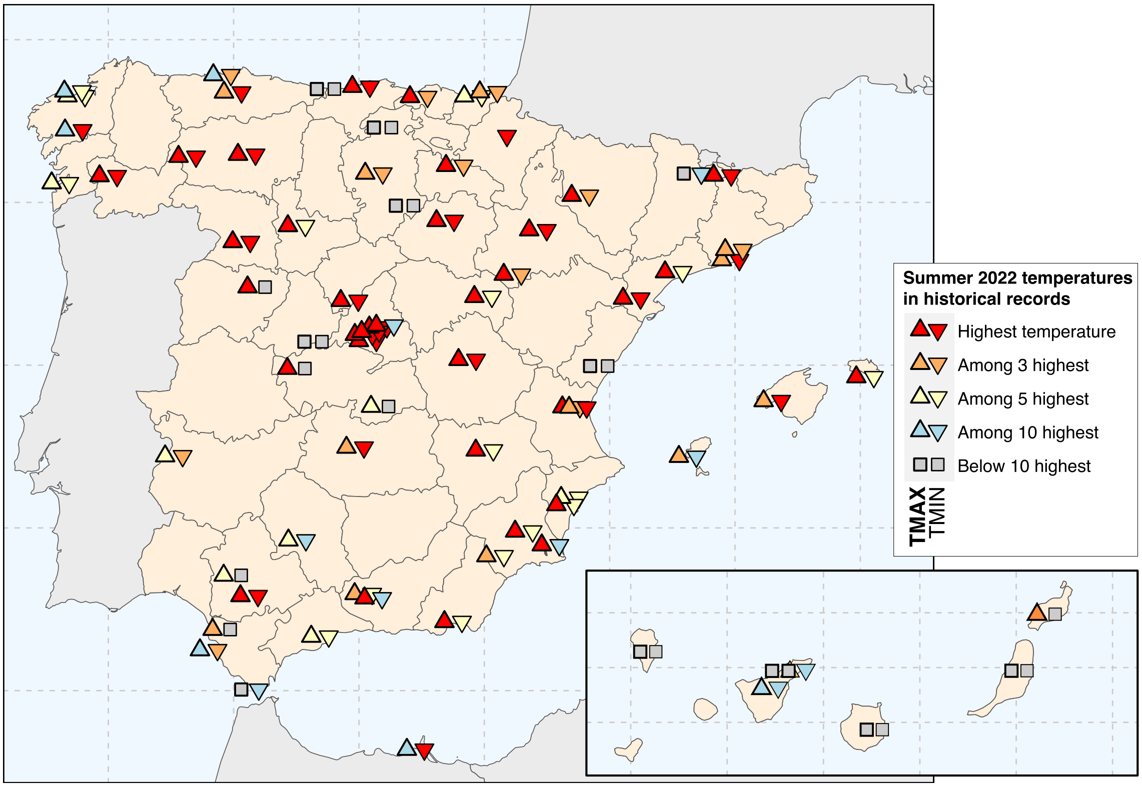

Fig. 4. Summer 2022 maximum (left, upward thick border triangles) and minimum (right, downward thin border triangles) temperature values ranked in their corresponding historical series of observations. Grey squared symbols indicate values of TMAX (left) and TMIN (right) within an ordinary summer.

temperature breaking records not only in Spain but in Europe (Barriopedro et al., 2011), and there is a high degree of confidence that these changes are human-induced, according to studies such as those by Vautard et al. (2020), and Ma et al. (2020).

During the summer of 2022, Spain experienced an unprecedented number of days under HW conditions. Out of the 75 stations taken into account, only 4 of them did not experience a HW event. However, every station recorded at least one day under HW conditions, defined as a minimum of 3 consecutive days. The average of all stations in Spain resulted in 14.6 days within a HW event, which was almost 14 times higher than the historical average of the 1971–2000 period (Fig. 5) and the maximum value since 1940. Despite the average value, a standard deviation (σ) of 11.4 indicated a high spatial variability. The average intensity of the HW was 35.2 °C (σ = 26.1), which broke the previous record, and was 39% higher than the second-ranking year, 2003. Although the mean duration of 5.2 days per event (σ = 2.2) was slightly lower than 2017 and 2003 (6 and 5, respectively), the extreme nature of the HW led to an excess of mortality higher than 5000 people (Tobías et al., 2022), which is higher than previous in episodes such as the 2003 HW (Tobías et al., 2010; Simon et al., 2005).

Although extreme temperatures affected the entire country, there was not a single unified HW event. Instead, a variable number of HW events occurred throughout the summer, exhibiting a high spatial variability. For example, Barcelona, a Mediterranean large city with moderate temperatures in summer, experienced very unusual warm conditions compared to a normal year (1971–2000 average) almost all

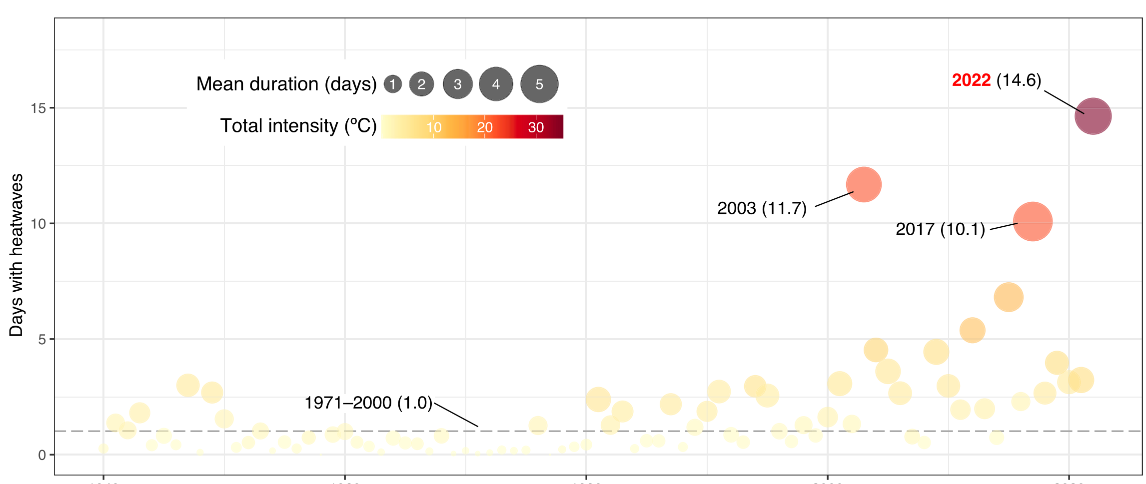

Fig. 5. Average annual days evolution within HW events in Spain. Circle sizes represent the mean duration (days) and colors show the intensity, expressed as the average accumulated temperature anomaly (°C) during a HW.

days of the summer (Fig. 6a), which caused five HW events, one of them spanning 22 days. Conversely, other inland cities like Madrid, with a higher amplitude of temperatures and prone to extremes typical from a more continental climate, registered a lower number of days within HW conditions compared to Barcelona but still higher than 1971–2000 average (Fig. 6b). In this case, a similar number of HW events (4) resulted in shorter durations and intensities, which conveys the necessity of individualized HW analyses at local scale instead of considering general behaviors of the whole network. While these examples are just a example of the summer conditions, they evidence a large spatial variability of HW occurrence (and therefore impacts) throughout the country.

The data presented in Fig. 7 indicates a steady rise in the number of tropical nights (TMIN>20 °C) since the mid-60s. This trend was previously reported by Olcina Cantos et al. (2019) in the Mediterranean area, who identified a strong correlation between SST in the frequency of such events. On average, 2022 registered 32.8 tropical nights, which is not the highest historical value. Instead, seven years (all of them in the 21st century) had slightly higher averages, with 2003 (37.4) and 2017 (37.1) being the highest. These numbers are significantly higher than the 19.9 average observed during the 1971–2000 period. Furthermore, there has been a steady increase in the occurrence of tropical nights since the 1980s, which was not as noticeable for HWs (Fig. 5). However, in the case of 2022, the difference from previous years is the standard deviation with a value of 29.1, the lowest since 1993. This suggests that the spatial coherence in the occurrence of tropical nights throughout Spain was the highest in the last 3 decades. In contrast to previous years where these vents were more regionally concentrated, in 2022, it was a generalized event in the entire country. Some locations at the Mediterranean coast, such as Valencia, reached the annual record for tropical nights (113) in 2022 (Aemet, 2022).

Among the diverse causes for the increase of tropical nights, a warmer SST (see section 3.1.2) is one of the most probable as shown in previous research (Deng et al., 2018; Efthymiadis et al., 2011), at least in the Mediterranean side of the IP (Pastor and Khodayar, 2023; Khodayar and Paredes-Fortuny, 2022; Pastor et al., 2020). While this relationship is not direct, due to the requirement of specific conditions such as the presence of subtropical air masses in the atmospheric column, and the surface stagnation of the air, the link between warmer SST in the warmest season and tropical nights has been expressed in the Mediterranean side of Spain in a clear positive trend since the 1980s (Olcina Cantos et al., 2019).

The average summer LST of the provincial capitals showed the highest values in 2022 (Fig. 8). This analysis intends to separate urban from natural areas, by averaging the LST of the urban areas from the 52 capitals. Artificial surfaces have a well-known effect on temperature increases with serious impacts on urban thermal comfort as previously shown in large Spanish cities (Marti and Royé, 2021; Lemus-Canocas et al., 2020; Rasilla et al., 2019). Here, the temporal evolution shows a positive trend since 2007 for day and night (Kendalls's τ: 0.38 and 0.43; *p-value*: 0.04 and 0.02, respectively), in agreement with previous research (Khorchani et al., 2018), and depicts an increase of >1.5 °C per decade in summer LST in Spain since mid-1980s. In this case, nighttime anomalies of the last 8 years of the series (2015–2022) were positive, with the maximum value in 2022 of almost +2 °C.

While the temporal evolution of the averaged LST showed a common trend, the climatic reality of the cities was very different between each other. The Surface Urban Heat Island (SUHI) compares the LST of the urban area with the LST of a near rural location, allowing for a quantification of the excess heat in the city. Nighttime SUHI at Spanish cities

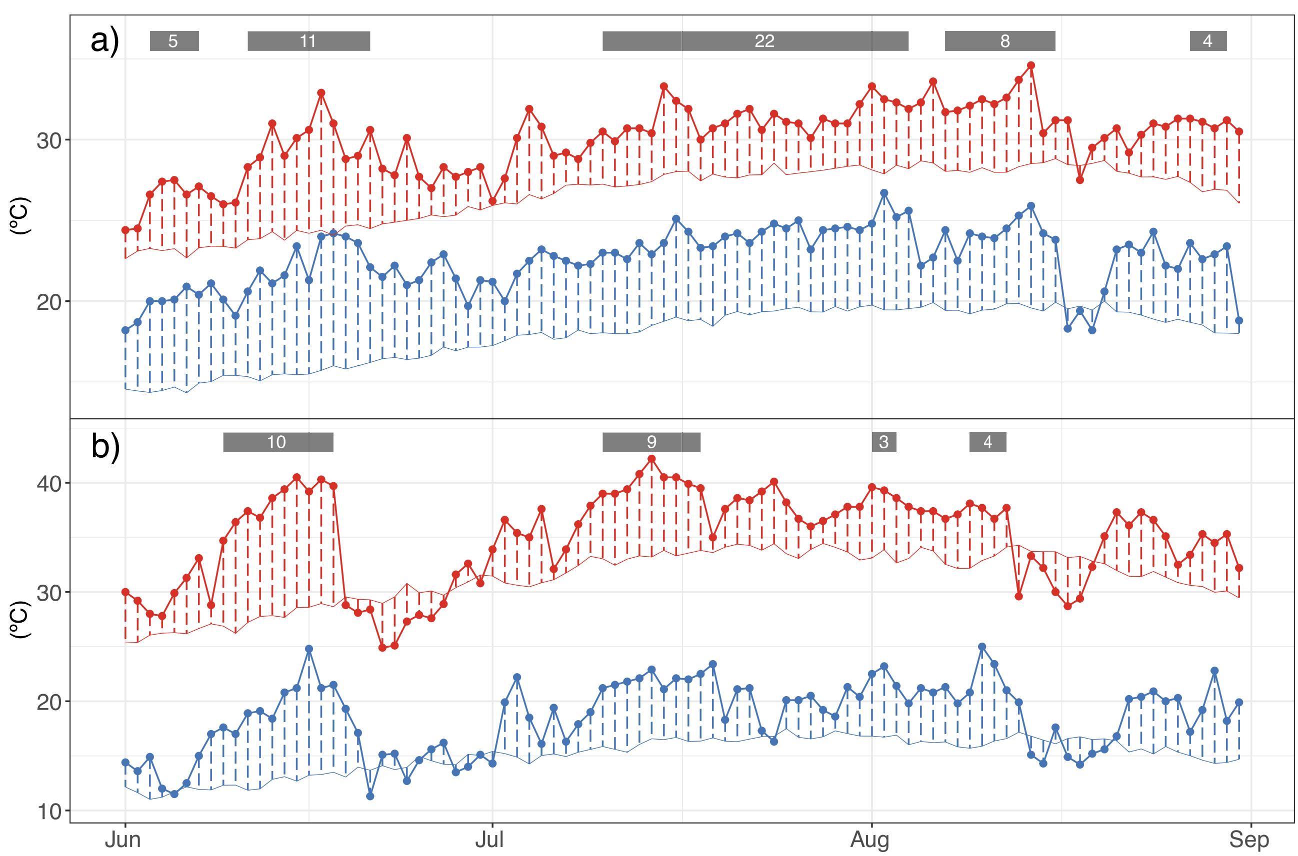

Fig. 6. Summer 2022 temperature evolution in a) Barcelona Airport and b) Madrid Airport. Red and blue lines represent TMAX and TMIN, respectively. Lines with dots are the observed temperatures in 2022 and vertical dashed lines are the excess of temperature in comparison with 1971–2000 daily average (solid thin lines). Grey horizontal bars represent the HW events and white numbers are the length of the event in days. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

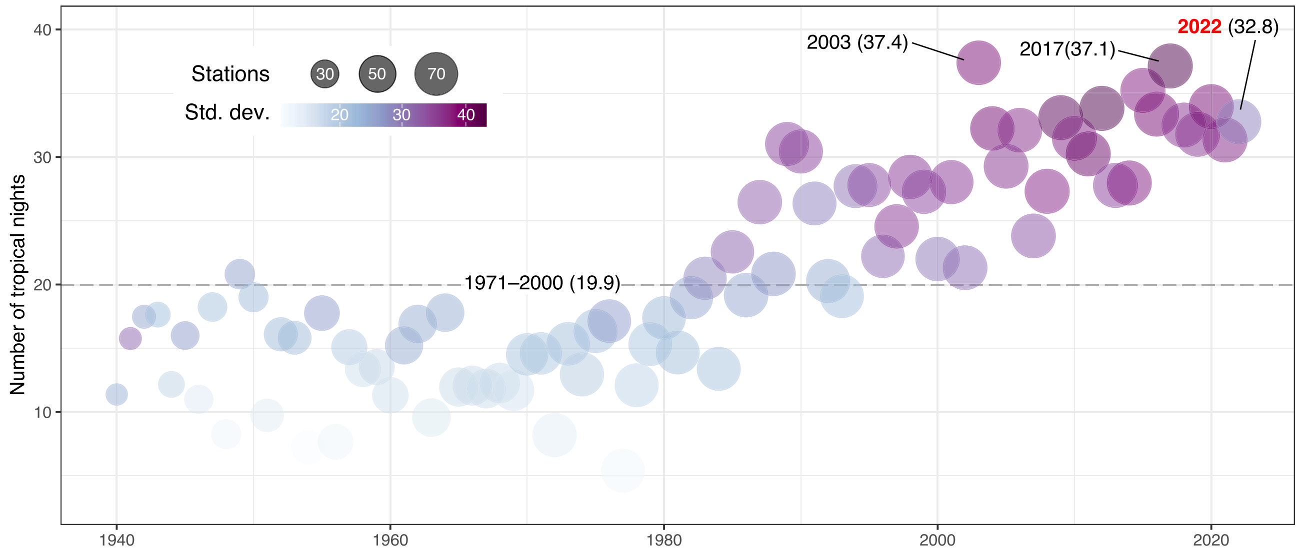

Fig. 7. Average number of tropical nights evolution in Spain. Circle sizes represent the number of available stations per year and colors show the standard deviation.

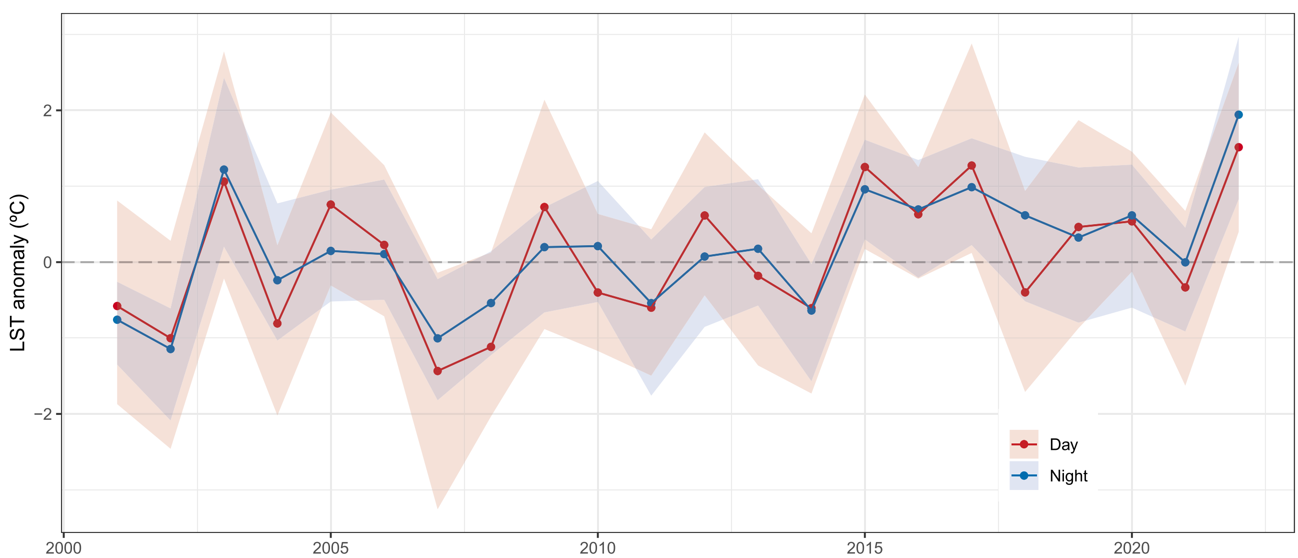

Fig. 8. Daytime (red) and nighttime (blue) evolution of annual LST anomalies (base period: 2001–2022) in urban areas in Spain. Dots connected by lines represent annual average values. Shaded areas are bounded by 5th and 95th percentiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in summer 2022 (JJA average) was, in general, more intense and larger than an average summer (period 2001–2021), although some of them experienced it in a lesser extent (Fig. 9). Barcelona intensified its SUHI by reaching values higher than 2 °C in most of its urban area and higher than 1 °C in several zones of the metropolitan area. Seville almost doubled its SUHI higher than 1 °C in extension and intensity, and Zaragoza kept similar values with a slight increase in extension northwards. On the contrary, Madrid and Valencia showed a significant reduction in intensity and extension compared to an average summer, which evidences the great differences between cities and the downside of considering the whole observation network to detect extreme events such as HW.

In this regard, the differences between an average summer and the complete summer 2022 could conceal other behaviors responding to individual events. For example, the different temperature patterns between cities described before (see also Fig. 6) showed that not all the HW events occurred simultaneously, nor the temperature values exceeded the average with the same intensity, therefore, the response of SUHI was very different individually, both by event and when considering the whole summer. The well-known relationship between HWs and urban heat island (Zhao et al., 2018; Ramamurthy et al., 2017) suggests that the SUHI under HW conditions may increase the values shown in this analysis, which intends to be an overarching depiction of the complete summer. However, further research is needed to evaluate the impact of individual extreme events and their contribution to an increased summer SUHI.

The effects of SUHI in urban areas showed to be spatially different inside the cities, with the most vulnerable populations affected by higher SUHI intensities (Dialesandro et al., 2021; Hidalgo, 2022; Hsu et al., 2021; Quintana-Talvac et al., 2021; Sarricolea et al., 2022), and, at the same time, have the less chances for adaptation and resilience. In summary, urban heat islands aggravate the effects of synoptic-scale heat waves and require special attention to urban centers and their local differences in terms of grey, blue and green infrastructure, as well as the existence of social groups at risk (the poor, the elderly, and infants), as suggested by climate-sensitive planning (Oke et al., 2017; Mehrotra

Fig. 9. Nighttime SUHI at 5 cities in Spain for (A) an average summer (period: 2001–2021) and (B) summer 2022. Numbers indicate the excess of temperature (°C) compared to non-urban near area.

et al., 2019).

The previously described occurrence of extreme temperatures has led to many negative impacts on the territory. Among the most significant effects on ecosystems were the damaging wildfires, which were particularly severe. The total area burned exceeded the 95th percentile of the historical records (2001−2021) by reaching 289,000 ha, and the persistently high temperatures caused severe dryness, which led to an increase in fuel moisture content (Rodrigues et al., 2023).

3.1.4. Hydroclimatic variability

Rainfall records were found to be within the normal range (i.e., not among the 10 driest years) in 79% of stations (Fig. 10). However, drought situations, as measured by the SPEI3, were only considered normal in 44% of stations. The SPEI considers not only the incident precipitation but also potential evapotranspiration, which is influenced by temperature. As a consequence, although the summer of 2022 was relatively normal in terms of rainfall, the high temperatures led to increased drought conditions in more than half of the country's territory.

The spatial distribution of rainfall across the IP during summer 2022 revealed a distinct NE-SW pattern that could be divided into four zones: 1) The northwest part of IP experienced a regular summer with only a few extreme records (among 5 and 10 driest years); 2) In contrast, the central area registered the highest number of records for both rainfall and drought, with a decreasing gradient from NW to SE; 3) On the Mediterranean coast, all the stations reported normal rainfall amounts, but several locations experienced extreme situations of SPEI3, with record-breaking values in Barcelona, Alicante and Granada. Lastly, 4) the Canary Islands had a regular season due to already scarce precipitation, with summer averages close to 6 mm, and very high interannual irregularity and concentrated events (Mayer et al., 2017). As a result, summer drought was the dominant feature in the islands, with Lanzarote Island (northeast extreme) among the 5 years with the lowest SPEI3 values.

The decoupling between the accumulated of summer precipitation and SPEI3 reveals a fundamental role of temperature on drought conditions. In addition to typical scarce summer rainfall in the country, the persistently high temperatures exacerbated the severity of the drought. This affection was lower in Canary Islands due to their summer rainfall regime, as explained before, but also in northwest IP, where the higher amounts of rainfall (between 100 and 300 mm on average) and lower temperature extremes (compared to the rest of the IP) keep low the atmospheric evaporative demand and, therefore, the SPEI values. By contrast, central, southern and eastern sectors of the IP registered the highest number of drought records due to abnormally high temperatures (see Fig. 4) favored, respectively, through compounded factors (described in sections 3.1.1, 3.1.2 and 3.1.3) such as: 1) a combination of continental effect and persistent anticyclonic conditions, 2) a direct reception of southerly flows of hot air masses, and 3) a positive anomaly of SST in the Mediterranean promoting heat events such as tropical nights.

3.2. A paleoclimatic perspective

To provide a broader historical context for the recorded temperature conditions of the year 2022, we must look at paleoclimatic evidence. Paleoclimatic studies have enabled us to gain insight into different climate epochs, such as the Late Antique Little Ice Age (536–660 CE) (Büntgen et al., 2016), the Little Ice Age (~1300–1850 CE) (i.e. Lapointe and Bradley, 2021) and the Medieval Warm Anomaly (~950 to ~1400 CE) (i.e., Peña-Monné et al., 2023; Bradley et al., 2003), which have been attributed to natural causes such as solar fluctuations, changes in ocean currents or volcanic events. While these climate epochs are well-documented in the northern hemisphere, they do not appear to be of the same intensity or to have occurred synchronously globally. On the other hand, the global climate warming that has been observed over the past 150 years has been coherent and synchronized globally (Neukom et al., 2019).

3.2.1. Temperature

On the IP, reconstructions of climate from various proxies tend to be biased towards the study of hydrological changes and extremes such as floods and droughts (i.e., Corella et al., 2021; Tejedor et al., 2019; Esper et al., 2015). Nevertheless, a few long-term reconstructions of tree-rings based on tree-ring width (TRW) (Tejedor et al., 2017a; Dorado-Liñán et al., 2015; Saz, 2003), maximum latewood density (MXD) (Esper et al., 2020; Büntgen et al., 2017; Dorado-Liñán et al., 2012; Büntgen et al.,

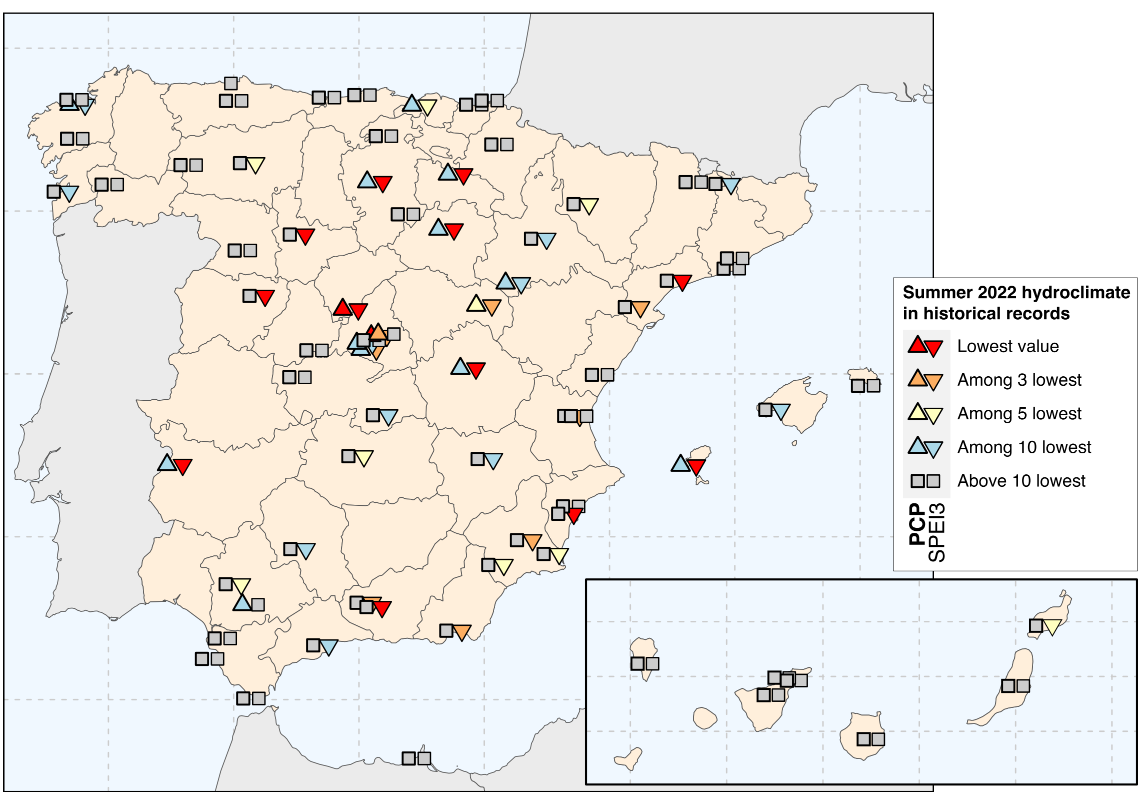

Fig. 10. Summer 2022 precipitation (left, upward thick border triangles) and SPEI 3 (right, downward thin border triangles) values ranked in their corresponding historical observations. Grey squared symbols indicate values of precipitation (left) and SPEI3 (right) within an ordinary summer.

2008) or stable carbon isotopes (Esper et al., 2015) do capture temperature signals as well. Furthermore, those reconstructions which utilize the TRW parameter can include information from the preceding growth season (i.e., Tejedor et al., 2017a). To provide a climatological context for the summer of 2022, we have therefore selected the most recent and accurately replicated warm season-only MXD reconstruction from the Spanish central Pyrenees (hereafter BUN17; Büntgen et al., 2017). BUN17 is based on 414 living and relic trees above 2000 m a.s.l. in the Spanish central Pyrenees and correlates significantly ($p < 0.01$) with the mean of May–June and August–September mean temperatures across most of the IP and northern Africa (r = 0.72; p < 0.01;1950–2014). The data for the calibration is based on the *E*-OBS v25 at 0.25° resolution and covers the period since 1950, to which we have added the observations from the Berkeley Observatory for the period since 1750 (r = 0.51; p < 0.01; 1750–2014). Figure 11 depicts the BUN17 reconstruction with the updated instrumental data, which show a remarkable positive anomaly of 3.9 °C with E-OBS data and 3.5 °C with the Berkeley data, compared to the previous 700 years. This finding is even more noteworthy due to the fact that July, the warmest month of the summer, was excluded when calculating the warm season. Although the first ~150 years of the BUN16 (1186–1300 CE) display higher temperatures within the uncertainty margins, such period has to be interpreted with caution because it has a low sample size (see Büntgen et al., 2017 for details). Among the last 700 years, which have a much better replication, only 8 years exceed the 3sd threshold (+2.76 °C), with the highest being 1933 at 3 °C, followed by four years in the XIV and XV centuries at almost 3 °C. Consequently, the anomalies shown by the instrumental data would qualify as a record-breaking and extremely unusual, placing them within the 4sd range in a multi-centennial context.

3.2.2. Hydroclimatic variability

In the last few years, various research studies have furthered our knowledge on past hydroclimatic conditions in the IP. For instance, historical documents liken rogation ceremonies have provided context for these conditions and allowed for the validation of other paleoclimatic reconstructions or historical events (see for example Vicente-Serrano and Cuadrat, 2007). Despite these recent advancements, the findings from these studies only offer qualitative or semi-quantitative, continuous hydroclimatic information (Tejedor et al., 2019). Thus, for a more detailed evaluation of the frequency, duration, and extremity of hydroclimatic variability, tree rings offer a better, high-resolution, and continuous source of information. From the existing tree-ring based reconstructions of past hydroclimatic conditions in the IP, two of them are located on the Iberian Range and have been developed using TRW data (Tejedor et al., 2016; Esper et al., 2015). These have included information regarding not just summer but also spring (Esper et al., 2015) or even the whole hydrological year (Tejedor et al., 2016). Andreu-Hayles et al. (2017) developed a 400-year reconstruction of summer hydroclimatic conditions in Northwestern Spain, however, this was done by inferring information from stable isotopes, which require more complex interactions between tree rings and climate. Here, we have instead focused on the reconstruction from Tejedor et al. (2017b) which used latewood width (LW) data to infer summer conditions of the Northeast of Spain. This reconstruction was based on 138 *Pinus uncinata* and 249 *Pinus sylvestris* trees (22 different sites) growing in high-elevation mountains (>1700 m a.s.l.) within the Pyrenees and the Iberian Range, with the LW parameter being well-correlated with the SPEI conditions of August, including the two months preceding it (r=)0.67, p < 0.01, 1950–2013). Furthermore, the LW reconstruction (TEJ17) also showed high correlations with central Spain (r > 0.55, p < 0.01), as well as moderate yet significant correlations with the Baetic system, northern Africa, and southern France (r > 0.40, p < 0.01).

Therefore, to assess the summer conditions of 2022, we have updated the instrumental data used to compute the SPEI2 of August (Figure 12). The composite instrumental data indicated that this summer has been the driest since 1950, displaying an SPEI value of −1.68, and falling below 1.5 standard deviations of the TEJ17 reconstruction since 1734. From the five most extreme dry years within the full reconstruction, three were recorded during the 21st century (2013, 2012, and 2005), confirming the increased risk of the current warming trend and frequent drought periods in the Mediterranean climate, which amplifies evapotranspiration and makes droughts even more extreme. Other dry periods, however, such as from 1734 to 1750 and 1802–1806, have occurred and the uncertainty values of their associated data may place them in the range of the summer of 2022. Nevertheless, based on the

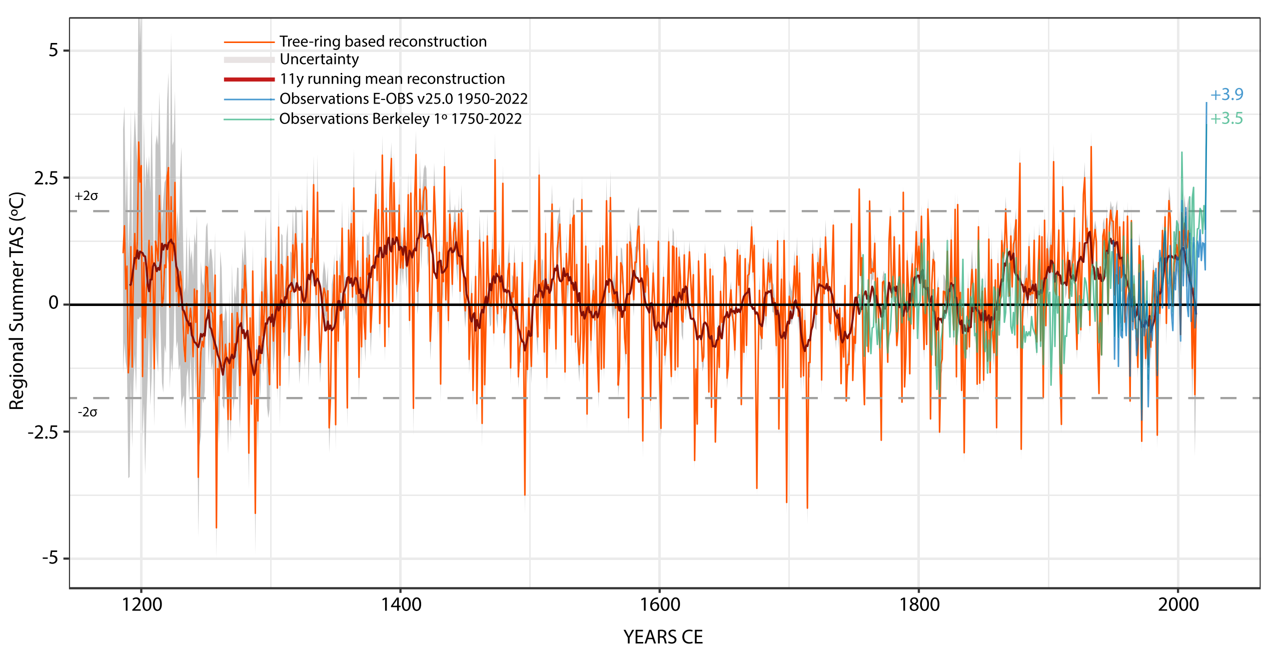

Fig. 11. Maximum latewood density-based warm-season (May–June & August–September) temperature reconstruction of the Spanish Pyrenees (Büntgen et al., 2017). The reconstruction (orange) is compared with the updated instrumental data used for calibration.

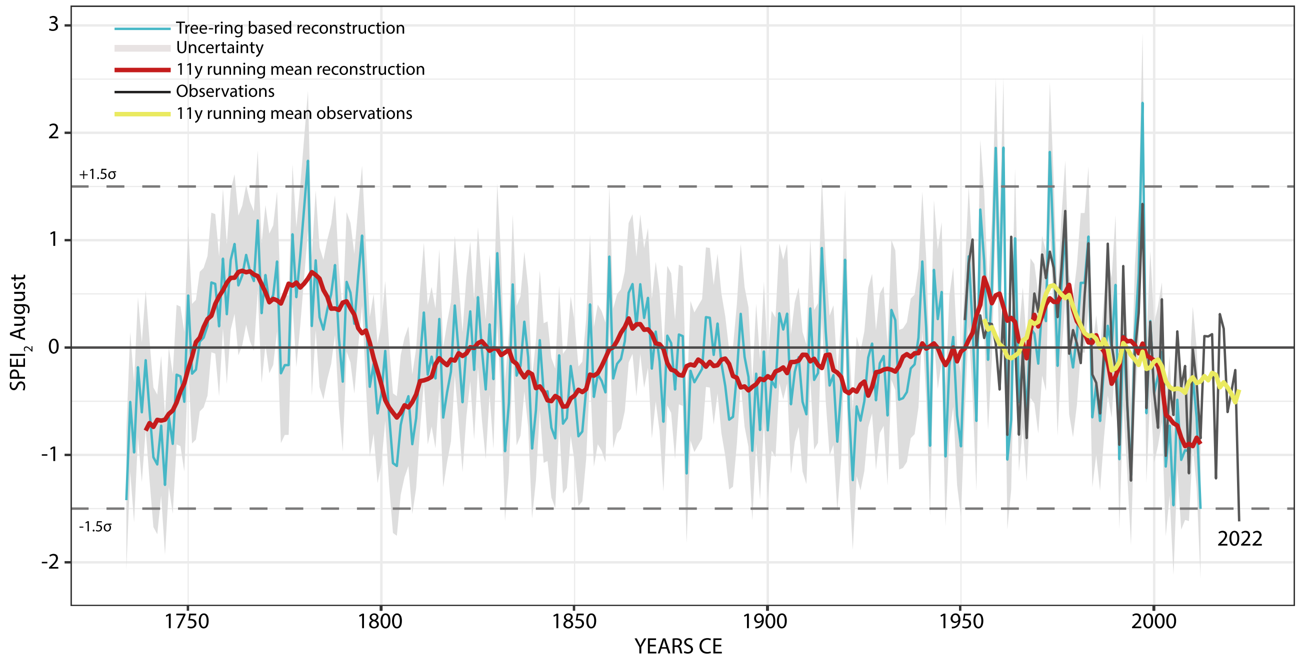

Fig. 12. Latewood-width based summer hydroclimatic reconstruction of Northeastern Spain (Tejedor et al., 2017b). The reconstruction is compared with the instrumental updated SPEI2August data used for calibration (in grey).

good agreement between the LW parameter and given the principle of linearity, it is very likely that the summer of 2022 may stand as the one with the most intense summer drought since 1734.

4. Conclusions

In our analysis, we examined the climate of summer 2022 in Spain and placed it in a historical and paleoclimatic context. Our findings indicate that the season was extremely warm when compared to the observations of the 20th century across the entire country and the previous 700 years in the Pyrenees. Although rainfall amounts were within the normal range for a typical Mediterranean summer in most of the stations, the persistent high temperatures led to increased evapotranspiration, resulting in severe drought conditions, particularly in the central part of the IP and along in the Mediterranean coast. The Canary Islands, due to their location outside the primary heat centers in the European continent, experienced a relatively typical summer.

The summer climate anomalies observed in Spain in 2022 were caused by an abnormally persistent atmospheric configuration, particularly during the main HW event in July. This led to record-breaking Mediterranean SST (+3.3 °C), average temperatures (+2.1 °C), number of days with HW conditions (+4 days compared to the previous hottest year, 2003), and urban LST (+2 °C). However, the number of tropical nights (32.8) was similar to the previous 15 years, and rainfall was within normal values for 79% of stations. The paleoclimatic perspective showed an extreme positive anomaly in the Pyrenees (> + 3.5 °C) and a breaking record for drought conditions in northeast Spain (<−1.5 std. dev.). However, further research is needed in this regard since the comparison between the temperature and hydroclimate reconstructions is an estimate, relying upon the correlations that were found during the instrumental period and assuming linearity. Although paleoclimatic reconstructions yielded reliable reconstructions, they explain 45–50% of variance, making allowance for an improvement of uncertainty.

The exceptional character of summer 2022 was not just the occurrence of local breaking records but the persistence of an atmospheric situation that favored extreme temperatures throughout the season. While occasional HW events can be managed in terms of adaptation, if they are intense and persistent such as the summer 2022 conditions, new social adaptation strategies will be needed.

Finally, it is important to note that while our analysis does not attempt to attribute the observed anomalies to climate change, previous research has suggested that extreme events like HWs and tropical nights are projected to be more frequent in southwest Europe (IPCC, 2021). Therefore, it is essential to adopt a precautionary and multi-faceted approach and prioritize the development of policies and plans that can mitigate the impacts of extreme heat events, especially in urban areas where the urban heat island effect can exacerbate the risks to vulnerable populations. This can be achieved through measures such as the establishment of climate shelters and climate-sensitive planning that enhances resilience and adaptation to climate change.

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CRediT authorship contribution statement

Roberto Serrano-Notivoli: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Ernesto Tejedor:** Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Pablo Sarricolea:** Formal analysis, Writing – review & editing. **Oliver Meseguer-Ruiz:** Writing – review & editing. **Martín de Luis:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision. **Miguel Ángel Saz:** Writing – review & editing, Resources. **Luis Alberto Longares:** Writing – review & editing, Resources. **Jorge Olcina:** Writing – original draft, Writing – review & editing, 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

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosres.2023.106931.

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